Selective transport phenomena in coastal sands
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Chapter 3

Experiments in a wave tunnel

3.1 Introduction

The experiments described in the former chapter had an exploratory character; the small flume allows only for low velocities and short wave periods which are not well representative of the conditions which occur on the Dutch coast. To overcome these restrictions, experiments were carried out in the Large Oscillating Wave Tunnel (LOWT) of Delft Hydraulics, ‘de Voorst’, in the spring of 1994. These experiments were supported by the EU programme ‘Human Capital and Mobility’ under its division Large Installations Programme.

The experiments described in this chapter are the first in the LOWT in which sand with a high concentration (≈40% of the mass) of heavy minerals was used. In the initial part of the tests, conditions were chosen as close as possible to the conditions used in the flume (Chapter 2). This meant that in the experiments a small section of the tunnel was covered with a thin bed of sediments and that peak velocities under crest and trough were chosen such that they had an overlap with the flume experiments. Complete overlap could not be achieved since the LOWT is not able to generate waves as short as in the flume experiments.

In the second part of the experiments conditions were chosen to correspond with the normal kind of experiments in the LOWT. For that purpose the test section of the tunnel was covered with a thick layer of sediment over its full length. Wave period and peak velocities were set similar to those used in earlier test-series, carried out with uniform light sediment ($\rho_s = 2.65 \text{ kg L}^{-1}$) [Rib94]. The velocities were higher than in the wave flume and correspond to the sheet-flow regime (see Chapter 1). These conditions are considered to be representative for conditions near the seabed in the field under moderate to
strong wave action. They were designed on the basis of estimated near-bed oscillatory flow conditions in the North Sea at the Dutch shoreface at water depths of 5-25 m in moderate to strong wave conditions [Rib94].

The experimental test-series can thus be divided in two types:

I : The ‘thin layer experiment’ consisting of test-series with an initial sediment bed of approximately $1.0 \times 0.3 \times 0.02$ m$^3$ (length $\times$ width $\times$ thickness). Two wave regimes were applied; one in the ripple regime (F1) and one in the sheet flow regime (F2).

II : The ‘thick layer experiment’ consisting of test-series with an initial sediment bed of $12.5 \times 0.3 \times 0.3$ m$^3$, i.e. covering the total length of the flume. All five test-series were in the sheet flow regime (F3 - F7).

Type (I) was carried out to get more insight in the selective transport mechanisms under the chosen conditions and to make a comparison possible with experiments carried out in the wave flume at Delft University of Technology in 1992 (see Chapter 2). Experiments of type (II) allow for a comparison between behaviour of sediment with a high concentration of heavy minerals and that of ‘normal’ (quartz) sand as used in experiments in the LOWT by Al-Salem and Ribberink in 1992 [Rib94].

During both experiments a BGO detector was used for detection of $\gamma$ radiation. This detector is part of the MEDUSA system as utilised by the Environmental Radioactivity Research Group (ERG) to study sediment transport near the Dutch Frisian Islands of Terschelling and Ameland. In those studies the MEDUSA system, containing among other sensors a BGO detector, is towed behind a vessel over the sea floor. In this way the natural radioactivity of the sediment is recorded and is collected to derive information on selective transport of heavy and light minerals. In the present study such a BGO detector system was also used to test its sensitivity under laboratory conditions and to validate the methodology to extract information on sediment composition from the natural $\gamma$ radiation emitted by the sediment. This validation could be made by taking samples from the sediment and analyse them for grain size, density and activity concentrations. Moreover the results of the analysis were used to derive sediment transport rates.

In case of the thick layer experiment the measured transport rates were lower than when ‘normal’ sand was used. The sample analysis and radiation measurements showed that the heavy mineral content in the bed was increasing. It will be shown that the observed changes in radiation levels may be described in a ‘two-layer-approach’. In this approach the sediment is considered to consists of a layer that is ‘active’ in the transport process and an
‘inactive’ layer. This approach also allows for a calculation of transport rates for heavy and light minerals separately and to derive an estimation of the thickness of the active layer from the data. To perform these calculations the results of the radiation measurements were used.

This chapter starts with the discussion of the experimental set-up and used methods. Then in section 3.3 the thin layer experiment will be discussed and compared to the waveflume experiment described in the former chapter. The thick layer experiment and the ‘two-layer-approach’ are discussed in section 3.4.

3.2 Experimental set-up

3.2.1 The Large Oscillating Wave Tunnel

![Diagram of the Large Oscillating Wave Tunnel](image)

**Figure 3.1: Large Oscillating Wave Tunnel**

The Large Oscillating Wave Tunnel (LOWT) was designed to simulate the situation under waves in the nearshore zone, in the region close to the bottom at a one to one scale. Figure 3.1 presents a schematic view of the LOWT. As can be seen the LOWT has a long rectangular horizontal test section with two cylindrical risers at either end. A piston system in the closed cylinder, driven by a hydraulic servo-cylinder, is capable of simulating near bottom velocities in the test section that correspond to moderate to rough wave conditions. The steering signal for the hydraulic piston is generated by a PC. The other riser is open to the atmosphere. Of the test section, that measures approximately $14 \times 0.3 \times 1.1$ m$^3$, the lower 0.3 m is available for a sand bed and the upper
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0.8 m for the oscillatory flow. At both ends of the test section a sand trap is located to collect the sediment that is transported out of the tunnel.

Test measurements indicated that the horizontal velocity amplitude is uniform in the central axis over the middle 10 m of the test section. For the vertical component, however, the uniform behaviour of the velocity fluctuations (the estimated velocity amplitude) is restricted to the central 7 m. No systematic variations in the horizontal velocity component in the lower 20 cm of the central 2.0 m were found [Rib89].

The positions in the test section are denoted with an x coordinate in the range of -6.25 up 6.25 m where x = -6.25 m corresponds to the position nearest to the piston.

All experiments were carried out with regular asymmetric second-order Stokes waves:

\[ U(t) = U_1 \cos \omega t + U_2 \cos 2\omega t, \]  

(3.1)

where \( U(t) \) is the near-bed horizontal orbital flow and \( \omega \) the angular frequency of the basic oscillation. The peak velocities under the crest and trough of the wave are given by \( U_c = U_1 + U_2 \) and \( U_t = U_1 - U_2 \), respectively. The root-mean square velocity \( U_{rms} = 0.5 \cdot (U_1^2 + U_2^2)^{0.5} \). 'Real' waves propagate in the direction of the crest velocity. In the LOWT the wave direction is equal to the direction of the largest peak velocity.

The LOWT is equipped with a forward-scatter laser-doppler system for the measurement of the horizontal and vertical velocity components at every desired position in the test section of the tunnel. It is based on the Doppler shift of incident laser light due to moving particles in the water. It determines water velocities with an accuracy of 1.7%. In the present experiments, the laser doppler system was positioned in the middle of the test section at \( x=2.0 \) m, at 40 cm above the bottom.

A transverse suction system, as developed by Bosman et al. (1987), was mounted in the test section to measure average suspended sediment concentration profiles \( C(z) \) [Bos87]. In figure 3.2 a schematic view of the transverse suction concentration meter is given. It was located in the middle of the LOWT at \( y = 0.15 \) m and \( x = 0.3 \) m with the nozzles (Ø 3 mm) perpendicular to the (horizontal) fluid mo-
3.2 Experimental set-up

The fluid with the suspended sediment was pumped out of the LOWT with a constant velocity and collected in reservoirs. In a volume meter the wet volume of the sand present in the reservoirs was determined from which the suspended sediment concentrations (g L\(^{-1}\)) in the suction samples were calculated assuming a certain porosity. The ratio between the concentration in the suction samples \(C_s\) and the actual sediment concentration in the flow \(C_c\) is given by the trapping efficiency \(\alpha = C_s/C_c\). This factor depends on the grain size and is constant if the suction velocity is high enough (≈ three times the fluid velocity). Its value was determined in a calibration procedure for several types of sediment [Bos87].

To test the effect of the presence of the suction system on the experiments two test-series (F6 and F7) were performed without the sediment concentration meter.

3.2.2 The BGO detector system

The BGO detector system as described in section 1.5.2 was used. For the thin layer experiments a lead shield was placed under the test section of the tunnel. This was necessary because the background level was relatively high compared to the radiation intensity of the sand. When the sediment bed is thicker than 10 cm the radiation level will be a factor 20 higher than the background; moreover the majority of the gammas coming from the concrete floor of the laboratory will be absorbed by the sand (a sediment bed with a density of 3.2 kg L\(^{-1}\) and a thickness of 10 cm will reduce the radiation level as generated by the floor by ≈ 80% which then makes a contribution of less than 1% to the total radiation level).

The distance from the bottom of the tunnel to the detector was kept constant throughout the test-series. The detector was never in contact with the sediment bed in order not to disturb it.

During the tests the detector was taken out of the tunnel. By letting out part of the water, avoiding disturbance of the sediment bed, the tunnel could be opened and the detector put in place.

The \(\gamma\) spectra as recorded by the BGO detector system are transformed to activity concentrations by spectrum deconvolution as described in section 1.5.3. No calibration sources are available for the LOWT and therefore the standard spectra were obtained on three concrete calibration pads used for the general calibration of the system (see section 1.5.3). Because the geometry in the tunnel differs from the pads, the output of the detector system is not equal to the activity concentrations. Therefore radiation intensities \(I\) will be given in arbitrary units (a.u).
The radiation intensity was measured in still water with the detector at a fixed height with respect to the bottom of the test section. If the height of the sediment bed is varying, measured radiation levels have to be corrected for the absorption of $\gamma$ rays by water according to the relation

$$I_m = I_0 e^{-\mu_w d},$$

where $I_m$ is the measured and $I_0$ the corrected radiation intensity. The term $e^{-\mu_w d}$ accounts for absorption by water. The absorption coefficient of water $\mu_w$ for the natural radiation spectrum was determined experimentally. To that end the radiations levels $I_m(d)$, measured at several heights $d$ above the sediment bed, are fitted with the function given in equation 3.2. In this way an absorption coefficient of $0.090 \pm 0.003$ cm$^{-1}$ for $^{214}$Bi and $^{232}$Th was found$^1$ (fig. 3.3). This agrees with an average of the values found in literature which range from 0.12 - 0.04 for the energy range from 300 to 3000 keV [Deb88].

The inaccuracy in the calculation of $I_0$ depends on the accuracy of the sediment-bed height measurements. The error ranges from 5 - 20 % for $^{214}$Bi and $^{232}$Th, where the higher value occurs only for the erosion hole due to the irregular structure of the bottom surface. In the main part of the test section where the bottom is smooth an uncertainty of 5-10 % is obtained.

The energy of the $\gamma$ rays emitted by $^{40}$K is lower than for some prominent peaks in the bismuth (uranium) and thorium spectra. Therefore the scattered radiation originating from the latter two contributes to the continuous part of the potassium spectrum. Due to the high concentrations of heavy minerals present in the tunnel the $^{214}$Bi and $^{232}$Th contribution are dominant in the $\gamma$ spectrum and results in relatively large uncertainties in the derived $^{40}$K radiation intensities (see fig.3.3). In view of these uncertainties the $^{40}$K activities will not be used in further analysis of the data.

