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Sediment transport for two sands with different grain diameters under combined wave-current sheet flow conditions

Part I: Data report
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Sediment transport for two sands with different grain diameters under combined wave-current sheet flow conditions

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CLIENT: Rijkswaterstaat, RIKZ

TITLE: Sediment transport for two sands with different grain diameters under combined wave-current sheet flow conditions
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ABSTRACT:
The report presents the data of two sets of experiments, performed in the Large Oscillating Water Tunnel of DELFT HYDRAULICS, on sand transport in oscillatory sheet flow. The aim of the experiments was to collect data of net transport rates for two uniform sands with different grain diameters (i.e. $D_{50} = 0.21$ and $0.32$ mm) and data of time dependent flow velocities and sediment concentrations for the coarser sand ($D_{50} = 0.32$ mm). The flow conditions of the present experiments are equal to the conditions of earlier experiments with fine sand ($D_{50} = 0.13$ mm).
This means that the effect of the grain diameter can be investigated. The data can be used to incorporate the effect of the grain size into mathematical sand transport models.

REFERENCES: Contract number: RIKZ-369, First phase
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<td>$a_g$</td>
<td>Amplification factor of electronic amplifier of OpCon (factor 1 or 10)</td>
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<td>$a_c$</td>
<td>Electronic conversion factor for the log-amplifier of the OpCon ($= 3 \cdot \log(e) = 1.303$ for the applied Opcon)</td>
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<tr>
<td>$c$</td>
<td>Sediment in concentration (m$^3$/m$^3$ or vol% or g/l)</td>
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<td>Sampling frequency (Hz)</td>
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<td>$T$</td>
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<td>$u$</td>
<td>Horizontal velocity (m/s)</td>
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<td>$\langle u \rangle$</td>
<td>Wave-averaged or net current horizontal velocity (m/s)</td>
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<td>$\dot{u}$</td>
<td>Amplitude of horizontal oscillatory (sinusoidal) velocity (m/s)</td>
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<tr>
<td>$\Delta V_{ip}$</td>
<td>$= \Delta V_{ip} + \Delta V_{rp} =$ total eroded volume, including pores, from the tunnel test section during one test (m$^3$)</td>
</tr>
<tr>
<td>$\Delta V_{ip}$</td>
<td>Total eroded volume, including pores, from the part of the tunnel test section to the left of the measurement location during one test (m$^3$)</td>
</tr>
<tr>
<td>$\Delta V_{rp}$</td>
<td>Total eroded volume, including pores, from the part of the tunnel test section to the right of the measurement location during one test (m$^3$)</td>
</tr>
</tbody>
</table>
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\[\delta_1\] Overall bed lowering during a test, see Figure 3.4.1 \hspace{1cm} (m)
\[\delta_2\] Bed level variation during the wave cycle, see Figure 3.4.1 \hspace{1cm} (m)
\[\varepsilon_0\] Porosity of sand \hspace{1cm} (-)
\[\rho_s\] Density of sand \hspace{1cm} (kg/m\(^3\))
\[\rho_w\] Density of water \hspace{1cm} (kg/m\(^3\))
1 Introduction

1.1 Background of the study

Correct predictions of sediment transport in the coastal zone are very important in order to take adequate measures in coastal zone management problems. Field observations show a considerable variation in sediment composition along the coastal profile. Process-based models still have insufficient predictive value, and do not take into account the variations observed in the field. It is thought that these variations are caused by selective transport processes. In order to verify this hypothesis, experimental data are required, collected under specified controlled hydraulic conditions. The followed strategy at this is, to perform experiments on the dominant sediment transport processes and to translate this knowledge into mathematical models that can be used to predict the sediment transport rate in practice (see Van Rijn and Ribberink, 1996).

This report presents the measured data of the most recent set of experiments on sand transport in oscillatory sheet flow, as obtained in the Large Oscillating Water Tunnel (LOWT) of DELFT HYDRAULICS. The experiments fit in a research program, which started several years ago and was performed within different frameworks: kustgenese (coastal genesis), MAST, STW/TUD (Technology Foundation/Delft University of Technology) and now continues with the KUST2000 program. A central topic in this research program is the mathematical modeling of the sand transport processes in oscillatory sheet flow conditions. The experimental program in the LOWT provides the necessary data for the model development and validation and may increase the physical understanding. An overview of all the previous experiments, relevant to the present study, is given in Table 1.1. Note that the first three series in this table are performed with purely oscillatory flow, while the others are performed under combined wave-current flow. The LOWT is a large-scale experimental facility that allows a full scale reproduction of wave- and current-related flow and transport phenomena near the bed. In 1992 the LOWT was extended with a recirculating flow system such that a steady current could be added to the oscillatory flow.

In order to model correctly the effect of variations in sediment composition on the transport rate, data are required for sand with varying grain diameter. Before investigating the effect of a sediment mixture on the transport rates, the influence of the grain diameter in uniform sand will be determined. Recently, experiments on net transport rates and transport mechanisms of very fine sand ($D_{s0} = 0.13$ mm) in oscillatory sheet flow conditions were performed (series H, see Table 1.1). Janssen & Ribberink (1996) compared the net transport rates of this fine sand with net transport rates of unsieved dunescand ($D_{s0} = 0.21$ mm).

In the present study, experiments on net transport rates and transport mechanisms for relatively coarse sand ($D_{s0} = 0.32$ mm) were performed. Besides, additional net transport measurements were performed with the unsieved dunescand, ($D_{s0} = 0.21$ mm) as the experiments performed by Katopodi et al., (1994, series E, see Table 1.1) only consisted of 4 different hydraulic conditions.

The present data together with the data of series E and series H form a complete data set on sand transport in combined wave-current sheet flow conditions for 3 different grain diameters ($D_{s0} = 0.13$; $0.21$ and $0.32$ mm). It is expected that these data provide enough
information to develop a model, that incorporates the effect of the grain size on the net transport rates for uniform sand. The data set may also be used to determine the most important parameters for the modelling of transport rates of graded sediments.

Net sediment transport rates are derived from the change of the bed level and the weight of the sand collected in the sand traps (a mass conservation technique as described in Appendix A1). The local bed level variation during the wave cycle was recorded by a standard video camera. Time-dependent concentration profiles were measured with an optical method (OpCon) and with an electro-resistance technique (CCM). Vertical profiles of time-dependent flow velocity were measured with a Forward-scatter Laser-Doppler Velocity meter (LDFM) and an Acoustic Doppler Velocity meter (ADV).

1.2 Aim of the experiments

The aim of the present experiments is to collect data of net transport rates for sand with different grain diameters under specified controlled hydraulic conditions. These data can be used for the verification and further development of the transport models, such that the effect of the grain size can be incorporated into the models. Next the models can be extended to include the effect of graded sediments. Existing models either only predict the net transport rates (e.g. Bailard, 1981; Dibajnia & Watanabe, 1992; Ribberink (see: Koelewijn, 1994)) or they also describe the transport mechanisms, i.e. flow velocity and sediment concentration (e.g. Fredsoe et al., 1985; Davies, 1992; Ribberink & Al-Salem, 1995). For an overview of the different existing transport models, see Janssen (1995a). In order to model the unsteady effects on the sand transport rates, also time-dependent measurements of velocity and concentration are performed.

In order to determine the influence of the grain size, the present experiments were performed with the hydraulic conditions set the same as in the earlier experiments with fine sand (Janssen et al., 1996), now using sand with larger grain diameters, i.e. $D_{50} = 0.21$ and 0.32 mm, respectively. The combined wave-current flow conditions of the fine sand experiments all lie in the sheet flow regime. Because the transport mechanism above ripples is very different, no bedforms are allowed to develop in the present experiments. Sheet flow conditions are important in sand transport processes, because they correspond to conditions of large velocities (i.e. storms) when large amounts of sand are in motion.

For the coarse sand, both net transport rates, and time-dependent velocity and concentration profiles were measured. For the 0.21 mm sand, only net transport measurements were performed, because time-dependent velocity and concentration measurements have already been performed by Katopodi et al. (1994).

1.3 Annotated contents

In Chapter 2, the experimental set-up of the study is described. A brief description is given of the experimental facility, the imposed and measured parameters, the test conditions (different combinations of sinusoidal waves and net currents), the measuring techniques used, the test programme and the data acquisition and storage.
In Chapter 3, the experimental results of the two sets of experiments are presented and briefly discussed. Apart from wave-averaged velocities and concentrations, also ensemble-averaged concentration time series are presented.

Chapter 4 contains the preliminary conclusions, drawn from the experimental study.

### 1.4 Framework and execution of the study

The experimental investigation was part of the research program "KUST*2000" (or COAST*2000) of Rijkswaterstaat and was funded by the Dutch Ministry of Transport and Public Works (Directorate General Rijkswaterstaat, National Institute for Coastal and Marine Management/RIKZ) during the first phase of contract RKZ-369. The experiments were performed in the Large Oscillating Water Tunnel of DELFT HYDRAULICS (reference: project number Z2137).

The experimental research was carried out from October 1996 until January 1997 (weeks 42 - 52 of 1996 and weeks 1 - 3 of 1997). The tunnel was operated by Henk Westhuis and Ella van der Hout. The data processing and analysis was performed by Ella van der Hout. The project management was done by Jan Ribberink and Marjolein Janssen, DELFT HYDRAULICS. Project leader for Rijkswaterstaat was Daan Dunsbergen.
2 Experimental set-up

2.1 The Large Oscillating Water Tunnel

The measurements were conducted in the Large Oscillating Water Tunnel (LOWT) of DELFT HYDRAULICS. In Figure 2.1.1 the general outline of the tunnel is shown. The tunnel has the shape of a vertical U-tube with a long rectangular horizontal section and two cylindrical risers on either end. This configuration enables the generation of a horizontal oscillatory flow, which is a simulation of the orbital velocity underneath a wave, very close to the bed.

The desired oscillatory water motion inside the horizontal rectangular test section of the tunnel is imposed by a steel piston in one of the risers. The other riser is open to the atmosphere. The piston is in direct contact with the water and is driven by a hydraulic servo-cylinder, mounted on top of the riser. An electro/hydraulic valve controls the piston motion on the basis of the measured difference between the (measured) actual piston position and the (desired) piston position (feedback system). The test section is 14 m long, 1.1 m high and 0.3 m wide and is provided with flow straighteners on either end. A 0.3 m thick sand bed can be brought into the test section, leaving 0.8 m height for the oscillatory flow above the bed. Two sand traps are constructed in the two cylindrical risers to collect the sand that has been removed from the test section during a test.

The side walls of the test section consist of thick glass windows supported by steal I-beams. The maximum piston amplitude is 0.75 m, which means a maximum semi-excursion length of the water particles in the test section of 2.45 m. The working range of the tunnel is shown in Figure 2.1.2. From this figure it is clear that the range of velocity amplitudes is 0.2 - 1.8 m/s and the range of oscillation periods is 4 - 15 seconds. It is possible to generate purely sinusoidal, regular asymmetric and irregular oscillatory motions with the piston. An extensive description of the water tunnel can be found in Ribberink (1989).

In 1992 the tunnel was extended with a recirculating flow system connected to the cylindrical risers, such that a steady current can be superimposed onto the oscillatory motion. The recirculating flow system is also provided with a sand trap consisting of a 12 meter long pipe with a diameter of 1.2 meter that is connected with the downstream cylindrical riser by a pipe with a diameter of 0.3 meter (see Figure 2.1.3). The trap was designed for trapping 90% of the suspended sediments (minimum grain size 100 microns) at maximum flow discharge. Downstream of the trap two pumps are installed for generating a net current. The maximum capacity of the larger pump is 100 l/s and of the smaller 20 l/s. The maximum superimposed current velocity in the test section of the tunnel is 0.45 m/s.

2.2 Measured and imposed parameters

The following parameters were measured during the experiments:

- Bed levels and sand trap volumes for the estimation of the net sediment transport rates.
- Bed level variation during the wave cycle.
- Time-dependent flow velocities $u(z,t)$, $v(z,t)$ and $w(z,t)$ at different levels above the bed.
• Time-dependent sediment concentration \( c(z,t) \) both in the suspension layer (for \( z > 0.01 \) m) and in the sheet flow layer.

For imposed and measured parameters see also Figure 2.2.1.