### 3.2.3 Radiation levels

To understand the measured radiation patterns over the flume, shown in figure 3.11, a two layer approach is assumed: the top layer is active in the transport process and changes in composition, and consequently in activity concentration, while the lower layer keeps its original composition. This corresponds to the assumptions that only the upper layer of the sediment bed is influenced by the fluid motion. A one-dimensional model for the radiation intensity in the tunnel will be given. With this same approach it is also possible to calculate transport rates for two separate fractions. Transport rates for a heavy and

$^1$Any geometrical effect is incorporated.
### 3.2 Experimental set-up

#### Figure 3.3: Measured radiation levels $I$ for $^{214}$Bi, $^{232}$Th and $^{40}$K as function of the distance between the detector and the sediment bed $d$. The lines through the data are fits of the form $I = I_0 e^{-\mu w d}$ where $\mu w$ is the absorption coefficient of water for natural $\gamma$ radiation. The value of $\mu w$ for $^{214}$Bi and $^{232}$Th is $0.090 \pm 0.003$ cm$^{-1}$; the $\chi^2_{\text{red}}$ values are 1.1 and 0.75, respectively.

Light fraction are calculated in section 3.2.6 where the results of the radiation measurements will be used.

As a first step a more general situation will be considered: the radiation level measured above a semi-infinitely extending homogeneous bed of sand [Gre89]. Consider a semi-infinitely extending bed of sand of thickness $z$ made out of homogeneous material with a density $\rho$ (kg m$^{-3}$) and an activity concentration $A$ (Bq kg$^{-1}$). What will be radiation intensity $I$ measured at the surface? First the contribution to $I$ of a thin layer at a depth of $z - z'$ under the surface is considered (fig. 3.4). If build-up effects are ignored, the radiation intensity originating from this layer that reaches the surface is given by

$$dI(z) = 0.5 \times \rho \times (1 - \varepsilon_0) \times A \times e^{-\mu(z-z')}dz'.$$

In this equation a factor 0.5 is the solid angle for detection (only half of it will go in the upward direction) and $\varepsilon_0$ is the porosity of the bed. The term $e^{-\mu(z-z')}$ accounts for absorption of photons by the covering layer of sand. The parameter $\mu$, the linear absorption or attenuation coefficient (usually
expressed in cm$^{-1}$), depends on the energy of photons and density of the material. Since the method of spectrum deconvolution is using the total $\gamma$ spectrum and not only the contents of the photo peak, $\mu$ is considered to be an energy average and can be regarded as a characteristic parameter of the sand.

The value of the absorption coefficient depends on the type of material and density:

$$\mu = \mu_w \times \frac{\rho(1 - \varepsilon_0) + \varepsilon_0 \rho_w}{\rho_w}, \quad (3.4)$$

with $\mu_w$ and $\rho_w$ being the absorption coefficient and the density of water, respectively. Introducing $r$ as the (dimensionless) bulk density,

$$r = \frac{\rho(1 - \varepsilon_0) + \varepsilon_0 \rho_w}{\rho_w}, \quad (3.5)$$

and integrating over the total depth, an expression is obtained for the radiation level at the surface

$$I(z) = \int_0^z dI(z) = 0.5 \frac{\rho A}{r \mu_w} (1 - e^{-\mu_w rz}). \quad (3.6)$$

If the sediment bed is thick enough the self-absorption term $e^{-\mu_w rz}$ can be neglected (for $r = 2$ and $z = 20$ cm $e^{-\mu_w rz}$ becomes 0.02) and the radiation level will be independent of the thickness of the sediment bed

$$I(z) = \int_0^z dI = 0.5 \frac{\rho A}{r \mu_w}. \quad (3.7)$$

Since $\mu_w$ is constant, the radiation level as measured above a homogeneous sediment bed is a function of density, activity concentration and porosity of the sand.

This model can easily be modified to the situation in the tunnel where the sand bed has finite dimensions by introducing a factor $c$ that takes into account the geometric situation in the LOWT$^{2}$:

$$I(z) = \int_0^z dI = c \frac{\rho A}{r \mu_w}. \quad (3.8)$$

This ‘one-layer-model’ can be extended to a ‘two-layer-model’. Consider a (finite) bed of sand of thickness $z_0$, a density $\rho_0$ and a activity concentration $A_0$. It is covered by a layer of sand with a thickness $d$, a density $\rho_d$ and

---

$^2$It also takes into account the factor 0.5 as used in equation (3.6)
an activity concentration $A_d$. This layer will not only absorb the radiation coming from the underlying sand but also produce photons itself. This leads to the following expression for the radiation level at the surface

$$I(z_0 + d) = I(z_0) e^{-\mu_w r_d d} + c \frac{P_0}{\mu_w r_d} A_d (1 - e^{-\mu_w r_d d}),$$

(3.9)

where $r_d = \rho_d (1 - \varepsilon_0) + \varepsilon_0 \rho_w$ and $I_0$ is considered to be constant. The factor $c = \frac{I_0 \rho_0 \mu_w}{\rho_0 A_0}$

From sample analysis the activity concentrations for bismuth and thorium $A_d^{Bi, Th}$ will be known as a function of density. Therefore equation 3.9 gives the radiation intensity as function of density of the sediment in the upper ‘active’ layer. Density and activity concentration $\rho_0$ and $A_0$ for the ‘original’ sediment are measured. The absorption coefficient for water $\mu_w$ was determined (see figure 3.3) and the detector measurements at $t = 0$ will provide the radiation intensity $I_0$. The porosity $\varepsilon_0$ is taken to be 0.4. This leaves the thickness $d$ of the top layer as the only unknown parameter.

### 3.2.4 Sampling analysis

During the thin layer experiments samples of several hundred gram were taken, using the same syphon method as with the experiments in the flume (Chapter 2). In case of the full sediment bed experiments, a surface layer with a thickness of about 2 cm was scooped off the bed with a shovel over a length of $\approx 10$ cm, after which the sand was stored in 0.5 L bottles. No effects of this procedure on the experiments have been observed.

From the sand samples that were collected during the experiments the following parameters were determined:

- density
- grain-size distributions
- $^{214}$Bi, $^{232}$Th and $^{40}$K activity concentrations

The first two measurements were done at Delft Hydraulics, the activity concentrations were measured at the KVI.

**Density measurements** The sand was weighed under water, dried at 100°C and than weighed again. From the two masses the specific density
of the samples $\rho_s$ follows from the relation:

$$\frac{\rho_s}{\rho_w} = \frac{M_d}{M_d - M_u}, \quad (3.10)$$

where $\rho_w$ is the specific density of water, $M_d$ the dry and $M_u$ the mass under water. Densities can be measured with an uncertainty of less than 1% provided there is enough material to perform the weighing procedure accurately\(^3\); the mentioned uncertainties are valid for samples of more than 10 g.

**Grain-size distributions** Grain-size distributions were determined by putting the dry samples through a stack of 15 sieves with mesh sizes in the range from 500 to 45 $\mu$m. About 70 g of material was sieved each time; larger samples were processed by dividing them in a number of sub samples. The $d_{50}$, $d_{30}$ and $d_{10}$ were obtained by linear interpolation. Only part of the samples were processed.

**Activity concentrations** Samples were measured on a HPGe detector with 0.25 L bottles as sample holder. The measuring time was long enough to register at least 1000 counts in the 609 keV peak (\(^{214}\)Bi ) ensuring sufficient counting statistics. Reasonable estimates for the inaccuracies in the results are 5% for samples with a density below 3.5 kg L\(^{-1}\) and 10% for the more heavy samples. The difference is a consequence of the larger uncertainty in the absorption coefficient for the more dense samples.

### 3.2.5 Sand

The sand used in this experiment was taken from the North Sea beach of the Dutch Island of Ameland (pole 17.800) where a heavy mineral placer was deposited on the beach during a storm in the winter of 1991-1992. In the spring of that same year 'big bag' samples with a total volume of $\approx 5$ m\(^3\) were collected from this area before the placer was covered by a beach nourishment a few months later. From the place where it was stored for two years, the sand was brought directly to the laboratory without any chemical preparation.

To determine the sediment characteristics, three samples were taken from each bag. Because the sand properties in the six bags were similar, only general characteristics will be given here. In the data report that is available from these experiments the characteristics for each sample separately are presented [Tan94].

\(^3\)this value is based on test measurements with sand of known density
3.2 Experimental set-up

- median grain size $d_{50} = 142 - 157 \mu m$,
- median settling velocity $w_{50} = 18.2 - 19.6 \text{ mm s}^{-1}$,
- density $\rho_n = 3.1 - 3.3 \text{ kg L}^{-1}$

In figure 3.5 the density per sieve fraction is plotted for a mixture of two samples from the same bag. One can see that for fractions on the sieves with a mesh size smaller than $150 \mu m$ the density is considerably larger than for those on larger sieves; average densities of the two fractions are $3860 \pm 70$ and $2750 \pm 30 \text{ kg m}^{-3}$, respectively. It was decided to divide samples in two fractions with a sieve with a mesh width of $150 \mu m$ to obtain information on the amount of heavy minerals present in a sample.

![Figure 3.5](image)

**Figure 3.5:** Density per sieve fraction of a mixture of two of the samples of the sand used in the experiments. The relatively high inaccuracies for the largest and smallest mesh sizes are because not enough material for an accurate density measurement was collected on these sieves.

The average of the bismuth and thorium activity concentrations of the samples taken from the six bags were (with standard deviation) $A_{Bi} = 400 \pm 60 \text{ Bq kg}^{-1}$, $A_{Th} = 280 \pm 40 \text{ Bq kg}^{-1}$, respectively. The spreading in the two values, which does also occur within the samples of one bag, is a consequence of the inhomogeneous mixing of heavy and light minerals.

For potassium only an upper value of $90 \text{ Bq kg}^{-1}$ can be given for the average activity concentration. Because the criterion to end a measurement was based on the contents of the $609 \text{ keV}$ line from the decay series of $^{214}\text{Bi}$
the measurements were not long enough to extract a more precise value (see also section 1.5.3).

The (average) bismuth to thorium ratio in the samples is $1.34 \pm 0.09$. This value differs from the value normally found at Ameland. This might be caused by a lower concentration of epidote, a heavy mineral with a density between 3.1 and 3.3 kg L$^{-1}$, a medium grain-size of $\approx 160 \mu$m and rich in thorium ($\approx 3000$ Bq kg$^{-1}$) [Sch85, Mei90]. Its bismuth to thorium ratio is in the order of 0.2 which is considerably lower than the average value for the total heavy mineral fraction and its absence will cause an increase of this ratio. Because epidote it is the lightest mineral within the heavy fraction it is possible that during the selective deposition on the beach the conditions prevented deposition of not only quartz but also of epidote.

3.2.6 Transport rates

The amount of sand transported in the LOWT can be calculated by applying the concepts of conservation of grain volume or grain mass. The first concept will give the net volume of transported sand, without pores; the latter the weight of transported sand (both per unit width and unit time). When sand contains only a small percentage of heavy minerals both methods will give the same results expressed in different units (the transported volume multiplied with the density of the sand will give the weight of sand that is moved).

In the present experiments sand contains a high percentage of heavy minerals and the two methods may give different results because the density of the sand in motion is unknown. Therefore the mass transport rate in the tunnel will be calculated by applying the two layer approach. In this way transport rates for a light and heavy fraction separately can be derived.

In this section both methods will be discussed.

Sand-balance method

Net sand-volume transport rates are calculated with a sand-balance method by considering the change in bed volume and the weight of sand collected in both sand traps [AIS93]. It is based on the conservation of grain volume within the tunnel system

$$\Delta V^{\text{tot}} = 0,$$

with $V^{\text{tot}}$ being the total volume occupied by the grains in the tunnel. This means that after a run the volume of sand that is collected in the sand traps at the left and right hand side of the tunnel, $V_l$ and $V_r$ respectively, must be equal to $\Delta V$ the difference in sediment volume, present in the test section of
the tunnel before and after a run:

\[- \Delta V^{tun} = \frac{M_l}{\rho_l} + \frac{M_r}{\rho_r} = V_l + V_r.\] (3.12)

Here $M_l$, $M_r$, $\rho_l$ and $\rho_r$ are the mass and density of the sand in the left and right sand trap, respectively. The total amount of sediment in the tunnel at $t = 0$ is given by

\[V^{tun} = L \times W \times z \times (1 - \varepsilon_0),\] (3.13)

with $L$ and $W$ the length and width of the tunnel, $z$ the height of the sand bed and, if we assume a constant porosity, $\varepsilon_0$ is the porosity of the sand. The change of sand volume in the tunnel between time $t_1$ and $t_2$ is given by

\[\Delta V^{tun} = V^{tun}(t_2) - V^{tun}(t_1) = (1 - \varepsilon_0)LW [z(t_2) - z(t_1)].\] (3.14)

By dividing the tunnel in two parts, calculating the loss of grain volume for each half and using the fact that total grain volume is preserved, the transport rate in the middle can be calculated. Using the change in volume in the left half of the tunnel gives the left trap estimation of the transport rate in the middle of the tunnel, [ALS93]:

\[\bar{q}_l = \frac{\Delta V_{lip}(1 - \varepsilon_0)}{\Delta t \cdot W} - \frac{M_l}{\rho_l} \frac{1}{\Delta t \cdot W},\] (3.15)

and that in the right half of the tunnel, the right trap estimation:

\[\bar{q}_r = -\frac{\Delta V_{rip}(1 - \varepsilon_0)}{\Delta t \cdot W} + \frac{M_r}{\rho_r} \frac{1}{\Delta t \cdot W}.\] (3.16)

Since the total grain volume in the sand traps must be equal to the loss of grain volume in the tunnel, the average porosity $\varepsilon_0$ may be computed by:

\[1 - \varepsilon_0 = \left( \frac{M_l}{\rho_l} + \frac{M_r}{\rho_r} \right) \frac{1}{\Delta V_{lip}}.\] (3.17)

In these equations:
- $\Delta V_{lip}$ = total eroded volume including pores from the tunnel (m$^3$)
- $\Delta V_{rip}$ = total eroded volume including pores from the left half of the tunnel test section (m$^3$)
- $\Delta V_{rip}$ = total eroded volume including pores from the right half of the tunnel test section (m$^3$)
\[ M = M_1 + M_r = \text{total (dry) weight of the sand collected in both traps (kg)} \]
\[ M_1 = \text{total dry weight of the sand collected in the left trap (kg)} \]
\[ M_r = \text{total dry weight of the sand collected in the right trap (kg)} \]
\[ \rho_l = \text{density of the sand in the left sand trap} \]
\[ \rho_{mr} = \text{density of the sand in the right sand trap} \]
\[ \varepsilon_0 = \text{sand porosity} \]
\[ W = \text{width of the tunnel} \]
\[ \Delta t = \text{duration of one test} = t_2 - t_1 \text{ (s)} \]
\[ q_m = \text{measured net transport rate in real sand volume (without pores) per unit width and time in the middle of the tunnel test section (m}^2\text{ s}^{-1}). \]

Equations (3.15) and (3.16) give the volume of sand (no pores) per unit width that is transported per second.

**Two layer approach for transport rates** Besides total volume, total mass of the sand within the tunnel system is preserved

\[
\Delta M_{\text{tun}} = M_{\text{tun}}(t_2) - M_{\text{tun}}(t_1) = (1 - \varepsilon_0)LW [z(t_2)\rho(t_2) - z(t_1)\rho(t_1)]
\]
\[
= M_1 + M_r. \tag{3.18}
\]

Changes in sand mass in the tunnel can be either due to a change in volume or a change in composition and hence in density of the sand. Selective transport mechanisms may cause a non-uniform distribution of heavy minerals and hence a non-uniform density of the bed: \( \rho(x_i) \neq \rho(x_j) \). To obtain an estimate of the mass transport rates, the test section can be divided in parts with a density that is changing in time but is constant over a section. Subsequently, the net change in mass has to be calculated for each part.

Consider a section in the tunnel of length \( l_i \), density \( \bar{\rho}_i \) and thickness \( \bar{z}_i \) (fig. 3.6). Any change of mass within such a section is due to a gradient in the mass flow \( q_m^M \) (kg s\(^{-1}\) m\(^{-1}\)):

\[
\frac{\partial q_m^M}{\partial x} + \frac{\partial (1 - \varepsilon_0)\bar{\rho}_i \bar{z}}{\partial t} = 0. \tag{3.19}
\]

A non-uniform density in the tunnel does occur predominantly in the upper part of the sediment bed as was shown in section 3.2.3 where the ‘two-layer-model’ was introduced to describe the measured radiation intensities. If it is assumed that the thickness of this ‘transport’ or ‘active’ layer is constant, the sediment bed may be split in two parts:
3.2 Experimental set-up

**Figure 3.6:** A section in the tunnel with a sediment flow \( q \). If the gradient of the sediment flow is positive erosion occurs. If the gradient is negative there is sedimentation within the section.

I: an upper ‘transport’-layer with a constant thickness \( d \) but a changing density \( \rho_i \)

II: a lower layer with a constant density \( \rho_0 \) but a changing thickness \( z_{0i} \).

As mentioned before the thickness of the active layer \( d \) might vary over the length of the tunnel. However, just as for the porosity \( \varepsilon_0 \) (see eq. 3.14) it is only possible to deduce an average value over the length of the test section from the data. Therefore \( d \) is considered to have a constant value for all sections.

Assuming a constant porosity \( \varepsilon_0 \), equation (3.19) may be written as

\[
\frac{\partial q_i^M}{\partial x} + (1 - \varepsilon_0) d \frac{\partial \rho}{\partial t} + (1 - \varepsilon_0) \rho_0 \frac{\partial z_{0i}}{\partial t} = 0.
\] (3.20)

Since only the situation before and after a run is known, equation (3.20) has to be written in a discrete form:

\[
q_i^M - q_{i+1}^M = \frac{\Delta M_i}{\Delta t} = -W_i (\rho_0 \Delta z_i + d \Delta \rho_i) \times \frac{(1 - \varepsilon_0)}{\Delta t},
\] (3.21)

where \( \Delta t = t_2 - t_1 \) is the duration of a run, \( \rho_0 \) is the density of the lower layer of ‘undisturbed’ sand, \( \Delta \rho_i = \rho_i(t_2) - \rho_i(t_1) \) the change in the specific density in tunnel section \( i \) (of the upper layer), \( \Delta z_i = \Delta z_{0i} = z_i(t_2) - z_i(t_1) \), \( d \) is the thickness of this layer and \( W_i \) is the area of a section.
In case of erosion the two-layer model seems quite acceptable but in case of sedimentation it will almost certainly give an incorrect estimate for the transport rates because the density of the deposited sand will most likely not be the same as in the lower part of the bed. For the calculation one has to estimate the density $\rho_{h,i}$ of the deposited material. As a reasonable approximation one can take average of the densities measured before and after a run $\rho_{h,i} = \frac{1}{2} [\rho_i(t_1) + \rho_i(t_2)]$. With this assumption equation (3.21) in case of sedimentation becomes

$$q_i^M - q_i^{M+1} = \frac{\Delta M_i}{\Delta t} = -W l_i (\rho_{h,i} \Delta z_i + d \Delta \rho_i) \times \frac{(1 - \varepsilon_0)}{\Delta t}. \quad (3.22)$$

It should be noted that sedimentation only occurs in relatively small part of the tunnel.

The amount of sand collected in the sand traps acts as a boundary condition from which the transport rate in the middle of the tunnel may be calculated. The mass-transport rate can be obtained either by using the boundary condition at the left or right side $q_1^M$ or $q_N^M$, respectively, given by the amount of sand collected in the sand traps. The mass transport rate $q_K^M$ at any position $x_K$ is given by:

$$q_K^M = q_1^M - \sum_{i=1}^{K-1} \frac{\Delta M_i}{\Delta x} \text{ or } q_K^M = q_N^M + \sum_{i=K}^{N} \frac{\Delta M_i}{\Delta x}, \quad (3.23)$$

where $N$ is the total number of sections in the tunnel (127).

The thickness $d$ follows from the condition that the total loss of mass in the tunnel must be equal to the mass collected in the sand traps. If from $N$ sections in the tunnel $N_e$ sections have suffered erosion and in $N_s$ sections sedimentation has occurred, the total loss of mass in the tunnel is given by:

$$\Delta M^{\text{run}} = W(1 - \varepsilon_0)[\rho_0 \sum_{i}^{N_e} \Delta x_i \Delta z_i + \sum_{i}^{N_s} l_i \Delta z_i \rho_{h,i} + d \sum_{i}^{N} l_i \Delta \rho_i]. \quad (3.24)$$

This gives for the thickness $d$

$$d = \frac{1}{\sum_{i}^{N} l_i \Delta \rho_i} \times \left\{ -\frac{[M_i + M_f]}{W(1 - \varepsilon_0)} - \rho_0 \sum_{i}^{N_e} l_i \Delta z_i - \sum_{i}^{N_s} l_i \Delta z_i \rho_{h,i} \right\}, \quad (3.25)$$

which is an average value over the length of the test section of the tunnel.
**3.3 Thin layer experiment**

**Transport per fraction** Consider the sediment to consist of two groups of minerals with average densities $\rho_i$ and $\rho_j$, respectively. If $p_i$ is the volume fraction occupied by the minerals of density $\rho_i$ the total mass $M$ is given by:

$$M = \rho V (1 - \varepsilon_0) = (\rho_i p_i V + \rho_j (1 - p_i)V)(1 - \varepsilon_0).$$  \hspace{1cm} (3.26)

If it is assumed that any change in density is only due to a change in the ratio of the two fractions, $\rho_i$ and $\rho_j$ are constant and $p_i$ can be written as:

$$p_i = \frac{\rho - \rho_j}{\rho_i - \rho_j}. \hspace{1cm} (3.27)$$

The change in mass in a section given by equations (3.21) or (3.22) can now be rewritten by replacing the density by the fraction $p_i$, which in this case is chosen to be the heavy mineral fraction. Instead of the change in mass equations yield the change in the volume of heavy minerals.