### 2.3 Test conditions

#### 2.3.1 Sand

**Series I**

As mentioned in Section 1.2, the main aim of the present experiments is to collect data on net sand transport rates and transport mechanisms for sand with different grain diameters, such that the effect of the grain size can be determined and the sediment transport models can be improved. The sand used in earlier experiments on net sand transport in oscillatory sheet flow conditions, performed in the LOWT, had a mean grain diameter of 0.13 or 0.21 mm. Therefore the first set of the present experiments was performed with coarser sand.

Initially, sand with a mean grain diameter of about 0.40 - 0.45 mm was chosen for series I. All previous experiments were performed in sheet flow conditions. In order to be able to determine the effect of the grain size on the net sand transport rates, bedforms should not occur during the tests with coarser sand, as the mechanisms of sand transport above ripples are very different. Therefore test measurements were performed first, in order to check the occurrence of bedforms for the coarse sand (0.40 - 0.45 mm). Various hydraulic conditions were imposed to the tunnel. Tables 2.1 and 2.2 show an overview of the hydraulic conditions and a description of the resulting bed forms. Table 2.1 contains the test conditions, consisting of sinusoidal oscillatory motion combined with a net current, while Table 2.2 shows the conditions for the tests with asymmetric (2\textsuperscript{nd}-order Stokes) oscillatory motion combined with a net current. Concerning the hydraulic conditions, the net current velocity at 10 cm above the bed \( (\langle u \rangle) \) is given, together with the amplitude of the sinusoidal velocity \( (\bar{u}) \) or the root-mean-square value of the asymmetric oscillatory velocity \( (u_{rms}) \). Additionally, the oscillation period \( (T) \) is given. With respect to the resulting bed forms, the approximate height \( (\eta) \) and length \( (\lambda) \) of the bedforms is given for the cases in which they were measured. Additionally, some description of the observed bedforms is presented.

As can be seen from the results, presented in the Tables 2.1 and 2.2, the sand with a mean grain diameter of about 0.40 - 0.45 mm, caused too much bedforms, such that the test conditions are not comparable to those in the fine sand experiments. Therefore it was decided to use somewhat finer sand. Sand with a mean grain diameter of 0.35 mm was ordered. However, it turned out that the mean grain diameter of this new sand was not exactly 0.35, but rather 0.39 mm. This was considered to be too close to the 0.40 - 0.45 mm sand, used in the bedform test measurements. Finally, two different sands were ordered such that either one of them or a mixture of the two would result in the desired mean grain diameter of about 0.3 mm. Sieve analyses showed that these two sands had mean grain diameters of 0.275 and 0.353 mm, respectively. The sand used in the series I measurements consisted of a 50%-50% mixture of these two sands. This mixture had the following characteristics (see also Figure 2.3.1):
\[ D_{10} = 0.22 \text{ mm} \]
\[ D_{50} = 0.32 \text{ mm} \]
\[ D_{90} = 0.46 \text{ mm} \]

Where:

- \( D_{10} \) = diameter, 10% by weight is finer
- \( D_{50} \) = diameter, 50% by weight is finer
- \( D_{90} \) = diameter, 90% by weight is finer

Although this sand consists of a mixture of two sands, still the width of the grain size distribution, characterised by the geometric standard deviation, \( \sigma_g \) is about the same (\( \sigma_g = 1.33 \)) as in the fine sand (\( \sigma_g = 1.30 \)) and the unsieved dunesand (\( \sigma_g = 1.29 \)). It was expected that the desired test conditions did not result in any bedforms for this sand. During the experiments it turned out that this was indeed the case.

**Series J**

Apart from the experiments with coarse sand, additional experiments with unsieved dunesand (\( D_{50} = 0.21 \text{ mm} \)) were performed. The reason to perform extra measurements with unsieved dunesand was that, so far, experiments with this sand were performed for only 4 conditions of sinusoidal oscillatory flow combined with a net current. (Other experiments with the 0.21 mm sand were performed with asymmetric oscillatory flow, which makes a direct comparison with the results of the fine sand experiments very difficult). Sieve analysis showed that the unsieved dunesand has the following characteristics (see also Figure 2.3.2):

\[ D_{10} = 0.15 \text{ mm} \]
\[ D_{50} = 0.21 \text{ mm} \]
\[ D_{90} = 0.32 \text{ mm} \]

As mentioned above, the geometric standard deviation (\( \sigma_g \)) of the unsieved dunesand is 1.29.

**2.3.2 Flow conditions**

**Series I**

The test conditions were chosen, according to the following considerations:

- As the main aim of the present experiments was to determine the effect of the grain size on the transport rate and the underlying mechanisms in sheet flow conditions under combined wave-current flow, the conditions were selected such that they were, at least partly, equal to the earlier experiments with fine sand, i.e. series H (see Janssen et al., 1996). This means that all conditions consisted of a sinusoidal oscillatory motion, combined with a steady flow. The oscillation period was 7.2 s.
- All conditions should be in the sheet-flow regime (i.e. no bedforms should be present in the tunnel), such that the transport is caused by the same mechanisms as in the earlier experiments.
- The conditions should be of course within the restrictions of the LOWT.
These considerations resulted in 5 test conditions, which are summarised in Table 2.3. The flow velocity at 10 cm above the sand bed (i.e. above the wave-boundary layer) is given by:

\[ u(t) = \langle u \rangle + \hat{u} \sin(\omega t) \]  \hspace{1cm} (2.1)

Here \( u(t) \) is the instantaneous horizontal velocity, \( \langle u \rangle \) is the net current velocity, \( \hat{u} \) is the amplitude of the sinusoidal velocity and \( \omega \) is the angular frequency \((2\pi/T, \text{where} \ T \text{is the oscillation period})\). Table 2.3 presents for each test condition the value of the net current velocity (at 10 cm above the bed), the amplitude of the sinusoidal velocity and the oscillation period. Additionally, the required pump discharge \( (Q_{\text{pump}}) \) and amplification percentage for the piston steering (A) to generate these flow conditions are presented.

Time-dependent measurements were performed in order to determine the unsteady effects. In the previous experiments with 0.21 mm sand (series E) and 0.13 mm sand (series H), it was found that the unsteady effects were most important for the condition with the largest oscillatory velocity and that they were more important for the 0.13 than for the 0.21 mm sand. Therefore it was decided to perform time-dependent measurements for the 0.32 mm sand for condition II only. This condition was chosen, because it is equal to one of the conditions of series G (fixed bed), series H (fine sand) and series E (unsieved dunesand) for which time-dependent measurements were performed. This means that a comparison between results for different grain diameters is possible.

**Series J**

The test conditions for series J were chosen, along the same considerations as described above. Additionally, two test conditions with a different wave period were chosen, because it turned out that for the fine sand the wave period had a very large effect on the net transport rate, especially for large oscillatory flow velocities. Therefore it was decided to study the effect of the wave period on the net sand transport rate for the unsieved dunesand too. These conditions were not selected for the coarse sand, because in that case they did not correspond to sheet flow conditions, but caused large bedforms in the tunnel. The 6 selected test conditions for series J are summarised in Table 2.4.

### 2.4 Measuring facilities and measuring techniques

In this section the different measuring facilities and measuring techniques are described shortly. In appendix A more information can be found about the measuring methods and the calibration of the instruments.

#### 2.4.1 Mass conservation technique

A mass conservation technique was used for the measurement of the sediment transport rates in the test section: The bed level along the test section was measured before and after each run by a bed level profiling system (see Section 2.4.1.1). This gives the volume of sand (including pores) removed from the test section during a tunnel run. This sand is collected in the three sand traps (underneath the piston, underneath the open cylindrical riser and in the recirculation system). The amount of sand collected in the three traps is determined by weighing the sand under water.
To determine the net sand transport rate at the measurement location (2 m downstream of the centre of the tunnel test section), the sediment continuity equation is solved twice (see also Appendix A1): the calculation is started from the left-hand side using as a boundary the volume of sand collected in the trap underneath the piston and from the right-hand side using as a boundary the volume of sand collected in the traps underneath the open cylindrical riser and in the recirculation system. This gives two estimates of the actual occurring transport rate at the measurement location for a specific test. In order to transfer the measured volume of sand (including pores), removed from the test section to the transported volume without pores, the porosity of the sand bed must be known.

The porosity of the sand is derived as follows: At the end of a test an erosion hole is developed due to the transport of sand from the test section. This erosion hole is refilled to create a flat bed again for the beginning of the next test. The difference between the bed level at the end of a test and the bed level at the beginning of the following test, gives the change in volume (including pores) due to the refilling of the erosion holes. Because the weight of sand (and thus the volume without pores), added to the tunnel, is known, the porosity can be determined.

Variations in porosity, inaccuracies in bed level measurements or a loss of sand from the traps, occurring when emptying the traps, may result in a difference between two estimates in transport rate, calculated from the left- and from the right-hand side. For more details about the accuracy of net transport measurements in the LOWT see Van der Wal (1996).

2.4.1.1 Bed level profiling system

The bed level profiling system consists of three bed profilers (which measure the bed level), a position counter (which determines the exact location of the profilers) and measuring and processing software. The profilers are positioned on a measurement carriage, such that the bed level can be measured at three locations across the width of the tunnel (in the centre and 0.1 m to the left and to the right, i.e. 0.05 m from the sidewalls). The configuration of the profilers on the measurement carriage is shown in Figure 2.4.1 and the configuration of the bed level profiling system in the tunnel is shown in Figure 2.4.2.

The profilers, developed by DELFT HYDRAULICS, are based on conductivity measurements. The instrument is organised such, that the conductivity in the sampling volume remains constant. This means that the probe tip remains at a constant distance from the sand bed. A potential meter registers the vertical position of the probe, which is a direct measure of the bed level in the tunnel.

2.4.2 Laser Doppler Velocity Meter (LDFM)

A forward scatter Laser Doppler Velocity meter (LDFM) was used for the measurement of the horizontal and vertical velocity components of the water particles between 20 and 100 mm above the bed. Below this level, it turned out to be impossible to measure velocities by LDFM, because of the large amount of sediment particles below this level. The particles block the laser beams and disturb the measurement. Rather than measuring directly the horizontal ($u$) and vertical ($w$) components of the velocity, two other more or less perpendicular components $v_A$ en $v_B$ in the same vertical plane (see Figure 2.4.3) were measured. The reason was that the velocity range is larger in the second configuration. The components $v_A$ en $v_B$ are
transferred to u and w afterwards. The LDFM was positioned on a measurement carriage that stands over the tunnel, rather than on top of it, such that vibrations of the tunnel do not disturb the LDFM. In Figure 2.4.4 the configuration of the laser system on the measurement carriage is shown. The configuration of the laser beams in the tunnel is shown in Figure 2.4.5.

2.4.3 Acoustic Doppler Velocity Meter (ADV)

An Acoustic-Doppler Velocity meter, developed by the U.S. Army Engineering Station (WES), as implemented by SonTek, was used for velocity measurements below z = 40 mm, because it is capable of measuring velocities in high concentrations of sediment.

The ADV is based on the doppler principle to measure the three components (u, v and w) of the velocity at a single point. The system includes three modules: a measurement probe, a signal conditioning module and a signal processing module. The measurement probe consists of four ultrasonic transducers; a transmit transducer located at the bottom end of the stem and three receive transducers, slanted 30° from the axis of the transmit transducer and pointed at the sampling volume. This sampling volume is located about 0.10 m below the probe tip, which means that the flow in the sampling volume is not disturbed too much by the probe. A schematic diagram of the measurement probe of the ADV is presented in Figure 2.4.6.

The recorded signals can be stored and analyzed by specific ADV software (processing module). However, it is also possible to record the signals on a different data acquisition system, via three analogue outputs. This was done in the present experiments in order to have all data in the same format. Figure 2.4.7 shows the configuration of the ADV system in the tunnel.

2.4.4 Optical Concentration Meter (opcon)

The time-dependent suspended sediment concentrations were measured using an optical concentration meter (OpCon). OpCon measures volume concentrations in the range 0.005-2.0 % (= 0.1-50 g/l) and is based on the extinction of infra-red light. The height of its sensing volume is 2.6 mm. Figure 2.4.8. shows a schematic diagram of the OpCon probe. The OpCon configuration in the tunnel is shown in Figure 2.4.9.