**Accuracies** Uncertainties are calculated numerically. It is assumed that the uncertainty $E(f)$ of a parameter $f$ that depends on $N$ measured quantities $x_1, \ldots, x_N$ is estimated by

$$E^2(f(x_1, \ldots, x_N)) = \sum_{i=1}^{N} (f(x_1, \ldots, x_i + E(x_i), \ldots, x_N) - f(x_1, \ldots, x_N))^2, \hspace{1cm} (3.28)$$

where $E(x_i)$ is the uncertainty in $x_i$. This does not include any correlations between parameters or systematic uncertainties.

**3.3.1 Experimental conditions and procedures**

The two test-series of this experiment (F1 and F2) consisted of several runs with the same hydraulic conditions (meaning the steering signals of the piston). Each run contained two parts (A and B) of the same length (4 or 10 minutes). Experimental conditions are listed in table 3.1. After the first part (A) the gamma radiation above the sediment was measured at several positions in the tunnel. No samples were taken nor was the bed flattened or was any sand added. After the second part of the run (B) the radiation was measured and samples were taken. Visual observations about the bed forms were recorded.

At the beginning of a test-series, sand was brought into the centre of tunnel and flattened with a brush mounted on the detector carriage. The
Experimental conditions of the test-series F1 and F2 with a thin sediment layer. The velocities under crest and trough $U_c$ and $U_t$, respectively, are average values over all runs in one series with the corresponding spreading. The positive direction is from the piston to the ‘open leg’ side of the LOWT. In the column with the header ‘runs’ the number of runs is given; they do not necessarily are of equal length. In all test-series the wave period was 6.5 seconds.

<table>
<thead>
<tr>
<th>Test series</th>
<th>$U_t$ (m s$^{-1}$)</th>
<th>$U_c$ (m s$^{-1}$)</th>
<th>$U_{rms}$ (m s$^{-1}$)</th>
<th>runs</th>
<th>$T_r$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F1</td>
<td>-0.335 ± 0.005</td>
<td>0.561 ± 0.010</td>
<td>0.302 ± 0.001</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>F2</td>
<td>-0.705 ± 0.008</td>
<td>1.273 ± 0.004</td>
<td>0.698 ± 0.006</td>
<td>6</td>
<td>5-2</td>
</tr>
</tbody>
</table>

detector was positioned 3 cm above the metal bottom of the tunnel which is approximately 1 cm above the sediment. A radio-activity measurement (with the lead shield under the tunnel) was done at the centre of the bed. During the runs the detector was taken out of the tunnel.

Unfortunately it was not possible to measure the precise thickness of the sediment bed during and after the runs because the lowest five centimeters of the side walls of the LOWT are from steel and not from glass. Any thickness of less than five centimeter could therefore not be determined accurately.

### 3.3.2 Results and discussion

After all runs the layer of sand was elongated predominantly in the wave direction. Only a small fraction of sand was transported in the direction opposite to the wave direction. In test-series F1, with a $U_{rms} = 0.3$ m s$^{-1}$, sample analysis revealed that the sediment that was transported backwards had a density of 3.0 - 3.3 kg L$^{-1}$. Light coloured sand was removed from the sediment layer and brought into suspension. It was found spread over the tunnel at the end of a run, at the downstream (or rather downwave) side of the original position. Under the conditions of F1 ripples developed within the original layer of sediment; at the front edge of the layer, ripples detached from the bulk and moved as entities over the bottom of the tunnel. Under the conditions of F2 the bed was flat and light coloured sand was distributed over the down stream halve of the test section of the tunnel. In both test-series a ‘lag deposit’ developed in the sense that part of the sand moved only over a small distance.

In figure 3.7 the density and grain size of samples taken along the sediment
patterns as formed during test-series F1 and F2, are shown. All distances $s$ are with respect to the centre of the starting position of the layer of sand ($s = 0$). The heavier and smaller mineral grains were moved over the shortest distance and were mainly found in the ‘lag deposit’. Going in the downstream direction density decreases and grain size increases. Note that this behaviour is exactly the opposite as to what was observed in the wave-flume experiments.

![Graphs showing sample analysis results for F1 and F2](image)

**Figure 3.7:** Results of the sample analysis of test-series F1 and F2. All distances are relative to the centre of the starting position at $s = 0$ m. Closed symbols denote measured densities. The open circles point out the weight percentage of grains with a grain size smaller than 150 μm of samples taken after the first run (F1, $t = 20$ min and F2, $t = 5$ min). The solid dashed and dotted lines connect values from the same run.

Under the more energetic conditions of test-series F2 winnowing of light mineral grains happens faster and more efficient and the heavy minerals have moved upstream. After the runs F2.1 and F2.2, with a run time of 10 minutes, samples with a density of 4.4 kg L$^{-1}$ that consisted for 90 % of grains smaller than 150 μm were found at $s \approx 1$ m. In the two runs of F1 the maximum density found was $\approx 3.5$ kg L$^{-1}$ at $s \approx 0 - 0.5$ m after 40 minutes of run time. Measured bismuth and thorium activity concentrations within the samples
shown in figure 3.8 show a similar pattern; whereas after runs F1.1 and F1.2 only a slight increase in activity can be observed, an increase of 400 % occurs after F2.1 and F2.2.

Figure 3.8: Activity concentrations of $^{214}$Bi (closed squares) and $^{232}$Th (open squares) in the samples taken during F1 and F2 as function from the distance to the starting position $s = 0$ m. Samples taken at $t = 0$ are denoted by circles.

Because it was not possible to measure the exact thickness of the layer in situ recorded radiation levels cannot be used to provide direct information on heavy mineral concentrations in the sediment. Only in situ measured bismuth to thorium ratios will therefore be shown that give information on the composition of the sediment.

Figure 3.9 is a plot of the bismuth to thorium ratios as measured by the BGO detector system after various runs. Also shown in the same plot by stars connected by a solid line are bismuth to thorium ratios as measured in samples on the HPGe detector. There is a good agreement between the two data sets. For test-series F1 the ratio is fairly constant; only a slight decrease can be observed for $s > 1$ m. In the runs of test-series F2 the ratio is increasing in the down stream (wave) direction, till a maximum is reached that roughly
3.3 Thin layer experiment

coincides with the edge of the remainder of the original layer of sand (or ‘lag deposit’), from whereon it decreases.

From these results one may conclude that a heavy (dense), small grained mineral with a relatively large bismuth content is an important ingredient of the ‘lag deposit’ as developed during the runs. Most likely this is zircon, a mineral with a typical activity concentration of more than 2000 Bq kg$^{-1}$, a bismuth to thorium ratio of 7, a density of 4.65 kg L$^{-1}$ and a median grain size of approximately 100 μm. It normally constitutes about 20% of the mass of the total heavy mineral fraction within the original sand; hence zircon is an important contributor to measured radiation intensities. The decreasing bismuth to thorium ratio in the downstream direction is due to the increasing contribution from quartz with a bismuth to thorium ratio of about unity.

![Figure 3.9: Bismuth to thorium ratio as measured by the BGO detector (circles) and by the HPGe detector (stars). The horizontal distances are relative to the center of the starting position ($s = 0$ m). At $t = 0$, $I_{\text{Bi}}/I_{\text{Th}} = 1.34 \pm 0.09$](image-url)
Model calculations  The semi-quantitative model as introduced in Chapter 2 will be applied to explain the present data. Based on the sample analysis as described in the former paragraph the grain trajectories are calculated for the following three sediment types:

- light: $\rho = 2.65 \text{ kg L}^{-1}$, $d_{30} = 200 \mu\text{m}$
- medium: $\rho = 3.4 \text{ kg L}^{-1}$, $d_{30} = 140 \mu\text{m}$
- heavy: $\rho = 4.4 \text{ kg L}^{-1}$, $d_{30} = 100 \mu\text{m}$

The peak velocities $U_c$ and $U_t$, and wave period are taken from table 3.1, the thickness of the boundary layer 2 cm and the $z_0$ level is 150 $\mu\text{m}$. The latter two values differ from the one used in the calculations for the wave flume. Because of the longer wave period the boundary layer has more time to develop and hence its thickness is expected to become larger. To account for the smoother stream pattern because of the longer wave period an effective friction coefficient $K$ is taken of 10 for test-series F1, with wave conditions in the ripple regime. For test-series F2 in the sheetflow regime a value of $K = 5$ was taken.

The outcome of the model is shown in figure 3.10 where calculated grain trajectories in one wave period are plotted in the xz plane. Note the difference in scale between F1 and F2. The results are in agreement with the mineral patterns as observed after the runs. It should be remembered (see Chapter 2) that distances have only a relative meaning. Due to the reduced influence of the the pick-up time in combination with the smoother flow pattern, the net distance ‘travelled’ by the grains is decreasing with increasing density under both conditions. For condition F1 the net distances are less than in F2 and the heavy mineral grain is moved only under the most energetic condition (F2).

Relative transport heights of heavy and light particles are correctly reproduced in case of F2: light grains are lifted higher from the bed than the heavy ones. All three grains make an oscillatory motion and do not make contact with the sediment bed. According to the calculations for the conditions of test-series F1 all of the sediment will not go into suspension but stays close to the bottom.

3.3.3 Conclusions

Selective transport was observed in both runs. Figures 3.7 to 3.9 show that under these controlled conditions results are very well reproduced. The degree
3.3 Thin layer experiment

Figure 3.10: Calculated trajectories of three mineral grains under two wave conditions F1 and F2 (see table 3.1): light: $\rho = 2.65$ kg L$^{-1}$, $d = 200 \, \mu$m, medium: $\rho = 3.4$ kg L$^{-1}$, $d = 140 \, \mu$m and heavy: $\rho = 4.4$ kg L$^{-1}$, $d = 100 \, \mu$m.

of selectivity is velocity dependent; when $U_{\text{rms}} = 0.7$ m s$^{-1}$ it took 10 minutes to form a deposit highly enriched with heavy minerals ($\rho = 4.4$ kg L$^{-1}$) whereas with $U_{\text{rms}} = 0.3$ m s$^{-1}$ even 40 minutes was not sufficient to obtain the same result. Contrary to the flume experiments in Delft, heavy and light minerals were mainly transported in the same downstream direction and the distance travelled is inversely correlated to density.

The model as developed for the TUD wave flume (Chapter 2) gave semi-quantitative agreement with the experimental patterns formed due to selective transport of the different minerals. Similar to the results of the TUD experiments absolute values for calculated distances do not agree with the observations. However, in view of the simplicity of the model the agreement with the data is quite reasonable.

The results of these experiments confirm the larger mobility of the lighter grains and indicate that the selectivity of the transport increases for higher velocity regimes (the different grains are separated better). Again it was found that it takes only a short time (minutes) before the effects of selective transport become clearly noticeable.

The agreement between the bismuth to thorium ratios measured in situ with the BGO detector and the one measured in the laboratory with the HPGe
detector was good. Therefore the output of the BGO detector system gives reliable information about the composition of the sediment. Unfortunately it was not possible to measure the exact thickness of the layer and the (online) radiometric data could not be translated to heavy mineral concentrations.