2.4.5 Conductivity Concentration Meter (CCM)

The concentration in the sheet flow layer and inside the bed was measured using a Conductivity Concentration Meter (CCM). The instrument measures large sand concentrations (5-50 vol% = 100-1500 g/l) with a four point electro-resistance method. The height of the sensing volume is 1 mm. A detailed plot of the CCM probe is shown in Figure 2.4.10. The CCM configuration in the tunnel is shown in Figure 2.4.11.
2.5 Measurement program

2.5.1 Overall

During the two series of experiments, 77 tests (tunnel runs) were carried out with different measuring techniques. In the net transport measurements, one test corresponds to one measurement of net transport rate. In the time-dependent experiments, different measurements of velocity or concentration were performed at different levels over the vertical during one test. The level \( z = 0 \) represents the corresponding still bed level during a test. The still bed level before and after the test is measured. Because the bed level may change slightly during the tests, the elevation of each instrument relative to the bed also changes. Therefore the bed level below the instrument was measured during an experimental run (in the time-dependent measurements). This was achieved by measuring the still bed level at flow reversal (zero velocity) through the glass window, once every 36 s (5 oscillation periods). Measurements are accurate to 1 mm. The realised instrument elevation was taken as the mean value of the measured elevations during a specific measurement.

Table 2.5 and 2.6 present the overall measurement program with the different test conditions, the different measuring techniques, the location of the instruments, the number of tests, the number of measurements and the data-acquisition sampling frequency for series I and series J, respectively. A short description of the different measurements in the two series is given below:

2.5.2 Net transport

Measurements on net transport rates were carried out for 5 different flow conditions in series I (I1 - I5, coded IX-Ti, x-condition number, i=test number) and for 6 different flow conditions in series J (J1 - J6, coded Jx-Ti). The test duration of the different experiments varied per condition in order to avoid influence of the upstream boundary on the transport rate at the measurement location (i.e. \( x = 2 \text{ m} \), which is 2 m downstream of the middle of the test section. The actual test duration of each test can be found in Table 3.1 for series I and in Table 3.8 for series J (Experimental results).

In order to determine the net transport rate, bed levels along the tunnel were measured using the bed level profiling system. Additionally, the weight of the sand collected in the traps was measured under water.

2.5.3 Bed level variation by video

Video recordings were taken to be used for the measurement of the variation of the bed level during the wave cycle and possibly the thickness of the sheet flow layer. Bed level variations were measured for all test conditions (I1-I5 and J1-J6). Additionally, video recordings were taken for the unsieved dunesand for two conditions which are equal to I1 and I4 (or E2 and E4 of Katopodi et al., 1994). One test per condition was realised.

The camera was focused at the horizontal position \( x = 2.05 \text{ m} \). The depth range covered was from \(-10 \text{ mm}\) to \(+40 \text{ mm}\) with respect to the initial bed level. A transparent ruler with scales in mm was placed in the recording area. First, the initial bed level was recorded for about 15 s. Then the tunnel was started and the variation of the bed level was recorded for about 30 oscillation periods.
2.5.4 Time-dependent velocities, measured by LDFM

A Laser Doppler Velocity meter (LDFM), was used for the measurement of the time-dependent velocities from 100 mm above the bed, down to 18 mm above the bed (coded II-Li, i=test number). The sampling frequency was 100 Hz. The instrument was positioned at \( x = 2.05 \text{ m} \).

Four tests (tunnel runs) were realised. During each tunnel run the velocity was measured at 2 or 3 elevations (coded II-Lij, i=test number, j=measurement number). The velocity at a specific elevation was measured for about 3 minutes (\( \approx 25 \) oscillation periods). The actual measurement started after 2.5 minutes of running the tunnel (to avoid initial effects). Therefore after about 5 to 6 minutes of running the tunnel the LDFM was lowered to the second measurement point and left there for another 3 minutes before it was moved to the next point. This was repeated until the velocity was measured at all desired levels. The actual levels of the LDFM during each measurement can be found in Table 3.3 (Experimental results).

2.5.5 Time-dependent velocities, measured by ADV

An Acoustic Doppler Velocity meter (ADV), was used for the measurement of the time-dependent velocities close to the bed (coded II-Ai, i=test number). The sampling frequency was 25 Hz. The instrument was positioned at \( x = 2.05 \text{ m} \). The range of elevations was from about 40 mm above the bed down to the initial still bed level.

Six tests (tunnel runs) were realised. During each tunnel run the velocity was measured at 4 - 5 elevations (coded II-Aij, i=test number, j=measurement number). In general the velocity at one elevation was measured for about 1 - 2 minutes (\( \approx 10 \) oscillation periods). First, the ADV was positioned at the highest elevation for that test in order to disturb the flow as little as possible. The actual measurement started after 2.5 minutes of running the tunnel (to avoid initial effects). Therefore after about 3 to 5 minutes of running the tunnel the ADV was lowered to the second measurement point and left there for another 1 - 2 minutes before it was moved to the next point. This was repeated until the velocity was measured at all desired levels. The actual levels of the ADV during each measurement can be found in Table 3.4 (Experimental results).

2.5.6 Suspended sediment concentrations, measured by opCon

An optical/electronic instrument (OpCon) was used for the measurement of the time-dependent suspended sediment concentration for condition II (coded II-Oi, i=test number). The sampling frequency was 25 Hz. The instrument was positioned at \( x = 2.05 \text{ m} \). The range of elevations was from about 100 mm above the bed down to 12 mm.

Six tests (tunnel runs) were realised. During each tunnel run (\( \approx 15 - 20 \) min) 3 - 7 measurements were performed (coded II-Oij, i=test number, j=measurement number) at different elevations (1 - 2 minutes for each elevation which corresponds to about 10 wave periods). The actual measurement started after 2.5 minutes of running the tunnel (to avoid initial effects). Therefore after about 3 - 5 minutes of running the tunnel the OpCon was moved to the second measurement point. This was repeated until the concentration was measured at all desired levels. The actual levels of the OpCon during each measurement can be found in Table 3.5 (Experimental results).
2.5.7 Sediment concentrations in the sheet flow layer, measured by CCM

During this sequence of tests, time-dependent concentrations in the sheet flow layer were measured, using a conductivity concentration meter, CCM (coded II-Ci, i = test number). The sampling frequency was 25 Hz. The CCM was positioned at x = 2.05 m. The CCM elevations covered the region from 10 mm above the bed down to about 7 mm inside the bed.

Four tests per condition were carried out. During each test (duration 17 - 25 minutes), 4 - 8 measurements were performed at different elevations (coded II-Cij, i = test number, j = measurement number). These different elevations were either imposed by moving the CCM or they were the result of the change in bed level, which caused a different elevation of the CCM relative to the still bed. The actual levels of the CCM measurements can be found in Table 3.6 (Experimental results).

2.6 Steering, data acquisition and storage

The steering of the piston was imposed by a steer signal generated on a PC. During each test the following time-dependent parameters were stored on computer files using a PC data-acquisition system: the steer signal, the measured piston position, piston velocity, piston pressure, pump discharge, the two components \( v_A \) and \( v_B \) of the velocity measured by LDFM at 100 mm above the bed and the signal of the measured quantity. The measured analogue signals were digitised by means of an analogue to digital (A/D) converter and stored on PC (two files for each test, a binary file with extension .dat and an ascii file with extension .seq). All the measured signals were also recorded on paper. In Table 2.7 information on all measured parameters can be found: the computer channels on which the different parameters are recorded, the codes and units of the measured parameters and their calibration factors (these data are also included in the "seq"-files). The system of piston steering and data acquisition is schematically shown in Figure 2.6.1.

The bed levels, measured by the bed level profiling system were recorded on a separate PC and stored directly in ascii files. The local bed levels, measured every 36 s during an experimental run of the time-dependent measurements were recorded on measuring forms.
3 Experimental results

3.1 General

Totally 77 tests were carried out during two series of experiments. Net transport measurements were performed for 5 wave-current conditions in series I ($D_{50} = 0.32$ mm) and for 6 wave-current conditions in series J ($D_{50} = 0.21$ mm). Time-dependent measurements were performed for one condition in series I. In this chapter the experimental results, as obtained by a first analysis are presented. For all measured parameters the ensemble-averaged signal is determined together with the time-averaged value, the standard deviation, the minimum and maximum value and the root-mean-square value of the original time-series and of the ensemble-averaged signal.

In this chapter net sediment transport rates, time-averaged concentration and velocity profiles and time-dependent concentrations (in an ensemble-averaged format) are presented.

3.2 Series I ($D_{50} = 0.32$ mm)

3.2.1 Net transport measurements

In series I net transport rates were measured for 5 combined wave-current flow conditions. For the computation of the net sediment transport rate, 4 tests were realised per condition, (coded 1x-Ti). The bed level along the test section was measured before and after the experiment and the weight of the sand collected in the sand traps was determined. The net sediment transport rate was computed solving the mass balance equation twice for each test, starting from either the sand trap at the left-hand side or the two sand traps at the right-hand side of the test section. Two estimates of the net transport rate were derived in this way. They were determined at the position where the bed level was not changing during the test, i.e. about 2 m downstream of the centre of the tunnel test section. Table 3.1 summarises the results of the net transport measurements of series I. The following parameters are included in this table:

- test name,
- measurement duration,
- wave period T, derived from velocity measurements by LDFM, at 100 mm above the bed,
- time-averaged velocity ($u$), measured by LDFM at 100 mm above the bed,
- amplitude of oscillatory velocity $\tilde{u}$, measured by LDFM at 100 mm above the bed,
- under water weight of sand in trap underneath piston,
- under water weight of sand in trap underneath "open leg",
- under water weight of sand in trap in recirculation system,
- total volume of sand (without pores) in sand traps,
- total sand volume change (without pores) in the tunnel test section derived from bed level measurement and calculated porosity (average value over all tests),
- loss of sand (sand volume removed from test section minus collected volume in traps),
- calculated porosity (see Section 2.4.1),
- net sand transport rate, calculated from left-hand-side (\(q_{\text{fl}}\)),
- net sand transport rate, calculated from right-hand-side (\(q_{\text{fr}}\)).

The measured under water weights can be transferred into dry weights by multiplying them by the ratio of the density of sand to the density of water \(\rho_s/\rho_w = 1.606\). Next they can be transferred into sand volumes (without pores) by dividing them by the density of the sediment.

Figures 3.2.1 - 3.2.5 show the net sediment transport rates along the test section, as calculated from the measured bed levels and weights of sand in the traps. In the left part of the figures the calculations are shown, which are based on the upstream boundary (the sand volume in the sand trap underneath the piston), while the calculations of the transport rate based on the downstream boundary (the sand volume in the sand trap underneath the open cylinder and in the trap of the recirculation system) are shown in the right-hand-side parts of the figures. Note that in these figures the origin of the x-axis is at the upstream end of the test section rather than in the middle. The middle of the test section corresponds to \(x = +6.17\) m.

In Table 3.2 the net transport rates, averaged per test condition, are presented together with the averaged flow condition for each condition. In general the transport rates are averaged over the last three tests in each condition, because it is known that often the first test of a new condition shows a somewhat different behaviour than the other tests. In some cases there was a reason to skip a specific test (e.g. deviating flow velocities). If it was decided to skip one of the tests for the calculation of the average transport rate, it is mentioned in the table, together with the reason to do so. The table also includes the standard deviation of the individual tests (\(\sigma\)), the relative error (\(r = \sigma/(q_\text{r})\)) and the relative error of the averaged transport rate \(r\sqrt{N}\), where \(N\) is the number of tests.

Note: The measured net transport rate is the transport rate, averaged over the width of the tunnel test section. However, the flow velocity is measured at the centre-line of the tunnel. Due to the presence of the sidewalls, the velocity decreases towards the sidewalls. Therefore the measured transport rates should be corrected such that they correspond to the measured (maximum) velocities. The procedure for this correction is described by Koelwijin (1994).

### 3.2.2 Video recordings of bed level variation

One video recording of about 4 minutes (30 oscillation periods) was made for the five test conditions of series I (coded IX-V1, \(x=\text{condition number}\)), in order to determine the bed level variation during the wave cycle (\(\delta_2\)). Additionally, the initial bed level before each test was recorded in order to determine the overall bed lowering during a test (\(\delta_1\)), caused by sand which remains in suspension during the test. During a wave cycle the still bed level is maximum (\(z = z_2\)) at the moment of flow reversal (zero velocity). When the velocity increases, sand is being picked up from the bed and the level of the still bed lowers to \(z = z_1\). The difference between the maximum and minimum level of the still bed is defined as \(\delta_2\), i.e. the variation in bed level during the wave cycle (\(\delta_2 = z_2 - z_1\)). However, the still bed level at the moment of flow reversal is still somewhat lower than the still bed level before the test (\(z = z_2\)), because some sediment remains in suspension at moments of flow reversal. The difference between the bed level before the test and the still bed level at flow
reversal \((z_3 - z_2)\) is defined as \(\delta_1\). The definitions of \(\delta_1\) and \(\delta_2\) are visualized in Figure 3.2.6. The actual values of \(\delta_1\) and \(\delta_2\) have not yet been determined from the video recordings.

### 3.2.3 Time-dependent velocities, measured by LDFM and ADV

Twelve tests were performed for test condition II, in order to measure the time-dependent velocity at different levels above the bed. Each test consisted of several measurements. For 4 tests the velocity was measured by LDFM. For 8 tests the velocity close to the bed was measured by ADV. From the individual time series of the velocity components \(u\), \((v)\) and \(w\), the following velocity characteristics were determined: the time-averaged velocity, the standard deviation of the measured velocity signal, the maximum ("crest") velocity, the minimum ("trough") velocity and the root-mean-square velocity. Table 3.3 and 3.4 present the actual level of the velocity measurement, the horizontal time-averaged velocity \((\bar{u})\), and the amplitude of the (ensemble-averaged) horizontal oscillatory velocity \(\hat{u}\) for the LDFM and ADV measurements, respectively. Additionally, these tables include the time-intervals (low - high), corresponding to the different measurements and the number of oscillation periods over which the parameters are determined. Table 3.4 (ADV measurements) also includes the horizontal time-averaged velocity \((\bar{u})\) and the amplitude of the (ensemble-averaged) horizontal oscillatory velocity \(\hat{u}\), measured by LDFM at the reference level (100 mm above the bed). Finally, some remarks about the measurements are also included. For example, during two laser measurements, the LDFM showed some peaks in the signal, probably caused by the large concentration of suspended sediments. This may have resulted in time-averaged values which are somewhat too large (compare the values of measurement L22 and L23 with the values of measurement L32 and L33). For the codes of the test names, used in these tables, see Sections 2.5.4 and 2.5.5.

**Net current profiles**

Figure 3.2.7 shows the time-averaged current profile, measured with LDFM (solid circles) and ADV (open squares). The results of the LDFM and the ADV agree rather well.

For a logarithmic velocity profile the velocity is given by:

\[
\frac{u}{u_*} = \frac{1}{\kappa} \ln \left( \frac{z}{z_0} \right)
\]  

(3.1)

Where:

- \(u\) = the horizontal velocity
- \(u_*\) = the friction velocity
- \(\kappa\) = the Von Karman constant (= 0.4)
- \(z\) = level above the initial bed level
- \(z_0\) = \(\kappa/30\), where \(k_0\) is the Nikuradse roughness height

The profile is plotted on a log-linear vertical scale such that a straight line represents a logarithmic velocity distribution. From the figure it is clear that the velocity profile follows more or less a logarithmic distribution for levels higher than about 20 mm above the bed.
Below \( z = 20 \text{ mm} \) the decrease in time-averaged velocity is much smaller. This could be attributed to the wave-current and flow-sediment interaction, which both result in decreasing velocities close to the bed, due to a larger apparent roughness. However, in the fine sand experiments (see Janssen et al., 1996), it was found that the ADV did not work correctly in very high concentrations of sediment: in those experiments the velocity did not decrease down to zero, but remained constant below 20 mm, which was considered to be unrealistic and probably caused by the inaccuracies of the instrument. Therefore it is not clear whether or not the velocity measurements below 20 mm are correct and the results should be treated with care.

The same behaviour is visible in Figure 3.2.8, where the profile of the amplitude of the oscillatory velocity is shown. Even at the level \( z = 0 \) (still bed level) the amplitude of the oscillatory velocity is still about 1.3 m/s, which seems unrealistically large.

### 3.2.4 Time-dependent concentrations, measured by OpCon and CCM

Ten tests were performed in order to measure the sediment concentration at different levels above the bed. In 6 tests the concentration of suspended sediment was measured using the OpCon. In 4 tests the concentration in the thin sheet flow layer was measured using the CCM. Each test consisted of several measurements. All tests were conducted at the horizontal position \( x = 2.10 \text{ m} \).

Table 3.5 and 3.6 present the actual level of the concentration measurement and the measured time-averaged concentration \( \langle c \rangle \) for the OpCon and CCM measurements, respectively. Additionally, these tables include the time-intervals (low - high), corresponding to the different measurements and the number of oscillation periods over which the time-averaged and ensemble-averaged concentrations were determined. In order to be able to check the actual flow condition, the velocity at 100 mm above the bed was measured by LDFM. The results (horizontal time-averaged velocity \( \langle u \rangle \) and the amplitude of the (ensemble-averaged) horizontal oscillatory velocity \( \dot{u} \)) are also included in these tables.

The calibration of the OpCon depends on an amplification factor, which can be set during the measurement at 1 or 10, and on the grain diameter. The amplification factor is only used to amplify voltage of the output signal by a factor of 10 in situations where the concentration is very small. Because the grain diameter is not constant over the height (finer grains are suspended higher), some uncertainty remains about the actual calibration factor and thus about the actual concentration. The calibration factor, used in the present experiments is equal to 1.5 g/l/Volt, corresponding to a grain diameter of about 0.24 mm (see Appendix A5). During the OpCon measurements the voltage for zero concentration was usually set at 0.0 or 1.0 Volt. The value of this zero-level, which is accounted for in the calculation of the concentration, is given in Table 3.5, together with the change in zero-level during the test. It can be seen that this change is very small and can be neglected in the calculation of the concentration. Also the value of the amplification factor (1 or 10) is added in the table.

The calibration of the CCM is independent of the grain size, but depends on the CCM output at zero concentration (clear water) (see Appendix A6). This zero-level \( \langle U_0 \rangle \) was recorded at the end of each run, when the piston and pump were switched off and the sand had settled to the bed. Table 3.6 presents the level of this zero-level for each test for the CCM measurements.
Time-averaged concentration profiles

The wave- or time-averaged concentration was obtained by averaging the OpCon and the CCM signal over a number of wave periods (5-20). In Figure 3.2.9 the complete time-averaged concentration profile is shown. Because the figures include measurements below the initial bed level (negative values for z) the elevation scale is linear, rather than logarithmic. The results of both instruments (OpCon, solid circles and CCM, open circles) are included in this figure. The results are satisfactory, in the sense that the measurements in the suspension and sheet-flow layer form one integrated profile.

Figure 3.2.10 shows the time-averaged suspended sediment concentration profile (measured by OpCon) on a log-log scale, together with a best fit through the data points. Best fit lines which are straight lines on a log-log scale imply a power-law distribution of the concentration. Ribberink and Al-Salem (1994) showed that in plane bed conditions with 0.21 mm sand the following power-law distribution for the time-averaged concentration was valid (waves alone):

\[
\langle c(z) \rangle = c_a \left( \frac{z}{z_a} \right)^\alpha
\]  

(3.2)

where:

\[
\langle c(z) \rangle = \text{time-averaged sediment concentration at level } z
\]

\[
c_a = \text{reference concentration at } z = z_a
\]

\[
\alpha = \text{concentration decay parameter}
\]

The concentration decay parameter was found to be a constant \(\alpha = 2.1 \pm 0.1\) for a wide range of velocities and wave periods. This behaviour was confirmed by Ramadan (1994) for asymmetric waves with a superimposed net current in plane bed conditions (0.21 mm sand) although with a slightly smaller \(\alpha\). In the series E experiments with combined wave-current flow (0.21 mm sand), the concentration decay parameter varied from 2.18 to 2.31. The fine sand (0.13 mm) experiments showed again similar results, with slightly smaller values of \(\alpha\) than in the series E experiments. In general \(\alpha\) varied between 1.83 and 2.11. The concentration decay parameter \(\alpha\) in the present experiments (0.32 mm sand) has a value of 2.05.

Figure 3.2.11 shows the time-averaged concentration profile in the sheet-flow layer. The concentration inside the bed is more or less constant (1350 - 1400 g/l). This value is similar to the values measured by Katopodi et al. (1994) in the series E experiments with 0.21 mm sand and somewhat larger than the values in the fine sand experiments. The concentration starts to decrease at a level of about 4 mm below the initial bed level. Between \(z = -1\) mm and \(z = +4\) mm, the concentration decreases very strongly and seems to follow an exponential distribution (a straight line on the log-linear plot). The level \(z = +4\) mm can be considered as the top of the sheet flow layer, because above that level, the concentrations are relatively small (smaller than 50 g/l which is about 2 vol%). The measurements above \(z = +4\) mm are somewhat less accurate, because the CCM is developed to measure velocities larger than about 100 g/l.
Time-dependent sediment concentrations

Time-dependent suspended sediment concentrations at different elevations above the average bed level are shown in Figure 3.2.12. The plot shows the concentration during one wave-cycle and was obtained from ensemble-averaging of 5 - 10 waves. It includes results of OPCON (coded oij) and CCM (coded cij) measurements down to 7 mm above the bed (because from the time-averaged concentration profile z = +4 mm was considered to be the top of the sheet flow layer). In the upper part of the figure the velocity measured by LDFM at 100 mm above the sand bed is shown.

It can be seen in this figure that near the bottom the concentration exhibits a (broad) local maximum, some time after the moment of maximum positive velocity. A somewhat smaller maximum occurs around the moment of maximum negative velocity. The asymmetry in concentration is caused by the asymmetry in flow velocity, due to the presence of a (positive) net current. A sharper peak in concentration occurs near the moments of flow reversal (at 10 cm above the bed). Similar peaks, but larger in magnitude, were observed in the series E (0.21 mm sand) experiments. In the fine sand experiments these peaks were even dominant over the peaks around maximum velocity. Apparently, the peaks at flow reversal become relatively more important for finer sand. A possible explanation for these peaks can be found in Foster et al. (1994) where it is argued that the suspension events at flow reversal may be a result of a shear instability of the bottom boundary layer. For higher elevations, the concentration decays rapidly and the maxima occur at a later moment (time-lag effect).

In Figure 3.2.13 the ensemble-averaged concentrations (over 10 - 20 waves) at various elevations in the sheet-flow layer are shown. The upper part of the figures shows the free-stream velocity measured at 100 mm above the sand bed by LDFM.

The concentration remains constant (≈ 1350 - 1400 g/l) over the wave cycle at 4 mm below the initial bed level. One mm higher, the concentration is smaller, but still almost constant in time. At levels between -2 and 0 mm the concentration decreases during moments of maximum (positive or negative) velocity, due to the fact that sediment is picked up from the bed. Therefore this layer is called pick-up layer. The asymmetric behaviour of the flow is also reflected in the concentrations in the pick-up layer, where the concentrations are more reduced during the larger positive velocity than during the period of smaller velocities occurring in negative direction.

In the upper sheet-flow layer, the layer just above the pick-up layer (z ≥ 1 mm), the concentration decays rapidly with height and shows a behaviour opposite to that of the pick-up layer. High concentrations are taking place at moments of maximum (positive or negative) velocity. Again the asymmetry is visible, however much less clear than in the suspension layer.

In the upper sheet-flow layer (at z = +2 mm and z = +4 mm) similar peaks in concentration as in the suspension layer occur, just before flow reversal (t = 3.7 s and t = 7.0 s). Again the peaks are much smaller than in finer sand. Note that these peaks are not present in the pick-up layer. As mentioned before, the CCM measurements may be somewhat less accurate at the highest measurement levels, because the concentration is smaller than 100 g/l during part of the wave-cycle.
Like in the suspension layer, the concentration in the sheet-flow layer is slightly shifted in phase for increased elevations, due to the fact that it takes time for the sediment particles to travel upward.

All the ensemble-averaged data of velocity and concentration, measured by LDFM, ADV, OpCon and CCM are stored in ascii-files (with extension.prn) on a floppy-disk. The names of the ascii-files correspond to the names of the measurements, presented in Tables 3.3 - 3.6. The "n" in front of the test name represents the fact that the file contains the ensemble-averaged data.