3.4 Thick layer experiments

3.4.1 Experimental conditions and procedures

An 0.3 m thick sediment bed was placed over the full length of the test section of the LOWT. The sand originated from the six Ameland bags and was homogenised by stirring. In total five test-series (F3-F7) were carried out, each consisting of several runs. The main goal of these experiments was to test the effect of a large heavy mineral concentration on the measured transport rates. The experimental conditions are listed in table 3.2. After each run the height and activity of the sediment bed was measured. The detector was positioned \( \approx 3.0 \) cm above the bed surface at \( t = 0 \). The \( \gamma \)-ray activity was measured at several positions along the tunnel and the bed height was recorded at every 10 cm along the length of the tunnel. This was repeated after every run together with the determination of the weight of the sediment collected in the sand traps. Because of the selective nature of the transport, removed sediment was not replaced during one test-series because the replaced sand would have had different composition and would thus have influenced the experiment.

Because a net sediment transport occurred during the measurement, an ‘erosion hole’ developed at the upstream boundary of the test section. This hole slowly propagated into the test section. The test-series were stopped if the bed height in the erosion hole became less than 10 cm, because otherwise the effects on the rest of the sediment bed would have become too large.

At the end of a test-series the top layer (\( \approx 5-10 \) cm) was removed from the tunnel and fresh sand was added to create again a homogeneous sediment bed. Because of the limited amount of sand available it was necessary to mix the sand from the test section with sand from the sand traps and use it again. In test-series F3-F7 this ‘recycled’ sand was used.

Sand samples were taken at regular time intervals at several locations along the test section.

The transverse suction system was used in three of the five experiments (F3-F5). Samples were taken from the collected sediment for further analysis. In test-series F7 the wave direction was reversed.
3.4 Thick layer experiments

Table 3.2: Conditions of the test-series F3 - F7 with a full sediment-bed. The velocities under crest and trough $U_c$ and $U_t$, respectively, are the average values over all runs in one series with the corresponding spreading. The positive direction is from the piston to the ‘open leg’ side of the LOWT. In the column with the header ‘runs’ the number of runs is given; they are not necessarily of equal length. In all runs the wave period was 6.5 seconds.

<table>
<thead>
<tr>
<th>Test series</th>
<th>$U_t$ (m s$^{-1}$)</th>
<th>$U_c$ (m s$^{-1}$)</th>
<th>$U_{rms}$ (m s$^{-1}$)</th>
<th>runs</th>
<th>suction</th>
</tr>
</thead>
<tbody>
<tr>
<td>F3</td>
<td>-0.59 ± 0.07</td>
<td>0.965 ± 0.009</td>
<td>0.510 ± 0.001</td>
<td>4</td>
<td>Y</td>
</tr>
<tr>
<td>F4</td>
<td>-0.97 ± 0.02</td>
<td>1.756 ± 0.013</td>
<td>0.932 ± 0.008</td>
<td>3</td>
<td>Y</td>
</tr>
<tr>
<td>F5</td>
<td>-0.719 ± 0.010</td>
<td>1.315 ± 0.016</td>
<td>0.704 ± 0.002</td>
<td>4</td>
<td>Y</td>
</tr>
<tr>
<td>F6</td>
<td>-0.894 ± 0.011</td>
<td>1.713 ± 0.008</td>
<td>0.920 ± 0.003</td>
<td>5</td>
<td>N</td>
</tr>
<tr>
<td>F7</td>
<td>0.582 ± 0.012</td>
<td>-0.972 ± 0.015</td>
<td>0.511 ± 0.002</td>
<td>6</td>
<td>N</td>
</tr>
</tbody>
</table>

3.4.2 Results of the measurements

The first part of this section shows the results of bed-height and radiation measurements as well as the contents of the sand traps. In the second part the suspended sediment concentration profiles are discussed.

Figure 3.11 shows the elevation and bismuth radiation intensity levels as measured in the five test-series F3-F7 at the beginning and end of a test-series. Since the bismuth to thorium ratio was approximately constant (1.4 ± 0.1) no thorium radiation levels are shown.

The figure shows the net sediment transport in the down stream direction (in test-series F7 the wave direction was reversed): the erosion hole propagates in the tunnel and sedimentation occurs at the down stream side of the test section ($x = 6$ m).

Bismuth radiation levels decrease inside the erosion hole but increase considerably directly downstream of the hole. Local maxima in the radiation levels are in general located at the downstream side of ‘bumps’ in the bottom topography. But although maxima in radiation are connected to bedforms, the presence of a bump is not necessarily accompanied by a peak in the radiation level. A decrease in the bismuth signal is observed at the location of the ‘sedimentation bump’ at the downstream side ($x = 6$ m) of the tunnel. From sample analysis it is known that sand deposited at this location consist almost entirely of light minerals.

Comparing series F3 and F7, which were both with $U_{rms} = 0.5$ m s$^{-1}$, shows the influence of the suction system located at $x = 0.3$ m during F3.
The presence of the suction system causes a distortion in the bed structure ranging roughly from $x = -3$ m to $x = 3$ m. At $x = -1$ m a relatively deep pit develops followed by two bumps at the downstream side. The small dip separating the bumps coincides with the location of the suction system. A similar bottom topography as in F3 is present in test series F5 where the suction system is also present. In test-series F4 no effect is visible. This is probably due to the presence of approximately 2 m long and 5-10 cm high ‘megaripples’ or ‘dunes’. These bed forms are apparently induced by the conditions since they are also present in test-series F6, with the same value for $U_{rms}$ (0.9 m s$^{-1}$). The presence of these bed forms apparently ‘overrides’ the influence of the suction system.

In table 3.3 the change in sediment volume (bulk) and contents of both sand traps is given. In general the density of the sand in the downstream trap is lower than the original sand in the tunnel, only in test-series F7 the sediment in both traps has a similar density. For test-series with low velocities (F3 and F7) only small amounts of sand were collected in the upstream trap. The contents of the upstream trap for F4 and F6 indicates that under higher velocities more and heavier sediment is transported in the upstream direction. The influence of the erosion hole is reflected by the increasing weight of the sediment collected in the upstream sand trap.

**Suspended sediment concentrations** In test-series F3-F5 the transverse suction system was used to determine time-averaged suspended sediment concentrations $\langle C(t) \rangle$ as function of height. For calculation of the actual sediment concentrations within the tunnel it is assumed that the trapping efficiency (see page 75) is constant ($\alpha = 0.74$) [Bos87] and that the collected sediment was loosely packed with a porosity of 0.46 [Als93]. It is customary to express suspended sediment concentrations in weight per volume. Analysis of the suction samples learned that the suspended sediment consisted mostly of quartz sand ($\rho_s = 2.65$ kg L$^{-1}$) which density was assumed for the calculation of the actual concentrations. The results are plotted in figure 3.12.

Measured concentration profiles can all three be described by a negative power distribution:

$$\langle C_s(t) \rangle = C_r \left( \frac{z}{z_r} \right)^{-\alpha_d},$$

where $z$ is height above the bed in centimeters, $z_r$ is a reference height, $C_r$ is a reference concentration and $\alpha_d$ the concentration decay parameter. This power distribution is expected as the solution for a convection-diffusion equa-
3.4 Thick layer experiments

Table 3.3: Underwater weight, $M_u$ and $M_d$, and density of the sediment collected in the up and downstream located sand trap, respectively (uncertainties in the weights are estimated to be less than 5%). Eroded in sediment volume in the up and downstream half of the tunnel $\Delta V_{\text{up}}$ and $\Delta V_{\text{dip}}$, respectively.

<table>
<thead>
<tr>
<th>run</th>
<th>$\Delta t$</th>
<th>$M_u$</th>
<th>$M_d$</th>
<th>$\rho_u$</th>
<th>$\rho_d$</th>
<th>$\Delta V_{\text{up}}$</th>
<th>$\Delta V_{\text{dip}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(s)</td>
<td>(kg)</td>
<td>(kg)</td>
<td>(kg m$^{-3}$)</td>
<td>(kg m$^{-3}$)</td>
<td>$10^{-2}$</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>F3.1</td>
<td>3444</td>
<td>0.35</td>
<td>20.30</td>
<td>2838 (5)</td>
<td>2740 (6)</td>
<td>2.2</td>
<td>-0.3</td>
</tr>
<tr>
<td>F3.2</td>
<td>3575</td>
<td>0.90</td>
<td>19.00</td>
<td>2858 (5)</td>
<td>2742 (9)</td>
<td>3.0</td>
<td>-0.6</td>
</tr>
<tr>
<td>F3.3</td>
<td>3601</td>
<td>1.60</td>
<td>21.60</td>
<td>2918 (6)</td>
<td>2737 (6)</td>
<td>2.4</td>
<td>-0.5</td>
</tr>
<tr>
<td>F4.1</td>
<td>1027</td>
<td>11.50</td>
<td>19.40</td>
<td>2841 (7)</td>
<td>2753 (7)</td>
<td>2.5</td>
<td>0.4</td>
</tr>
<tr>
<td>F4.2</td>
<td>1046</td>
<td>12.70</td>
<td>16.00</td>
<td>2842 (18)</td>
<td>2743 (15)</td>
<td>2.4</td>
<td>0.6</td>
</tr>
<tr>
<td>F4.3</td>
<td>1020</td>
<td>20.00</td>
<td>16.20</td>
<td>3265 (8)</td>
<td>2710 (11)</td>
<td>3.5</td>
<td>0.0</td>
</tr>
<tr>
<td>F5.1</td>
<td>1034</td>
<td>1.80</td>
<td>11.00</td>
<td>2928 (10)</td>
<td>2683 (7)</td>
<td>2.2</td>
<td>0.2</td>
</tr>
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<td>F5.2</td>
<td>1027</td>
<td>5.80</td>
<td>11.80</td>
<td>3351 (13)</td>
<td>2684 (8)</td>
<td>2.2</td>
<td>0.3</td>
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<tr>
<td>F5.3</td>
<td>487.4</td>
<td>2.60</td>
<td>5.40</td>
<td>3201 (12)</td>
<td>2683 (7)</td>
<td>1.2</td>
<td>0.0</td>
</tr>
<tr>
<td>F5.4</td>
<td>475</td>
<td>3.10</td>
<td>5.40</td>
<td>3192 (8)</td>
<td>2714 (7)</td>
<td>1.1</td>
<td>-0.1</td>
</tr>
<tr>
<td>F6.1</td>
<td>598</td>
<td>6.30</td>
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<td>2780 (6)</td>
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<td>604</td>
<td>6.30</td>
<td>9.80</td>
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<td>2662 (6)</td>
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<td>0.3</td>
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<td>591</td>
<td>7.10</td>
<td>9.40</td>
<td>3324 (13)</td>
<td>2671 (7)</td>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>F6.4</td>
<td>591</td>
<td>13.60</td>
<td>8.90</td>
<td>3648 (13)</td>
<td>2673 (8)</td>
<td>1.9</td>
<td>0.2</td>
</tr>
<tr>
<td>F6.5</td>
<td>591</td>
<td>13.20</td>
<td>7.90</td>
<td>3445 (11)</td>
<td>2692 (10)</td>
<td>1.7</td>
<td>0.5</td>
</tr>
<tr>
<td>F7.1</td>
<td>1781</td>
<td>0.50</td>
<td>6.80</td>
<td>2722 (15)</td>
<td>2738 (11)</td>
<td>1.0</td>
<td>-0.1</td>
</tr>
<tr>
<td>F7.2</td>
<td>1794</td>
<td>0.40</td>
<td>7.70</td>
<td>2804 (5)</td>
<td>2704 (11)</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>F7.3</td>
<td>1781</td>
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<td>8.20</td>
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<td>2791 (10)</td>
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</tr>
<tr>
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<td>1794</td>
<td>0.75</td>
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<td>2806 (12)</td>
<td>2810 (13)</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
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<td>1788</td>
<td>1.10</td>
<td>7.40</td>
<td>2806 (9)</td>
<td>2809 (20)</td>
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</tr>
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<td>8.60</td>
<td>2867 (10)</td>
<td>2869 (9)</td>
<td>1.1</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

For the sediment in suspension [Rib93]

$$w_u(C) + \varepsilon_u \frac{\partial(C)}{\partial z} = 0,$$

where $w_u$ is the settling velocity and $\varepsilon_u$ the diffusion or mixing coefficient. Assuming a linear increasing mixing coefficient with distance $z$ above the bed, $\varepsilon_u = az$, the concentration decay parameter $\alpha_d$ in equation 3.29 becomes equal to $\frac{w_u}{\varepsilon_u} = \frac{w_u}{a}$.

From figure 3.12 one can see that the value for the concentration decay
Figure 3.11: Measured radiation levels for $^{214}$Bi and the height of the sediment bed during test-series F3 and F7. Dotted lines represent the situation at $t=0$ and solid lines at the end of a test-series. The dashed line is at some intermediate moment as indicated above each plot. The positions of the radiation measurements are denoted by symbols.
3.4 Thick layer experiments

parameter $\alpha_d$ is approximately 2 for all three conditions and is thus velocity independent in the range of: $U_{\text{rms}} = 0.5 - 0.9 \text{ m s}^{-1}$. This is the same value as reported by Al-Salem and Ribberink: $\alpha_d = 2.10 \pm 0.11$ in the velocity range of $U_{\text{rms}} = 0.3 - 0.9 \text{ m s}^{-1}$ [Rib94]. Considering the differences in fall velocities as determined for the average sediment, $w_s = 0.026 \text{ m s}^{-1}$ in case of the experiments by Al-Salem versus $w_s = 0.02 \text{ m s}^{-1}$ in the present experiments, this is somewhat surprising. This can either mean that the concentration decay parameter $\alpha_d$ is not equal to $\frac{w_s}{\varepsilon}$ ($\varepsilon \neq a z$) or that only a specific part of the sediment goes into suspension.

The reference concentration $C_r$ at $z = 1 \text{ cm}$ is $10 - 20 \text{ g L}^{-1}$ for F3 and F5 ($U_{\text{rms}} = 0.5$ and $0.7 \text{ m s}^{-1}$ respectively) and $\approx 100 \text{ g L}^{-1}$ in case of F4 ($U_{\text{rms}} = 0.9 \text{ m s}^{-1}$). These values are higher than found by Al-Salem and Ribberink (5-10 g L$^{-1}$ for $U_{\text{rms}} = 0.5 \text{ m s}^{-1}$ and 20 g L$^{-1}$ for $U_{\text{rms}} = 0.9 \text{ m s}^{-1}$). This can be explained by the coarser grained sediment ($d_{50} = 210 \mu m$) as used by Al-Salem and Ribberink.

![Figure 3.12: Time averaged concentration profiles as measured in test-series F3-F5. The solid lines have a slope of -2.](image-url)

Between the concentrations found for $U_{\text{rms}} = 0.5$ and $0.7 \text{ m s}^{-1}$ there is no significant difference whereas for $U_{\text{rms}} = 0.9 \text{ m s}^{-1}$ concentrations have increased by a factor 5 - 10. A phenomena that was also observed in the results of Al-Salem and Ribberink. A possible explanation is the presence of very low ripples in case of the lowest root mean square velocity, which, in
the present experiments were only visible due to color differences within the sediment. Although they are only in the order of one millimeter high they can have a significant effect on the amount of sediment that goes into suspension.

3.4.3 Results of the sample analysis

In this section the relation between density, grain size and activity concentrations of the samples will be discussed.

Density and activity concentration In figure 3.13 the $^{214}$Bi and $^{232}$Th activity concentrations in the samples are plotted as function of the measured densities. The solid lines are linear fits where each data point has the same weight. Given error ranges are estimated by considering the spreading of the data and do not include uncertainties within the measurements:

\[
\begin{align*}
A_{Bi} &= (-60 \pm 70) + (750 \pm 100)(\rho - \rho_0) \\
A_{Th} &= (-50 \pm 60) + (490 \pm 100)(\rho - \rho_0),
\end{align*}
\]

where $\rho_0 = 2.65$ kg L$^{-1}$. Such a linear relation between activity concentration and density was also found in the wave flume experiment over a large part of the covered density range (see fig. 2.7). For the present experiments it seems to be valid over the range of densities between 2.65 and 4.0 kg L$^{-1}$; for densities larger than 4.0 kg L$^{-1}$ some deviations can be observed. Measured bismuth and thorium radiation intensities with the BGO detector, are plotted as function of the measured activity concentrations with the HPGe detector in figure 3.14. Both lines indicated in this figure have a slope of 0.7. The constant bismuth to thorium ratio indicates that, contrary to the thin layer experiments, no separation has occurred within the heavy fraction.

These results, a linear increase of activity concentration with density and a constant bismuth to thorium ratio, point at a sand that may be regarded as a mixture of two sediment types with a certain density and activity concentration. Since both features are characteristic for minerals, this suggests two sediment types of constant composition.

Density and grain size Figure 3.16 shows the relation between grain size and density of the bed samples of test-series F1-F7. The left part of this figure shows the mass percentage of grains with a size smaller than 150 $\mu$m as function of density. The right part shows the $d_{10}$, $d_{50}$ and the $d_{90}$ of the samples as function of density. The nature of these relations will be explained in the following discussion.
Figure 3.13: Specific density of the bed samples versus the bismuth and thorium activity concentration as measured with the HPGe detector. The solid lines are linear fits (see text).

Figure 3.14: A: Measured $^{214}$Bi and $^{232}$Th activity concentrations in the samples. B: Measured bismuth and thorium radiation levels (in a.u.) with the BGO detector at the positions of the samples. Both lines have a slope of 0.7.
Figure 3.15: Grain size distributions of three arbitrary bed samples with a density of 2.7, 3.5 and 4.2 kg L\(^{-1}\). The dashed lines are fitted Gauss functions with a mean grain size of 175, 131 and 111 \(\mu\)m and a variance of 31, 31 and 26 \(\mu\)m, respectively.

In section 1.2 it was stated that ideally grains are distributed according to a log-normal distribution. As may be concluded from figure 3.15 the grain size distribution may well be approximated by a normal (Gaussian) distribution. Because a Gaussian distribution has certain advantages in calculations, for simplicity reasons the Gaussian distribution will be adapted. In the first-order approximation of hydraulic equivalence one expects a decreasing variance of the grain size distribution with increasing density. However, figure 3.15, which shows the grain-size distribution of three arbitrary bed samples, shows that the differences are small and it may be assumed that the variance is a constant. With this assumption the mass fraction of grains with a size smaller than 150 \(\mu\)m as a function of density, shown in the left part of figure 3.16, can be described with an error function (erf\(x\)) which is the integral of 0 to \(x\) over a normal distribution:

\[
erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt = \sqrt{\frac{2}{\pi}} \int_0^x e^{-\frac{t^2}{2}} dt.
\]  \hspace{1cm} (3.32)

When \(\rho= 2.65 \text{ kg L}^{-1}\), the distribution lies almost entirely on the right (coarse) side of \(d = 150 \mu\)m. When the density \(\rho\) is increasing, an increasing part of the distribution will shift to values under that of \(d = 150 \mu\)m where for \(\rho= 4.5 \text{ kg L}^{-1}\) roughly all grains are smaller than 150 \(\mu\)m. The solid line through the data points is erf\(x\) where \(x = 0.02 + \frac{1}{\sqrt{2}} \cdot (\rho_s - \rho_0); \rho_0 = 2.65 \text{ kg L}^{-1}\). The value of 0.02 represents the fact that for \(\rho_s\) is 2.65 kg L\(^{-1}\) part of the grains will be smaller than 150 \(\mu\)m.

When the density is increasing from \(\rho = 2.65\) to approximately 4.4 kg
3.4 Thick layer experiments

Figure 3.16: Left: the mass fraction of grains smaller than 150 μm versus specific density. The solid line represents equation 3.32 (see text). The samples from the thin layer experiments F1 and F2 are denoted by triangles. Right: the $d_{10}$ (circles), $d_{50}$ (squares) and $d_{90}$ (triangles) versus the specific density of the bed, trap and suction samples from test-series F1-F7. The lines represent equations (3.33) and (3.34).

L$^{-1}$ the $d_{50}$ decreases from $\approx 150 \, \mu m + 2\sigma$ to $150 \, \mu m - 2\sigma$. This means that if the value of the variance $\sigma$ is known the median grain size of each of the samples can be fairly well deduced. The right part of figure 3.16 shows measured values for the $d_{10}$, $d_{50}$ and $d_{90}$ as a function of density. For $\rho_0 \simeq 2.65 \, \text{kg L}^{-1}$ the $d_{50} \simeq 195 \, \mu m$ which would imply that $\sigma \simeq 23$. Using this value gives the following linear relationship between density $\rho_a$ (kg L$^{-1}$) and $d_{50}$ (μm):

$$d_{50} \simeq 195 - 52 \times (\rho_a - \rho_0),$$

(3.33)

where $\rho_0 = 2.65 \, \text{kg L}^{-1}$ and the proportionality factor (52) is expressed in $10^{-9} \, \text{m}^4 \, \text{kg}^{-1}$. This relationship is indicated by a solid line in right part of figure 3.16.

Under the condition of hydraulic equivalence, the grain size $d$ is proportional to the reciprocal of some power of the density $\rho_a$, which for small grains is 0.5 (see eq. (1.3)). The dashed line in figure 3.16 represents

$$d = \frac{2.2 \cdot 10^{-4}}{\sqrt{\Delta}},$$

(3.34)
where \( \Delta = (\rho_b - \rho)/\rho \) and the proportionality factor \( 2.2 \times 10^{-4} \) (m) is obtained from equation 1.3 using \( \rho_b = 3.4 \) kg L\(^{-1}\) and \( d_{50} = 140 \) \( \mu \)m.

Equations 3.33 and 3.34 both show reasonable agreement with the data where equation 3.33 somewhat overrates the measured \( d_{50} \) in the density range from \( \rho_b = 3 \) to 3.8 kg L\(^{-1}\). The value for \( \sigma \) of 23 \( \mu \)m, used to obtain equation 3.33 is lower than one would expect considering figure 3.15. This indicates that the assumption of a constant variance is not valid for all samples as is also suggested the values of the \( d_{10} \) and \( d_{90} \) as shown in the right hand side of figure 3.16.

In figure 3.17 the density and grain size of samples taken from the suspended sediment pumped out through the lowest one or two tubes of the suction system. These samples consist of finer grained sediment than the bed samples and can not be described with the same (error) function. The rate at which the median grain size of the suspended sediment changes with increasing density is higher than for the bed samples.