All files contain at least three columns: the time (s), the velocity of the piston (m/s), which generates the oscillatory flow in the test section and the horizontal velocity measured by LDFM (m/s). In the case of the ADV, the OpCon and the CCM measurements this is the velocity, measured at the reference level, i.e. 10 cm above the bed. In the case of the LDFM measurements this is the actual measured velocity at the level specified in Table 3.3.

The files for the ADV, the OpCon and the CCM measurements contain one extra column with the actual measured parameter, i.e. the horizontal velocity, measured by ADV (m/s) or the concentration, measured either by OpCon or by CCM (g/l).

In the LDFM files the time runs from 0.0 to 7.1875 s, because the sampling frequency in these tests was 80 Hz and the ensemble-averaged value of the velocity at 7.2 s is equal to the one at 0.0 s. In the other files the time runs from 0.0 to 7.16 s because the sampling frequency was 25 Hz. in these tests.

In all the files the starting point for the ensemble-averaging is taken at the moment when the piston velocity has a downward zero-crossing. This means that the flow velocity in the test section can be described by:

\[ u(t) = \langle u \rangle + \hat{u} \sin(\omega t) \]  \hspace{1cm} (3.3)

where:

\[ \langle u \rangle \quad \text{time-averaged velocity} \]

\[ \hat{u} \quad \text{amplitude of the horizontal oscillatory velocity, and} \]

\[ \omega \quad \text{angular frequency, defined as } 2\pi/T, \text{ with } T \text{ the oscillation period} \]

The contents of the files is also summarized in Table 3.7.

### 3.3 Series J (D_{60} = 0.21 mm)

#### 3.3.1 Net transport measurements

In series J, net transport rates were measured for 6 combined wave-current flow conditions. For the computation of the net sediment transport rate, 4 tests were realised per condition, (coded Jx-Ti, x=condition number, i=test number). The bed level along the test section was measured before and after the experiment and the weight of the sand collected in the sand traps was determined. Next the net sediment transport rate was computed solving the mass
balance equation twice for each test, starting from either the left or the right sand trap. Two estimates of the net transport rate were derived in this way. They were determined at the position where the bed level was not changing during the test, i.e. about 2 m downstream of the centre of the tunnel test section. Table 3.8 summarises the results of the net transport measurements of series J. The following parameters are included in this table:

- test name,
- measurement duration,
- wave period $T$, derived from velocity measurements by LDFM, at 100 mm above the bed,
- time-averaged velocity $\langle u \rangle$, measured by LDFM at 100 mm above the bed,
- amplitude of oscillatory velocity $\hat{u}$, measured by LDFM at 100 mm above the bed,
- under water weight of sand in trap underneath piston,
- under water weight of sand in trap underneath "open leg",
- under water weight of sand in trap in recirculation system,
- total volume of sand (without pores) in sand traps,
- total sand volume change (without pores) in the tunnel test section derived from bed level measurement and calculated porosity (average value over all tests),
- loss of sand (sand volume removed from test section minus collected volume in traps),
- calculated porosity (see Section 2.4.1),
- net sand transport rate, calculated from left-hand-side ($\langle q_L \rangle$),
- net sand transport rate, calculated from right-hand-side ($\langle q_R \rangle$).

The measured under water weights can be transferred into dry weights by multiplying them by the ratio of the density of sand to the density of water ($\rho_s/\rho_w = 1.606$). Next they can be transferred into sand volumes (without pores) by dividing them by the density of the sediment.

Figures 3.3.1 - 3.3.6 show the net sediment transport rates along the test section, as calculated from the measured bed levels and weights of sand in the traps. In the left part of the figures the calculations are shown, which are based on the upstream boundary (the sand volume in the sand trap underneath the piston), while the calculations of the transport rate based on the downstream boundary (the sand volume in the sand trap underneath the open cylinder and in the trap of the recirculation system) are shown in the right-hand-side parts of the figures. Note that in these figures the origin of the x-axis is at the upstream end of the test section rather than in the middle. The middle of the test section corresponds to $x = +6.17$ m.

In Table 3.9 the net transport rates, averaged per test condition are presented together with the averaged flow condition for each condition. In general the transport rates are averaged over the last three tests in each condition, because it is known that often the first test of a new condition shows a somewhat different behaviour than the other tests. In some cases there was a reason to skip a specific test (e.g. deviating flow velocities). If it was decided to skip one of the tests for the calculation of the average transport rate, it is mentioned in the table, together with the reason to do so. The table also includes the standard deviation of the individual tests ($\sigma$), the relative error ($r = \sigma/\langle q \rangle$) and the relative error of the averaged transport rate $r/\sqrt{N}$, where $N$ is the number of tests.
3.3.2 Video recordings of bed level variation

One video recording of about 2 - 6 minutes (30 oscillation periods) was made for the 6 test conditions of series J and for 2 test conditions of series E (i.e. E2 and E4, corresponding to I1 and I4, respectively), in order to determine the bed level variation during the wave cycle ($\delta_2$). Additionally, the initial bed level before each test was recorded in order to determine the overall bed lowering during a test ($\delta_1$), caused by sand which remains in suspension during the test. For a more detailed description of $\delta_1$ and $\delta_2$, see Section 3.2.2 and Figure 3.2.6. The measured signals are stored in files #JV-T1 (condition, J1, J2, E2), #JV-T2 (condition J5), #JV-T3 (condition J6) and #JV-T4 (condition J3, J4, E4). The actual values of $\delta_1$ and $\delta_2$ have not yet been determined from the video recordings.
4 Summary and conclusions

4.1 Summary

A data set is presented of net transport rates and time-dependent concentrations and velocities under combined sinusoidal wave/net current conditions in the case of coarse sand ($D_{50} = 0.32$ mm, series I) and net sand transport rates in the case of unsieved dunesand ($D_{50} = 0.21$ mm, series J). The experiments were conducted in the Large Oscillating Water Tunnel of DELFT HYDRAULICS. Net transport rates were measured for 5 different flow conditions in series I and for 6 different flow conditions in series J. Time-dependent measurements of concentration and velocity were performed for one of the 5 flow conditions in series I. During all the conditions the bed was plane (sheet flow).

The following quantities were measured: Net transport rates, bed-level variation during the wave cycle (using a standard video camera), time-dependent velocities between 20 and 100 mm above the bed (using a Laser Doppler Velocity meter, LDFM) and close to the bed (using an Acoustic Doppler Velocity meter, ADV), time-dependent concentrations in the suspension layer (using an optical method, OpCon) and in the sheet flow layer (using a Conductivity Concentration Meter, CCM).

The various measured parameters (net transport rates, concentrations, velocities and bed level variation) are discussed in Section 4.2 and some preliminary conclusions are presented.

4.2 Conclusions on measured parameters

Net transport rates

Net transport rates increase for increasing oscillatory velocities, both for the unsieved dunesand ($D_{50} = 0.21$ mm) and for the coarse sand ($D_{50} = 0.32$ mm). In the case of the unsieved dunesand, the effect of the oscillation period on the net transport rates is much smaller than in the case of the fine sand ($D_{50} = 0.13$ mm, series H, Janssen et al., 1996). Comparison between series I and series J (and E) shows that in general the transport rates for the coarse sand are smaller than for the unsieved dunesand, for conditions with the same flow velocities.

Flow velocities

From the velocity measurements, performed using the LDFM and the ADV, the net current profile and the vertical profile of the amplitude of the oscillatory velocity were calculated. The time-averaged velocity profile follows a logarithmic distribution for levels higher than 20 mm above the bed.

The profiles of time-averaged velocity and velocity amplitude do not show a decrease down to zero at the still bed level. This is unrealistic and may be caused by inaccuracies of the ADV due to the very high concentration of sediment in this layer. This was observed before in the fine sand experiments (Janssen et al., 1996). Therefore the results of the velocity measurements below 20 mm above the bed should be treated very carefully. For example calculations of the sediment fluxes below 20 mm may give results which are too large.
Concentrations

Time-averaged concentration
The time-averaged suspended sediment concentration, computed from the time-dependent OpCon signal, follows more or less a power law distribution, with a value of the concentration decay parameter $\alpha$ (see Section 3.2.4) of about 2.05. This value is very similar to the values measured in the experiments with unsieved dune sand ($\alpha = 2.2 - 2.3$, see Katopodi et al., 1994) and the fine sand experiments ($\alpha = 1.8 - 2.1$, see Janssen et al., 1996).

The time-averaged concentration in the sheet flow layer, computed from the time-dependent CCM signal, shows a constant concentration inside the bed (1350-1400 g/l). The concentration profile in the upper sheet-flow layer follows an exponential distribution.

The value of constant concentration in the lower part of the sheet flow layer is somewhat larger than the values measured in the fine sand ($D_{50} = 0.13$ mm, Janssen et al., 1996) and in the unsieved dunesand experiments ($D_{50} = 0.21$ mm, Katopodi et al., 1994). The difference may be caused by inaccuracies in the CCM calibration.

Time-dependent concentrations
The ensemble-averaged concentration in the suspension layer, measured by OpCon and in the upper sheet flow layer, measured by CCM show two maxima during the wave cycle more or less in phase with the maximum positive and negative free stream velocities. The asymmetry in the flow, due to the presence of a (positive) net current is also observed in the concentrations in these layers. In the suspension layer the maximum concentration occurs somewhat after the moment of maximum positive velocity due to the fact that it takes some time for the sediment particles to travel upward.

Both in the suspension layer and in the upper sheet flow layer, additional concentration peaks appear, approximately just before the moments of flow reversal (at 10 cm above the bed). These peaks were also observed in the earlier experiments with finer sand ($D_{50} = 0.21$ and 0.13 mm). However, in the present tests ($D_{50} = 0.32$ mm), the peaks are relatively much smaller in magnitude. Apparently the peaks increase in magnitude for decreasing grain diameter.

The main concentration as well as the peaks at flow reversal decay rapidly with elevation and lag behind the velocity.

A complete change occurs in the time-dependent concentration (measured by CCM) as we go from the upper sheet flow layer to the pick-up layer and the bed. Now the concentration is more or less constant during parts of the wave cycle with small velocities and two concentration minima occur at moments of maximum positive or negative free stream velocities. This is a result of the fact that sediment is picked up from the bed at moments of maximum flow velocity. No peaks at flow reversal occur.
References


<table>
<thead>
<tr>
<th>Series</th>
<th>type</th>
<th>D$_{50}$ (mm)</th>
<th>reg/irreg</th>
<th>sin/asym</th>
<th>$\langle u \rangle$ (m/s)</th>
<th>$u_{rms}$ (m/s)</th>
<th>T (s)</th>
<th>N (-)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>$\langle q_0 \rangle$</td>
<td>0.21</td>
<td>r, ir</td>
<td>as</td>
<td>-</td>
<td>0.5 - 0.9</td>
<td>5 - 12</td>
<td>16</td>
<td>Al-Salem (1993)</td>
</tr>
<tr>
<td>C</td>
<td>u, c</td>
<td>0.21</td>
<td>r</td>
<td>as, sin</td>
<td>-</td>
<td>0.6 - 1.2</td>
<td>6.5 - 9.1</td>
<td>3</td>
<td>Al-Salem (1993)</td>
</tr>
<tr>
<td>D</td>
<td>$\langle q_0 \rangle$</td>
<td>0.13</td>
<td>r</td>
<td>as</td>
<td>-</td>
<td>0.5 - 0.9</td>
<td>6.5</td>
<td>4</td>
<td>Ribberink &amp; Chen (1993)</td>
</tr>
<tr>
<td>C</td>
<td>$\langle q_0 \rangle$</td>
<td>0.21</td>
<td>r</td>
<td>as</td>
<td>-0.4 - 0.4</td>
<td>0.5 - 0.8</td>
<td>6.5</td>
<td>10</td>
<td>Ramadan (1994)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Ribberink &amp; Ramadan (1994)</td>
</tr>
<tr>
<td>E</td>
<td>$\langle q_0 \rangle$</td>
<td>0.21</td>
<td>r</td>
<td>sin</td>
<td>0.15 - 0.45</td>
<td>0.65 - 1.2</td>
<td>7.2</td>
<td>4</td>
<td>Katopodi et al. (1994)</td>
</tr>
<tr>
<td>G</td>
<td>u</td>
<td>fixed bed (0.21 mm sand glued onto bottom)</td>
<td>sin</td>
<td></td>
<td>0.0 - 0.45</td>
<td>0.0 - 1.3</td>
<td>7.2</td>
<td>7</td>
<td>Janssen (1995b)</td>
</tr>
<tr>
<td>H</td>
<td>$\langle q_0 \rangle$</td>
<td>0.13</td>
<td>r</td>
<td>sin</td>
<td>0.25 - 0.45</td>
<td>0.65 - 1.1</td>
<td>4 - 12</td>
<td>12</td>
<td>Janssen et al. (1996)</td>
</tr>
</tbody>
</table>

**Explanation of contents:**
- series name
- the type of experiment: net transport rate measurements ($\langle q_0 \rangle$), time-dependent measurements of velocity and concentration (u, c)
- the mean grain diameter of the sand (D$_{50}$)
- the type of oscillatory flow: regular (reg) or irregular (ir), sinusoidal (sin) or asymmetric 2$^{nd}$-order Stokes (as)
- the imposed net current velocity at 10 cm above the bed ($+u_0$)
- the root-mean-square value of the oscillatory flow ($u_{rms}$)
- the oscillation period (T)
- the number of hydraulic conditions (N)
- the reference to the data
<table>
<thead>
<tr>
<th>Hydraulic conditions</th>
<th>Resulting bedforms</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{u}$ (m/s)</td>
<td>$\bar{u}$ (m/s)</td>
<td>$T$ (s)</td>
</tr>
</tbody>
</table>
| 0.25                  | 1.1                | 7.2     | 0.1 - 0.2  | 0.05 - 0.13  | 0.08 - 0.18  | Initial situation: flat bed  
Result: large bedforms, caused by hydraulic conditions  
Result: large bedforms caused by boundary, sheet flow over it, finally a few eddies developed behind bedforms |
| 0.25                  | 1.3                | 7.2     | 0.1 - 0.2  | 0.03 - 0.25  | 1.0 - 1.9    | Initial situation: flat bed  
Result: large bedforms caused by boundary, sheet flow over it, finally a few eddies developed behind bedforms |
| 0.25                  | 1.1                | 12.0    | 0.1 - 0.2  | 0.05 - 0.13  | 0.08 - 0.18  | Initial situation: flat bed  
Result: bedforms from previous test  
Result: bedforms do not disappear  
Result: bedforms become much shorter, but do not disappear, eddies formed behind them |
| 0.45                  | 1.5                | 7.2     | 0.1 - 0.2  | 0.03 - 0.25  | 1.0 - 1.9    | Initial situation: flat bed  
Result: large bedforms caused by boundary, sheet flow over it, finally a few eddies developed behind bedforms |
| 0.45                  | 1.3                | 7.2     | 0.1 - 0.2  | 0.03 - 0.25  | 1.0 - 1.9    | Initial situation: flat bed  
Result: large bedforms caused by boundary, sheet flow over it, finally a few eddies developed behind bedforms |
<table>
<thead>
<tr>
<th>Hydraulics condition</th>
<th>$&lt;u&gt;$ (m/s)</th>
<th>$u_{rms}$ (m/s)</th>
<th>$T$ (s)</th>
<th>$\eta$ (m)</th>
<th>$\lambda$ (m)</th>
<th>Remarks</th>
</tr>
</thead>
</table>
| 0.45                 | 0.8         | 6.5             |        |             |             | Initial situation: flat bed  
Result: large bedforms caused by boundary, sheet flow over it |
| 0.45                 | 0.7         | 6.5             |        |             |             | Initial situation: bedforms from previous test  
Result: large bedforms caused by boundary, sheet flow over it |
| 0.45                 | 0.55        | 6.5             |        |             |             | Initial situation: bedforms from previous test  
Result: large bedforms caused by boundary, sheet flow over it,  
eddies developed behind bedforms |
| 0.45                 | 0.55        | 6.5             |        |             |             | Initial situation: flat bed  
Result: large bedforms caused by boundary, sheet flow over it,  
finally a few eddies developed behind bedforms |
| 0.30                 | 0.8         | 6.5             |        |             |             | Initial situation: flat bed  
Result: large bedforms caused by boundary, sheet flow over it |
| 0.30                 | 0.7         | 6.5             |        |             |             | Initial situation: bedforms from previous test  
Result: large bedforms caused by boundary, sheet flow over it |
| 0.30                 | 0.55        | 6.5             |        |             |             | Initial situation: bedforms from previous test  
Result: large bedforms caused by boundary, sheet flow over it  
finally a few eddies developed behind bedforms |
| 0.15                 | 0.7         | 6.5             |        |             |             | Initial situation: flat bed  
after 0:30 minutes |
| 0.15                 | 0.7         | 6.5             | 0.01   | 1.0         |             | after 1:30 minutes |
| 0.15                 | 0.7         | 6.5             | 0.02   | 1.2         |             | after 3:00 minutes |
| 0.15                 | 0.7         | 6.5             | 0.03   | 1.5         |             | after 6:40 minutes: bedforms caused by boundary,  
sheet flow over it |
| 0.0                  | 0.7         | 6.5             |        |             |             | Initial situation: flat bed  
for about 2 minutes |
| 0.0                  | 0.8         | 6.5             |        |             |             | for about 3 minutes |
| 0.0                  | 0.9         | 6.5             |        |             |             | for about 3 minutes  
Result: large bedforms, caused by boundary,  
eddies developed behind some of them |
| 0.15                 | 0.8         | 6.5             | 0.02   | 1.5         |             | Initial situation: flat bed  
Result: bedforms caused by boundary, sheet flow over it |
| 0.075                | 0.8         | 6.5             | 0.05   | 1.5         |             | Initial situation: flat bed  
Result: large bedforms caused by boundary, sheet flow over it,  
eddies developed behind some of them |
### Table 2.3 Test conditions with imposed parameters in series I ($D_{50} = 0.32$ mm)

<table>
<thead>
<tr>
<th>Condition</th>
<th>$T$ (s)</th>
<th>$\langle u \rangle$ (m/s)</th>
<th>$\phi$ (m/s)</th>
<th>$Q_{\text{pump}}$ (m$^3$/s)</th>
<th>$A_{\text{piston}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>7.2</td>
<td>0.23</td>
<td>1.50</td>
<td>0.0465</td>
<td>66.5</td>
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<td>I2</td>
<td>7.2</td>
<td>0.23</td>
<td>1.70</td>
<td>0.0465</td>
<td>76.9</td>
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<tr>
<td>I3</td>
<td>7.2</td>
<td>0.44</td>
<td>0.70</td>
<td>0.0889</td>
<td>30.0</td>
</tr>
<tr>
<td>I4</td>
<td>7.2</td>
<td>0.44</td>
<td>0.95</td>
<td>0.0889</td>
<td>42.2</td>
</tr>
<tr>
<td>I5</td>
<td>7.2</td>
<td>0.44</td>
<td>1.50</td>
<td>0.0889</td>
<td>66.5</td>
</tr>
</tbody>
</table>

### Table 2.4 Test conditions with imposed parameters in series J ($D_{50} = 0.21$ mm)

<table>
<thead>
<tr>
<th>Condition</th>
<th>$T$ (s)</th>
<th>$\langle u \rangle$ (m/s)</th>
<th>$\phi$ (m/s)</th>
<th>$Q_{\text{pump}}$ (m$^3$/s)</th>
<th>$A_{\text{piston}}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1</td>
<td>7.2</td>
<td>0.23</td>
<td>1.10</td>
<td>0.0465</td>
<td>49.2</td>
</tr>
<tr>
<td>J2</td>
<td>7.2</td>
<td>0.23</td>
<td>1.30</td>
<td>0.0465</td>
<td>58.8</td>
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<td>J3</td>
<td>7.2</td>
<td>0.44</td>
<td>0.50</td>
<td>0.0889</td>
<td>21.1</td>
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<tr>
<td>J4</td>
<td>7.2</td>
<td>0.44</td>
<td>0.70</td>
<td>0.0889</td>
<td>30.0</td>
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<tr>
<td>J5</td>
<td>4.0</td>
<td>0.23</td>
<td>1.10</td>
<td>0.0465</td>
<td>43.2</td>
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<tr>
<td>J6</td>
<td>1.0</td>
<td>0.23</td>
<td>1.10</td>
<td>0.0465</td>
<td>78.5</td>
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</table>
### Table 2.5 Overall measurement program series I \((D_{50} = 0.32 \text{ mm})\)

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Test conditions</th>
<th>Measurement technique</th>
<th>z (mm)</th>
<th>No. of tests (\ast)</th>
<th>No. of measurements (\ast)</th>
<th>Sampling freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net transport ((+q_n))</td>
<td>I1 - I5</td>
<td>Mass conservation technique</td>
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<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Bed level variation ((\delta_1, \delta_2))</td>
<td>I1 - I5</td>
<td>Video camera</td>
<td>-10 - +40</td>
<td>5</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Time-dependent velocity ((u(z,t)))</td>
<td>II</td>
<td>LDA</td>
<td>18 - 100</td>
<td>4</td>
<td>11</td>
<td>80</td>
</tr>
<tr>
<td>Time-dependent velocity, close to the bed ((u(z,t)))</td>
<td>II</td>
<td>ADV</td>
<td>0 - 40</td>
<td>6</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Time-dependent concentration in the suspension layer ((c(z,t)))</td>
<td>II</td>
<td>OpCon</td>
<td>10 - 100</td>
<td>6</td>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>Time-dependent concentration in the sheet flow layer ((c(z,t)))</td>
<td>II</td>
<td>CCM</td>
<td>-7 - +10</td>
<td>4</td>
<td>25</td>
<td>25</td>
</tr>
</tbody>
</table>

### Table 2.6 Overall measurement program series J \((D_{50} = 0.21 \text{ mm})\)

<table>
<thead>
<tr>
<th>Measured parameter</th>
<th>Test conditions</th>
<th>Measurement technique</th>
<th>z (mm)</th>
<th>No. of tests (\ast)</th>
<th>No. of measurements (\ast)</th>
<th>Sampling freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net transport ((+q_n))</td>
<td>J1 - J6</td>
<td>Mass conservation technique</td>
<td></td>
<td>24</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>Bed level variation ((\delta_1, \delta_2))</td>
<td>J1 - J6, E2, E4</td>
<td>Video camera</td>
<td>-10 - +40</td>
<td>8</td>
<td>8</td>
<td>20</td>
</tr>
</tbody>
</table>