![Figure 3.17: Mass fraction of grains smaller than 150 \( \mu \)m versus density of the suspended sediment samples.](image)

### 3.4.4 Radiation intensity levels as function of density

With equation 3.9 we can calculate the radiation intensity as function of the density of the top active layer. Since the density \( \rho_0 \) and activity concentration \( A_0 \) at \( t = 0 \) have been measured and the activity concentrations is known as function of density (eq. 3.31) the only unknown parameter is the thickness \( d \) of the top layer.

Although it is assumed that the layer thickness \( d \) is a constant it is very likely that it varies over the length of the test section. Inside the erosion hole, for example, it will be larger than at the down stream side of the tunnel. Therefore it is to be expected that not all data points can be described with one function. In figure 3.18 measured bismuth and thorium levels are plotted against the density of sand in the upper layer. Curves for three values of the layer thickness are shown: the dashed line for \( d = 1 \), the solid line for \( d = 2 \) and the dotted line for \( d = 3 \) cm.
3.4 Thick layer experiments

Figure 3.18: Specific density of the bed samples versus the bismuth and thorium radiation intensity level (arbitrary units) measured with the BGO-detector system on the sample locations. The lines are the calculated curves according to eq. 3.9: dashed for $d = 1$, solid for $d = 2$, and dotted line for $d = 3$ cm. $I_0 \approx 300$.

It may be concluded that the ‘two-layer-model’ accounts reasonably well for the recorded radiation levels. Measured values indicate an ‘active’ layer thickness in the range from approximately 1-3 cm. Radiation measurements therefore not only give direct information about the composition of the upper layer of sediment but they also support the assumption that the transport takes place in a thin layer and therefore helps to describe the selection processes.

3.4.5 Results of the transport calculations

The volume transport rates were calculated with equations 3.15 and 3.16, using the measured values for the volumes in both sand traps and the measured bed heights in the test section of the tunnel. To calculate the heavy mineral fraction in the sand the density of the heavy and light minerals were chosen to be 4.40 kg L$^{-1}$ and 2.65 kg L$^{-1}$, respectively. These rather extreme values were necessary to cover the total range of densities of the samples. For the original sand this gives a heavy mineral content of 30% . The density in each section was determined from the samples in combination with the measured radiation levels.

In table 3.4 the results of the transport calculations are given. The re-
pective columns show the calculated porosity $\varepsilon_0$, the thickness of the ‘active’ layer $d$, the total (volume) transport rate and the heavy-mineral fraction $p_{h,T} = \frac{\rho_{h} - \rho}{\rho_{h} + \rho} d$ in the transported sand.

The calculated values for the porosity are relatively high and show considerable variation. The thickness of the ‘transport layer’ is within the estimated range of 1-3 cm. Due to the large inaccuracies no conclusions about any correlation between the hydraulic conditions and the layer thickness can be drawn. From found values for $p_{h,T}$, shown in the last column of table 3.4, it can be concluded that the transport has been selective because transported sand has a lower heavy mineral content than the original sediment. The fact that $p_{h,T}$ is increasing with time points at the fast removal of light minerals from the test section of the tunnel. Consequently the concentration of heavy minerals in the sand in motion increases.

### 3.4.6 Comparison with other studies and model calculations

As mentioned earlier the present experiments are similar to experiments performed by Al-Salem and Ribberink (A & R) in 1992 [Rib94, AlS93]. Although the hydraulic conditions were the same the sediment was different: quartz sand was used with a density of 2.65 kg L$^{-1}$ and a median grain size of 210 $\mu$m. In the present experiments finer sand, $d_{50} = 150 \mu$m, with a high concentration of heavy minerals was used, $\rho = 3.20$ kg L$^{-1}$. The results of both experiments are shown in figure 3.19. To compare the results of both sediment types, transport rates transformed to a dimensionless quantity $\Phi_{bw}$ by dividing the transport rates by the square root of the under water weight of grains [Rib94]:

$$\Phi_{bw} = \frac{q_T}{(\Delta g d_{50}^2)^{1/2}}$$

where $\Delta = (\rho_h - \rho_w)/\rho_w$ and $g$ is the acceleration of gravity. The dimensionless transport rates in the present experiments are calculated using parameters that represent the characteristics of the transported sand, $\rho_h = 3.00$ kg L$^{-1}$ and $d_{50} = 165 \mu$m. In table 3.5 the results of the two experiments are shown.

For the lowest velocity, $U_{rms} = 0.5$ m s$^{-1}$, results of both experiments are similar where the somewhat higher transport rates of test-series F3 could be due to the presence of the suction system. For increasing velocity the differences with the experiments of A & R increase, as shown in figure 3.19: under the most energetic conditions, $U_{rms} = 0.9$ m s$^{-1}$, transport rates of the present experiments are approximately 50% lower than were found by A & R. Therefore the scarce data obtained so far are suggestive for a transport...
3.4 Thick layer experiments

Table 3.4: Result of the transport calculations from the experiments. The second and the third column show the calculated value for porosity and thickness of the transport layer \(d\), respectively. The next column contains the transport rates \(\dot{q}^V\) \((m^3 \text{ s}^{-1})\) expressed in grain volume per unit width and time. The heavy mineral fraction \(p_{h,T}\) in the transported sand is given in the last column (the original sand contained 30% heavy minerals); the density of the heavy fraction is chosen to be 4.40 kg \(L^{-1}\) and of the light fraction 2.65 kg \(L^{-1}\). For test-series F6 and F7 runs had to be combined because samples were not taken after all individual runs.

<table>
<thead>
<tr>
<th>(U_{\text{rms}}) (\text{m s}^{-1})</th>
<th>run (\text{F})</th>
<th>(\varepsilon_0)</th>
<th>(d) (\text{(10}^{-2} \text{ m)})</th>
<th>(\frac{\dot{q}^V}{10^{-6}})</th>
<th>(p_{h,T})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.510</td>
<td>F3.1</td>
<td>0.4 ± 0.05</td>
<td>3 ± 1</td>
<td>12.7 ± 0.5</td>
<td>0.10 ± 0.08</td>
</tr>
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<td>0.510</td>
<td>F3.2</td>
<td>0.53 ± 0.03</td>
<td>7 ± 4</td>
<td>12.7 ± 0.7</td>
<td>0.24 ± 0.06</td>
</tr>
<tr>
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<td>F3.3</td>
<td>0.32 ± 0.06</td>
<td>2.1 ± 1.2</td>
<td>14.4 ± 0.9</td>
<td>0.28 ± 0.06</td>
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<td>0.932</td>
<td>F4.1</td>
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<td>5 ± 2</td>
<td>28.1 ± 1.6</td>
<td>0.07 ± 0.14</td>
</tr>
<tr>
<td>0.932</td>
<td>F4.2</td>
<td>0.46 ± 0.03</td>
<td>5 ± 2</td>
<td>19.7 ± 1.4</td>
<td>0.10 ± 0.19</td>
</tr>
<tr>
<td>0.932</td>
<td>F4.3</td>
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<td>-4 ± 4</td>
<td>31 ± 3</td>
<td>0.25 ± 0.13</td>
</tr>
<tr>
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<td>5 ± 2</td>
<td>23.9 ± 1.0</td>
<td>0.04 ± 0.11</td>
</tr>
<tr>
<td>0.704</td>
<td>F5.2</td>
<td>0.51 ± 0.04</td>
<td>1.9 ± 1.1</td>
<td>27.7 ± 1.8</td>
<td>0.00 ± 0.16</td>
</tr>
<tr>
<td>0.704</td>
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<td>0.64 ± 0.05</td>
<td>1 ± 1</td>
<td>22 ± 2</td>
<td>0.35 ± 0.05</td>
</tr>
<tr>
<td>0.704</td>
<td>F5.4</td>
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<td>-1.0 ± 1.5</td>
<td>24 ± 4</td>
<td>0.32 ± 0.15</td>
</tr>
<tr>
<td>0.920</td>
<td>F6.1</td>
<td>0.42 ± 0.06</td>
<td>1.7 ± 0.8</td>
<td>25 ± 2</td>
<td>0.17 ± 0.14</td>
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<td>0.23 ± 0.08</td>
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<td>-5 ± 20</td>
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<td>0.10 ± 0.02</td>
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<td>0.2 ± 0.6</td>
<td>-11.5 ± 0.8</td>
<td>0.19 ± 0.07</td>
</tr>
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</table>

rate that becomes velocity independent for \(U_{\text{rms}} \leq 0.7 \text{ m s}^{-1}\), whereas in the experiments of A & R the rates increase with \(U_{\text{rms}}\).

Comparison to model calculations In table 3.6 estimations of the three models discussed in Chapter 1, Bailard, bed load and suspended (eq. 1.27), Ribberink (eq. 1.29) and Dibajnia & Watanbe (D & W) (eq. 1.36), for the three experimental conditions are given. To perform th calculations a Pascal programme was used, developed by Kooi (1994) [Koe94]. The chosen
present experiments
[SAL93]

Figure 3.19: Transport rates as found in the present experiments (squares) and by Al-Salem and Ribberink (circles). The latter can be described by a third order power law: \( \langle q^V \rangle = a(U^3) \).

Table 3.5: Dimensionless transport rates of the present experiments (F) and the one performed by Al-Salem and Ribberink (B) where sand with a medium grain-size of 210 μm and a density of 2.65 kg \( L^{-1} \) was used. In test-series F3-F7 the moving sand was found to consist of lighter and larger grains than the original sediment. The dimensionless transport rates \( \Phi \) are therefore calculated by eq. (3.35) using \( \rho_s = 3.00 \) kg \( L^{-1} \) and \( d_{50} = 165 \) μm.

<table>
<thead>
<tr>
<th>( U_{rms} ) (m ( s^{-1} ))</th>
<th>( \Phi_{bw} ) run</th>
<th>( \Phi_{bw} ) run</th>
<th>( \Phi_{bw} ) run</th>
<th>( \Phi_{bw} ) run</th>
</tr>
</thead>
<tbody>
<tr>
<td>B7</td>
<td>1.01 ± 0.08</td>
<td>B8</td>
<td>3.19 ± 0.16</td>
<td>B9</td>
</tr>
<tr>
<td>F3.1</td>
<td>1.33 ± 0.05</td>
<td>F5.1</td>
<td>2.50 ± 0.11</td>
<td>F4.1</td>
</tr>
<tr>
<td>F3.2</td>
<td>1.33 ± 0.07</td>
<td>F5.2</td>
<td>2.85 ± 0.18</td>
<td>F4.2</td>
</tr>
<tr>
<td>F3.3</td>
<td>1.51 ± 0.10</td>
<td>F5.3</td>
<td>2.32 ± 0.18</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>F5.4</td>
<td>2.5 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>F7.1-2</td>
<td>0.85 ± 0.04</td>
<td></td>
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</tr>
<tr>
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<td>0.95 ± 0.03</td>
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<td>1.20 ± 0.08</td>
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<td></td>
<td>F6.4-5</td>
</tr>
</tbody>
</table>

Input parameters are listed in appendix B.