\(\ast\) Note:
The number of tests is equal to the number of tunnel runs.
In the time-dependent measurements the velocity or concentration is measured at several points over the vertical during one test (tunnel run). Therefore the number of measurements in the time-dependent measurements is larger than the number of tests.
<table>
<thead>
<tr>
<th>Computer recording channel</th>
<th>Measured parameter</th>
<th>Units</th>
<th>Code (in .seq file)</th>
<th>Calibration factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Steer signal</td>
<td>m</td>
<td>ssn01</td>
<td>C₁ [units]/Volt</td>
</tr>
<tr>
<td>2</td>
<td>Piston motion</td>
<td>m</td>
<td>vpl01</td>
<td>0.075</td>
</tr>
<tr>
<td>3</td>
<td>Piston velocity</td>
<td>m/s</td>
<td>shm01</td>
<td>0.0847</td>
</tr>
<tr>
<td>4</td>
<td>Piston pressure</td>
<td>kN/m²</td>
<td>dro01</td>
<td>1.87</td>
</tr>
<tr>
<td>5</td>
<td>Component vₐ of flow velocity in tunnel, measured by LDA</td>
<td>m/s</td>
<td>shm02</td>
<td>0.145</td>
</tr>
<tr>
<td>6</td>
<td>Component vₐ of flow velocity in tunnel, measured by LDA</td>
<td>m/s</td>
<td>shm03</td>
<td>0.143</td>
</tr>
<tr>
<td>7</td>
<td>Pump discharge</td>
<td>m³/s</td>
<td>dbm01</td>
<td>0.01</td>
</tr>
<tr>
<td>8</td>
<td>Component u (in x-direction) of flow velocity in tunnel, measured by ADV</td>
<td>m/s</td>
<td>shm11</td>
<td>0.2503</td>
</tr>
<tr>
<td>9</td>
<td>Component v (in y-direction) of flow velocity in tunnel, measured by ADV</td>
<td>m/s</td>
<td>shm12</td>
<td>0.2503</td>
</tr>
<tr>
<td>10</td>
<td>Component w (in z-direction) of flow velocity in tunnel, measured by ADV</td>
<td>m/s</td>
<td>shm13</td>
<td>0.2513</td>
</tr>
<tr>
<td>8</td>
<td>Concentration, measured by OpCon</td>
<td>g/l</td>
<td>con01</td>
<td>22.2 (15.3)</td>
</tr>
<tr>
<td>8</td>
<td>Concentration, measured by CCM</td>
<td>Volts</td>
<td>con01</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Note: Both the u-component of the velocity, measured by ADV and the concentrations measured by OpCon and CCM are recorded on computer channel 8, because they are not measured simultaneously.
<table>
<thead>
<tr>
<th>test</th>
<th>duration (sec)</th>
<th>condition</th>
<th>sandtraps (weight under water)</th>
<th>sandtraps (volume)</th>
<th>test section (volume)</th>
<th>loss of sand (l)</th>
<th>calc. porosity</th>
<th>transport rate at x=2 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>piston (kg)</td>
<td>open leg (kg)</td>
<td>recirc. (kg)</td>
<td>total (l)</td>
<td>total (l) (without pores)</td>
<td>(10^-6 m^3/s)</td>
</tr>
<tr>
<td>I1-t1</td>
<td>576</td>
<td>7.2</td>
<td>0.248</td>
<td>1.47</td>
<td>6.6</td>
<td>10.5</td>
<td>2.5</td>
<td>11.88</td>
</tr>
<tr>
<td>I1-t2</td>
<td>643</td>
<td>7.2</td>
<td>0.264</td>
<td>1.48</td>
<td>8.2</td>
<td>10.4</td>
<td>2.6</td>
<td>12.85</td>
</tr>
<tr>
<td>I1-t3</td>
<td>475</td>
<td>7.2</td>
<td>0.258</td>
<td>1.48</td>
<td>5.9</td>
<td>8.9</td>
<td>2.2</td>
<td>10.30</td>
</tr>
<tr>
<td>I1-t4</td>
<td>490</td>
<td>7.2</td>
<td>0.265</td>
<td>1.46</td>
<td>4.9</td>
<td>9.9</td>
<td>2.1</td>
<td>10.24</td>
</tr>
<tr>
<td>I2-t1</td>
<td>470</td>
<td>7.2</td>
<td>0.258</td>
<td>1.72</td>
<td>19.0</td>
<td>12.8</td>
<td>4.6</td>
<td>22.06</td>
</tr>
<tr>
<td>I2-t2</td>
<td>445</td>
<td>7.2</td>
<td>---</td>
<td>---</td>
<td>11.8</td>
<td>14.1</td>
<td>4.5</td>
<td>18.42</td>
</tr>
<tr>
<td>I2-t3</td>
<td>461</td>
<td>7.2</td>
<td>0.262</td>
<td>1.68</td>
<td>12.7</td>
<td>14.5</td>
<td>5.5</td>
<td>19.81</td>
</tr>
<tr>
<td>I2-t4</td>
<td>390</td>
<td>7.2</td>
<td>0.242</td>
<td>1.70</td>
<td>9.3</td>
<td>12.8</td>
<td>4.3</td>
<td>16.00</td>
</tr>
<tr>
<td>I3-t1</td>
<td>878</td>
<td>7.2</td>
<td>0.417</td>
<td>0.74</td>
<td>0.0</td>
<td>6.3</td>
<td>2.8</td>
<td>5.52</td>
</tr>
<tr>
<td>I3-t2</td>
<td>769</td>
<td>7.2</td>
<td>0.422</td>
<td>0.65</td>
<td>0.0</td>
<td>4.5</td>
<td>2.0</td>
<td>3.94</td>
</tr>
<tr>
<td>I3-t3</td>
<td>886</td>
<td>7.2</td>
<td>0.424</td>
<td>0.67</td>
<td>0.0</td>
<td>6.5</td>
<td>2.6</td>
<td>5.52</td>
</tr>
<tr>
<td>I3-t4</td>
<td>814</td>
<td>7.2</td>
<td>0.410</td>
<td>0.64</td>
<td>0.0</td>
<td>5.7</td>
<td>2.6</td>
<td>5.03</td>
</tr>
<tr>
<td>I4-t1</td>
<td>756</td>
<td>7.2</td>
<td>0.422</td>
<td>0.92</td>
<td>0.0</td>
<td>12.7</td>
<td>6.6</td>
<td>11.70</td>
</tr>
<tr>
<td>I4-t2</td>
<td>742</td>
<td>7.2</td>
<td>0.415</td>
<td>0.92</td>
<td>0.0</td>
<td>10.2</td>
<td>6.0</td>
<td>9.82</td>
</tr>
<tr>
<td>I4-t3</td>
<td>771</td>
<td>7.2</td>
<td>0.416</td>
<td>0.91</td>
<td>0.0</td>
<td>11.2</td>
<td>7.0</td>
<td>11.03</td>
</tr>
<tr>
<td>I4-t4</td>
<td>812</td>
<td>7.2</td>
<td>0.415</td>
<td>0.92</td>
<td>0.0</td>
<td>10.2</td>
<td>6.1</td>
<td>9.88</td>
</tr>
<tr>
<td>I5-t1</td>
<td>320</td>
<td>7.2</td>
<td>0.438</td>
<td>1.49</td>
<td>5.2</td>
<td>17.2</td>
<td>10.7</td>
<td>20.06</td>
</tr>
<tr>
<td>I5-t2</td>
<td>360</td>
<td>7.2</td>
<td>0.471</td>
<td>1.52</td>
<td>6.5</td>
<td>17.8</td>
<td>10.2</td>
<td>20.91</td>
</tr>
<tr>
<td>I5-t3</td>
<td>360</td>
<td>7.2</td>
<td>0.457</td>
<td>1.51</td>
<td>7.2</td>
<td>18.1</td>
<td>11.0</td>
<td>22.00</td>
</tr>
<tr>
<td>I5-t4</td>
<td>328</td>
<td>7.2</td>
<td>0.427</td>
<td>1.48</td>
<td>6.5</td>
<td>17.4</td>
<td>10.1</td>
<td>20.61</td>
</tr>
</tbody>
</table>
Table 3.2 Average transport rate per condition, standard deviation and relative error in series I

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\langle u \rangle$ (m/s)</th>
<th>$\bar{u}$ (m/s)</th>
<th>$\langle q_u \rangle_{\text{avg}}$ (m$^3$/s)</th>
<th>$\sigma$ (m$^3$/s)</th>
<th>$r = \sigma/\langle q_u \rangle_{\text{avg}}$ (%)</th>
<th>$r_{\text{avg}} = r/\sqrt{N}$ (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>I1</td>
<td>0.26</td>
<td>1.47</td>
<td>79.7</td>
<td>2.43</td>
<td>3.04</td>
<td>1.52</td>
<td></td>
</tr>
<tr>
<td>I2</td>
<td>0.25</td>
<td>1.70</td>
<td>129.1</td>
<td>4.33</td>
<td>3.35</td>
<td>1.94</td>
<td>Test 2 skipped, LDFM not working</td>
</tr>
<tr>
<td>I3</td>
<td>0.42</td>
<td>0.65</td>
<td>19.2</td>
<td>1.72</td>
<td>9.00</td>
<td>5.20</td>
<td>Test 1 skipped, oscillatory velocity too high</td>
</tr>
<tr>
<td>I4</td>
<td>0.42</td>
<td>0.92</td>
<td>44.1</td>
<td>2.33</td>
<td>5.29</td>
<td>3.06</td>
<td>Test 1 skipped, first test of new condition</td>
</tr>
<tr>
<td>I5</td>
<td>0.45</td>
<td>1.50</td>
<td>162.8</td>
<td>2.47</td>
<td>1.52</td>
<td>0.8</td>
<td>Test 1 skipped, first test of new condition</td>
</tr>
</tbody>
</table>
Table 3.3 Results of velocity measurements, performed by LDFM in series I

<table>
<thead>
<tr>
<th>Test</th>
<th>height (mm)</th>
<th>low (s)</th>
<th>high (s)</th>
<th>(u) (m/s)</th>
<th>( \bar{u} ) (m/s)</th>
<th>Number of waves for ensemble-averaging</th>
<th>remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>II-L11</td>
<td>95</td>
<td>408.4</td>
<td>552.4</td>
<td>0.233</td>
<td>1.48</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>II-L12</td>
<td>64</td>
<td>638.8</td>
<td>782.8</td>
<td>0.216</td>
<td>1.51</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>II-L21</td>
<td>48</td>
<td>194.4</td>
<td>338.4</td>
<td>0.191</td>
<td>1.54</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>II-L22</td>
<td>24</td>
<td>543.8</td>
<td>687.8</td>
<td>0.170</td>
<td>1.55</td>
<td>20</td>
<td>some peaks in laser signal</td>
</tr>
<tr>
<td>II-L23</td>
<td>18</td>
<td>730.8</td>
<td>795.6</td>
<td>0.152</td>
<td>1.52</td>
<td>20</td>
<td>some peaks in laser signal</td>
</tr>
<tr>
<td>II-L31</td>
<td>36</td>
<td>544.8</td>
<td>688.8</td>
<td>0.170</td>
<td>1.56</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>II-L32</td>
<td>25</td>
<td>717.5</td>
<td>861.5</td>
<td>0.162</td>
<td>1.55</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>II-L33</td>
<td>18</td>
<td>879.4</td>
<td>987.4</td>
<td>0.133</td>
<td>1.47</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>II-L41</td>
<td>101</td>
<td>432.1</td>
<td>576.1</td>
<td>0.249</td>
<td>1.47</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>II-L42</td>
<td>70</td>
<td>597.7</td>
<td>705.7</td>
<td>0.222</td>
<td>1.49</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>II-L43</td>
<td>47</td>
<td>734.5</td>
<td>878.5</td>
<td>0.194</td>
<td>1.55</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Test</td>
<td>height (mm)</td>
<td>low (s)</td>
<td>high (s)</td>
<td>$\langle u \rangle$ (m/s)</td>
<td>$\bar{u}$ (m/s)</td>
<td>LDFM 100 mm $&lt;u&gt;$ (m/s)</td>
<td>LDFM 100 mm $\bar{u}$ (m/s)</td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td>---------</td>
<td>----------</td>
<td>----------------</td>
<td>---------------</td>
<td>-------------------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>I1-A21</td>
<td>38</td>
<td>185.04</td>
<td>257.04</td>
<td>0.172</td>
<td>1.50</td>
<td>0.222</td>
<td>1.48</td>
</tr>
<tr>
<td>I1-A22</td>
<td>39</td>
<td>257.04</td>
<td>329.04</td>
<td>0.186</td>
<td>1.44</td>
<td>0.226</td>
<td>1.49</td>
</tr>
<tr>
<td>I1-A23</td>
<td>15</td>
<td>350.6</td>
<td>422.6</td>
<td>0.147</td>
<td>1.52</td>
<td>0.225</td>
<td>1.47</td>
</tr>
<tr>
<td>I1-A24</td>
<td>16</td>
<td>479.56</td>
<td>551.56</td>
<td>0.139</td>
<td>1.52</td>
<td>0.224</td>
<td>1.45</td>
</tr>
<tr>
<td>I1-A41</td>
<td>27</td>
<td>142.2</td>
<td>178.2</td>
<td>0.172</td>
<td>1.50</td>
<td>0.226</td>
<td>1.48</td>
</tr>
<tr>
<td>I1-A42</td>
<td>29</td>
<td>293.32</td>
<td>365.32</td>
<td>0.189</td>
<td>1.47</td>
<td>0.234</td>
<td>1.48</td>
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<tr>
<td>I1-A43</td>
<td>10</td>
<td>379.76</td>
<td>415.76</td>
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<td>1.40</td>
<td>0.236</td>
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<td>11</td>
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<td>1.40</td>
<td>0.233</td>
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<td>0.178</td>
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<td>329.6</td>
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<td>0.227</td>
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<td>380</td>
<td>452</td>
<td>0.153</td>
<td>1.43</td>
<td>0.233</td>
<td>1.49</td>
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<tr>
<td>I1-A54</td>
<td>17</td>
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<td>0.222</td>
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<td>14</td>
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<td>163.68</td>
<td>0.147</td>
<td>1.54</td>
<td>0.222</td>
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<td>19</td>
<td>279.0</td>
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<td>1.55</td>
<td>0.227</td>
<td>1.48</td>
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<td>8</td>
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<td>487.76</td>
<td>0.133</td>
<td>1.44</td>
<td>0.234</td>
<td>1.46</td>
</tr>
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<td>487.52</td>
<td>552.32</td>
<td>0.150</td>
<td>1.46</td>
<td>0.235</td>
<td>1.47</td>
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<td>10</td>
<td>194.32</td>
<td>266.32</td>
<td>0.155</td>
<td>1.49</td>
<td>0.224</td>
<td>1.49</td>
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<tr>
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<td>2</td>
<td>367.4</td>
<td>439.4</td>
<td>0.132</td>
<td>1.41</td>
<td>0.231</td>
<td>1.48</td>
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<td>576.4</td>
<td>0.147</td>
<td>1.46</td>
<td>0.231</td>
<td>1.49</td>
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<td>669.84</td>
<td>0.114</td>
<td>1.33</td>
<td>0.234</td>
<td>1.49</td>
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<td>705.2</td>
<td>777.2</td>
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<td>1.38</td>
<td>0.218</td>
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<td>236.48</td>
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<td>0.125</td>
<td>1.36</td>
<td>0.226</td>
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### Table 3.7: Contents of data files of time-dependent measurements