Total transport rates \( q_{tot} \) are calculated with the average sediment characteristics, \( \rho_s = 3.20 \) kg \( L^{-1} \) and \( d_{50} = 150 \) μm, and for a sediment consisting out of two fractions: a light one (70% of the grain volume), \( \rho_s = 2.65 \) kg.
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$L^{-1}$ and $d_{50} = 180 \mu m$, and a heavy one (30 % of the grain volume), 4.40 kg $L^{-1}$ and $d_{50} = 90 \mu m$. In the latter case transport rates $q_{frac}$ are calculated according to:

$$q_{frac} = 0.7q_{light} + 0.3q_{heavy}, \quad (3.36)$$

where 0.7 and 0.3 are the light and heavy fraction in the original sand, respectively. The contribution of heavy minerals to the transported sand $p_{h,T}$ is given by

$$p_{h,T} = \frac{0.3q_{heavy}}{(0.7q_{light} + 0.3q_{heavy})}. \quad (3.37)$$

It is assumed that all grains are hydraulically equivalent and have a settling velocity $w_s = 1.9 \text{ cm s}^{-1}$. This means that, according to equations 1.39 and 1.40, the models of Ballard and Ribberink will predict a heavy minerals fraction within the transported sand of $p_{h,T} = 0.17$. This value is, within the inaccuracies, in agreement with the experimental values 4 (see last column of table 3.4). The only exception is test-series F7 where a lower heavy mineral content of the sand in motion was found. However, in view of the large uncertainties in the experimental results it is not meaningful to draw any conclusions about the performance of the models on this aspect.

| Table 3.6: Results of model calculations for transport rates under sheet flow conditions. Three models are considered: Ballard's model (suspended and bedload), Ribberink' model and Dibajnia & Watanbe's model. Total transport rates $q_{tot}$, for homogeneous sediment $\rho_s = 3.20 \text{ kg L}^{-1}$, $d_{50} = 150 \mu m$, and $q_{frac}$ for a sediment consisting out of two fractions, a light and heavy one (see text). For the model of D & W the heavy mineral fraction in the transported sand $p_{h,T}$ is given between brackets. Transport rates are given in $10^{-6} \text{ m}^3 \text{ s}^{-1}$. |
|---|---|---|---|---|---|
| $U_{rms}$ | 0.5 m s$^{-1}$ | 0.7 m s$^{-1}$ | 0.9 m s$^{-1}$ | $q_{tot}$ | $q_{frac}$ | $q_{tot}$ | $q_{frac}$ | $q_{tot}$ | $q_{frac}$ |
| Ballard | 23 | 25 | 70 | 79 | 207 | 238 | |
| - bed | 3 | 4 | 7 | 8 | 17 | 14 | |
| - sus | 19 | 22 | 63 | 70 | 190 | 219 | |
| Ribberink | 13 | 14 | 34 | 39 | 88 | 107 | |
| D & W | 11 | 13 (0.18) | 32 | 38 (0.18) | 61 | 47 (0.36) | |

4Because the heavy mineral content in the sediment bed is changing in time, the model calculations should only be compared to the results of the first run of each test-series.
The outcome of the model calculations are given in table 3.6 and shown in figure 3.20. For the model of D & W the heavy mineral fraction in the transported sand ($p_h$) is given between brackets.

Total transport rates are estimated well for the lowest two velocities by Ribberink’s and D & W’s model. Bailard’s model overestimates measured transport rates for all three velocities by a factor of 2 - 8 because suspension transport is overrated. In this respect the remark should be made that the outcome depends on the choice of the expression for the bottom roughness $k_n$. In the present calculations $k_n = 3d_{100}$ whereas the model of Bailard gives lower (better) results for $k_n = d_{50}$ [Koe94]. For the highest velocity all models overrate the measured transport rate by a factor 2 - 8.

Calculating transport rates by considering two separate fractions increases the estimated values in case of the models of Bailard and Ribberink. The model of D & W gives a somewhat higher transport rate for the lower velocities. However, for the roughest wave condition, $U_{rms} = 0.9$ m s$^{-1}$, the transport rate decreases when two separate fractions are considered. According to this model, the net transport rate of the light minerals in the downstream direction has decreased, because light material is transported in the
3.4 Thick layer experiments

opposite direction. This is reflected by the considerably higher contribution of heavy minerals to the net transported sand in the direction of the waves, 0.36 versus 0.18.

On basis of the experimental results it is impossible to tell whether the transport of light minerals in suspension against the wave direction as the model of D & W predict, is the cause of the low transport rates found for the higher velocity regime. Unfortunately no thin layer experiments have been performed with such a high velocity. The calculated transport rates are still a factor two higher than the experimental values and the predicted heavy mineral fraction in the transported sand is considerably higher than found in runs F4.1 and F6.1. However, from the three models considered the model of Dibajnia & Watanabe shows the best agreement with the experiments.

Hiding and sheltering To test the effect of applying hiding factors as discussed in section 1.4.1 the model of Ribberink is used. It is the only one, of the three models discussed, where beginning of motion and effective shear stress are included and consequently correction factors affecting both parameters may play a role. The corrections will be applied to the transport of the light and heavy fraction separately.

The correction factor on critical shear stress according to Ezigaroff (eq. 1.23) is considered plus the method of Komar et al. (eq. 1.22). For the effective shear stress the factors according to Misri and Day are used, (eq. 1.24) and (eq. 1.25), respectively. The method of Misri implies a considerably higher effective shear stress for the light fraction. Because it is questionable if this is a correct approach, results are also given if the correction factor is applied only on the small heavy fraction (Misri (h)). Input parameters are listed in appendix B.

The results are shown in table 3.7. Adjusting the critical shear stress for initiation of motion has hardly any effect on total transport rates where the corrections according to Ezigaroff and Komar give the same results. Applying a hiding correction on the effective shear stress gives the largest reduction of the transport rates. However, the best agreement between experiment and model calculation is still obtained by using average sediment characteristics instead of separate fractions as input parameters (see table 3.6). Moreover, applying Day’s correction factor on the average sediment results in a reduction of 20 % on calculated transport rates for the highest velocity. This reduction is still by far not sufficient to explain the observed lower transport rate in the

\[\text{Since the correction factor suggested by Day is based on the gradation of the sediment (steepness of the grain size distribution) it can also be applied to the average sediment.}\]


Table 3.7: Effect of several correction factors on estimated transport rates \( q_{\text{frac}} \times 10^{-6} \text{ m}^2 \text{ s}^{-1} \) according to the model of Ribberink. The bottom row shows the result when no correction is applied.

<table>
<thead>
<tr>
<th></th>
<th>( U_{\text{rms}} = 0.5 \text{ m s}^{-1} )</th>
<th>( U_{\text{rms}} = 0.7 \text{ m s}^{-1} )</th>
<th>( U_{\text{rms}} = 0.9 \text{ m s}^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Komar</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Ezi.</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Misri</td>
<td>34</td>
<td>92</td>
<td>250</td>
</tr>
<tr>
<td>Misri (h)</td>
<td>13</td>
<td>0.07</td>
<td>97</td>
</tr>
<tr>
<td>Day</td>
<td>13</td>
<td>0.10</td>
<td>94</td>
</tr>
<tr>
<td>no cor.</td>
<td>14</td>
<td>0.17</td>
<td>107</td>
</tr>
</tbody>
</table>

present data.

Armouring  The results in table 3.7 indicate that the low transport rates as observed in the present experiments can not be modelled by a correction for hiding on the effective or critical shear stress. Moreover, the deviation between observed and calculated transport rates as well as between the results of the present experiments and the one of Al-Salem and Ribberink, is increasing with increasing velocity. In view of the results of the thin layer experiments this may be because the removal of light material is more effective under the most energetic conditions; the heavy material moves considerably slower and stay close to the bottom under these conditions. This implies that transport rates depend highly on the amount of light material ‘available’ to meet the ‘demands’ of the velocity. In case of low velocities, as in test-series F3 and F7, enough light material was available but for the more energetic conditions it may not have been sufficient. If there is no light material any more in the upper part of the sediment bed heavy minerals may form an ‘armouring layer’ for the underlying sediment, preventing deeper light minerals to be transported, and thus decreasing the transport rate.

3.4.7 Conclusions

The conclusions from the thick layer experiments can be summarised as follows:

- Accumulations of heavy minerals in general occurred at bed forms like the ‘mega ripples’ or ‘dunes’ as did develop in test-series F4 and F6.
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However, not every bed form is marked by such an accumulation.

- The material in suspension consisted mainly out of somewhat lighter minerals with a relative small grain size (figure 3.16). Concentration profiles of the material in suspension could all be described with a power law with a constant concentration decay parameter \( \alpha_d \approx 2 \). Unfortunately the use of the suction system seems to influence the experiment, an effect most evident in the test-series F3.

- The BGO detector system is sensitive enough to detect changes in composition of the sediment which are occurring in the upper layer of the bed; a good correlation between measured radiation levels and density of this layer does exist. The results are reproduced by a ‘two-layer-model’ that describes the radiation above a homogeneous sediment-bed covered with a layer with different characteristics. Since it was also shown that the density of a sample is related to its grain size (fig.3.16), radiation measurements give information on density and, to some extent, grain size distribution of the underlying sediment.

- The grain size distributions of the bed samples in this experiment may be described by a Gaussian shape with a approximately constant variance and a mean grain size which is a function of density. This allows for the determination of the median grain size based on the separation of samples in two fractions only.

- The ‘two layer approach’ used to calculate the transport rates per fraction gives a good description of the observed features. The thickness of the ‘transport layer’ is in the order of centimeters. No correlation was found between the thickness of this layer and the hydraulic conditions. A more dense set of measuring points along the test section will provide more detailed information on the variations in the thickness of the active layer.

- From the contents of the downstream sand trap it may be concluded that the light fraction of the sediment is rather efficiently removed from the test section.

- Calculated dimensionless sediment transport rates in the present experiments are in general lower than in experiments by Al-Salem and Ribberink in 1992 [AlS93, Rib94]. In the present experiments transport rates under the most energetic conditions (\( U_{rms} = 0.9 \) m s\(^{-1}\)) are as much as 50% lower. The composition of the transported sand indicates
that this decrease may be due to ‘armouring’ by high concentrations of heavy minerals. From the top layer of the sediment bed the light material is removed and therefore consists mainly of a slowly moving heavy sediment. This layer prevents light sediments to be transported (armouring). Because the process of enrichment with heavy minerals is going faster under rougher conditions, as can be seen in the thin layer experiments, this effect is most effective for test-series F4 and F6.

- Three transport models have been compared to the data: the models of Bailard, Ribberink and Dibajnia & Watanabe. The model of Bailard is over estimating the data with a factor 2-10 mainly by a overrating of the suspension transport rate. The other two models are capable of reproducing transport rates for low velocities reasonably well. The models of Ribberink and D & W overestimate transport rates for the most energetic condition by a factor of 3 and 2, respectively. This large deviation can, in the case of the model by Ribberink, not be explained by hiding or sheltering effect caused by non-uniform sediment.

The model of D & W shows better agreement with the measured transport rate in case of the highest velocity when the transport rate for a heavy and a light fraction was calculated separately. This due to a offshore directed transport of light minerals (according to the model). However, the calculated heavy mineral fraction in the transported sand is considerably higher than the experimental values (see tables 3.4 and 3.6).