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### Table 3.9 Averaged transport rate per condition, standard deviation and relative error in series J

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</tbody>
</table>
from: Ribberink, 1989
- flow discharge $Q$ and piston motion
- flow velocities $U(z,t)$
- sediment concentrations $C(z,t)$
- net sediment transport rate $<a_d(x)>$
  (mass conservation technique)
GRAIN SIZE DISTRIBUTION OF COARSE SAND
USED IN SERIES I EXPERIMENTS

DELT W HYDRAULICS

Z 2137

FIG. 2.3.1
GRAIN SIZE DISTRIBUTION OF UNSIEVED DUNESAND
USED IN SERIES J EXPERIMENTS

DELFt HYDRAULICS

Z 2137 FIG. 2.3.2
PLAN VIEW

measures in mm

SCHEMATIC DIAGRAM OF PROFILES ON MEASUREMENT CARRIAGE

DELFt HYDRAULICS

Z 2137 FIG. 2.4.1
CONFIGURATION OF MEASURED VELOCITY COMPONENTS BY LDFM IN THE TUNNEL

DELFt HYDRAULICS
SCHEMATIC DIAGRAM OF CCM PROBE

DELFT HYDRAULICS

Z 2137 FIG. 2.4.10
CCM CONFIGURATION IN TUNNEL

DELFT HYDRAULICS

Z 2137 FIG. 2.4.11
**Signal:**
1. Measured piston position
2. Measured piston position
3. Measured piston velocity
4. Measured piston pressure
5. Measured A-component LDFM
6. Measured B-component LDFM
7. Measured pump discharge
8. Measured x-component ADV
9. Measured y-component ADV
10. Measured z-component ADV
11. Measured OPCON signal
12. Measured CCM signal
CALCULATED SEDIMENT TRANSPORT RATE ALONG THE TUNNEL, II

DELFIT HYDRAULICS

Z 2137 \ FIG. 3.2.1
CALCULATED SEDIMENT TRANSPORT RATE
ALONG THE TUNNEL, I2

DELT HYDRAULICS
CALCULATED SEDIMENT TRANSPORT RATE
ALONG THE TUNNEL, I3

DELFt HYDRAULICS
CALCULATED SEDIMENT TRANSPORT RATE ALONG THE TUNNEL, I4

DELFt HYDRAULICS
CALCULATED SEDIMENT TRANSPORT RATE
ALONG THE TUNNEL, I5

DELFt HYDRAULICS

FIG. 3.2.5
$Z_1$ = still bed level at max. velocity
$Z_2$ = still bed level at zero velocity (at flow reversal)
$Z_3$ = still bed level before test
TIME-AVERAGED CONCENTRATION PROFILE
(OPCON/CCM)

DELTFT HYDRAULICS

Z 2137 FIG. 3.2.9
TIME-AVERAGED SUSPENDED SEDIMENT CONCENTRATION PROFILE (OPCON)

DELFt HYDRAULICS Z 2137 FIG. 3.2.10
TIME SERIES OF ENSEMBLE-AVERAGED CONCENTRATIONS OF SUSPENDED SEDIMENT (OPCON)

DELFT HYDRAULICS

Z 2137  FIG. 3.2.12
TIME SERIES OF ENSEMBLE-AVERAGED CONCENTRATIONS IN THE SHEET-FLOW LAYER (CCM)

DELFT HYDRAULICS

Z 2137 FIG. 3.2.13
CALCULATED SEDIMENT TRANSPORT RATE
ALONG THE TUNNEL, J2

DELFT HYDRAULICS
CALCULATED SEDIMENT TRANSPORT RATE ALONG THE TUNNEL, J4

DELFIT HYDRAULICS
CALCULATED SEDIMENT TRANSPORT RATE
ALONG THE TUNNEL, J5

DELFT HYDRAULICS
CALCULATED SEDIMENT TRANSPORT RATE
ALONG THE TUNNEL, J6

DELFt HYDRAULICS
Appendix A

Measuring techniques
General information and calibration
A1 Mass conservation technique

A mass conservation technique was used for calculating the net sediment transport rates. The bottom of the cylindrical risers and the recirculation pipe are provided with valves that enable the removal of trapped sand, which is transported out of the test section, and can be applied for the measurement of the sand transport at both ends of the section.

Because sediment traps are used on either side of the tunnel test section, the sediment continuity equation can be integrated from the left-hand-side and also from the right-hand-side. Consequently, during each test two estimates can be obtained of the transport rate at the measurement location, under the condition that the porosity of the sand bed in the test section is known. The porosity of the sand in the tunnel can be determined from the collected sand weights in the traps (volume without pores) and the volume change (including pores) in the tunnel test section (see Section 2.4.1).

In principle the following equations are used in the analysis:

**Measured porosity:**

\[
1 - \varepsilon_0 = \frac{G}{\rho_s \Delta V_{lp}} \quad (A.1)
\]

Transport rate at the measurement location:

**Left trap estimate:**

\[
q_{sl} = \frac{(1 - \varepsilon_0) \Delta V_{lp}}{\Delta t \ W} - \frac{G_i}{\rho_s \Delta t \ W} \quad (A.2)
\]

**Right trap estimate:**

\[
q_{sr} = \frac{(1 - \varepsilon_0) \Delta V_{rip}}{\Delta t \ W} + \frac{G_r}{\rho_s \Delta t \ W} \quad (A.3)
\]

In which:

- \( \Delta V_{lp} = \Delta V_{lp} + \Delta V_{rip} \) = total eroded volume, including pores, from the tunnel test section during one test (m³)
- \( \Delta V_{lp} \) = Total eroded volume, including pores, from the part of the tunnel test section to the left of the measurement location during one test (m³)
- \( \Delta V_{rip} \) = Total eroded volume, including pores, from the part of the tunnel test section to the right of the measurement location during one test (m³)
- \( G = G_i + G_r \) = total (dry) weight of the sand collected in both traps (kg)
- \( G_i \) = Total (dry) weight of the sand collected in the left trap (underneath the piston) (kg)
- \( G_r \) = Total (dry) weight of the sand collected in the right traps (underneath the open cylindrical riser and in the recirculation system) (kg)
- \( \rho_s \) = Density of sand (2650 kg/m³)
- \( \varepsilon_0 \) = Porosity of sand (-)
\[ W = \text{Width of tunnel test section (m)} \]
\[ q_s = \text{Measured net transport rate in real sand volume (without pores) per unit width and time during one test at the measurement location (m}^2/\text{s}) \]
\[ \Delta t = \text{Test duration (s)} \]

Both Equation A.2 and A.3 give the same answer for the measured transport rate for a certain test as long as the measured porosity during the same test is substituted. However, variations were found in the measured porosity during different tests. The possible extremes are 0.54 (loosely packed) and 0.67 (fully packed). The measured variation may be caused by errors in the bed level measurement.

The test duration is limited because bed level disturbances, generated at the boundaries, propagate into the tunnel and will ultimately reach the location where the actual transport measurements take place. For this reason a number of tests with a limited duration was carried out for each experiment. Between the separate tests the observed boundary effects were removed.

For the present study the measured transport rates are obtained by using Eqs. (A.2) and (A.3) in combination with the averaged measured porosity over all tests \((1-c_0 = 0.61)\). The values are corrected for the occurrence of systematic errors. The averaged value of the different tests was considered as the measured transport rate for a specific flow condition.

**A2 Bed level profiling system**

A bed level profiling system was used to measure the bed level along the tunnel before and after a test. The system consists of three bed profilers, a position counter and measuring and processing software.

**Lay-out**

The profilers are positioned on a measurement carriage, as shown in Figure 2.4.1. The measurement carriage can be drawn along the tunnel over a pair of rails by means of a steel cable. The rails are fixed to the sidewalls just underneath the roof of the tunnel, while the steel cable is connected to the measurement carriage and led over two wheels at both ends of the tunnel. One of the wheels is connected to an axle and handle in order to draw the measurement carriage along the tunnel, while the other is fixed to an axle with a position-counter in order to determine the exact location of the measurement carriage in the tunnel.

**Working of profilers and calibration**

The profilers, developed by DELFT HYDRAULICS consist of a 0.4 m long stem, with a probe at the end. The instrument measures conductivity and has to be operated with the probe tip under water. The sampling volume is located just below the probe tip. The conductivity in the sampling volume is determined by the ratio of the parts of the sampling volume, occupied by the sand and by the water. Because the conductivity of water is much larger than that of sand, the conductivity in the sampling volume will be larger if a smaller part of the sampling volume is occupied by the sand, i.e. if the probe tip is further away from the bed. The profilers are organised such that the conductivity in the sampling volume remains constant.
This means that the probe tip remains at a constant distance from the sand bed. A potential meter registers the movement of the probe, such that the bed level variations can be derived from the movement of the probe.

The calibration factor of the three profilers is 0.04 m/V (0.30 m corresponds to 7.5 Volts). The calibration of the profilers was performed for the fine sand experiments. It turned out that the difference (ds) between the measured distance and the actual distance is always smaller than 0.4 mm. Before the start of the experiments, the calibration of the profilers was checked by means of a calibration stick, with which it is possible to put the probe of the profilers at seven fixed positions, 0.05 m apart. Because the calibration factor of these profilers is 0.04 m/Volts, each step should correspond to a change in voltage of 1.25 Volts.

In order to derive the absolute bed level in the tunnel, a horizontal dummy bottom, made of artificial material (with a smaller conductivity than water!) and a length of about 0.15 m was installed in the upstream end of the tunnel as a reference level.

Positioning system

The axle, connected to the wheel at the downstream end of the tunnel, is turning when the measurement carriage is drawn along the tunnel, because the steel cable is led over this wheel. Therefore the number of rotations of the axle determines the distance covered by the measurement carriage. A position counter, which is fixed to this axle, sends 500 pulses per rotation to the positioning system. So every pulse corresponds to a distance of $2\pi r/500$, in which $r$ is the radius of the wheel. The system is calibrated by measuring the distance, covered by the measurement carriage, by hand (12.34 m) and linking that to the number of pulses, counted by the position counter.

A3 LDFM

A Laser-Doppler system with a 'forward scatter reference beam method', developed by DELFT HYDRAULICS, was used for 2-dimensional flow velocity measurements. The doppler-frequency shift of scattered light (by small particles) with respect to the frequency of the incident laser light is directly proportional to the velocity. A lens of 400 mm focal length is used for focusing the incident and reference beams (wave length laser light 633 nm). This lens was chosen because it has the smallest sampling volume for the required velocity range. (The larger the velocity range, the larger also the sampling volume). The height and the width of the sampling volume in flow direction of the LDFM is 0.215 mm. However, the width in cross direction is much larger (6.47 mm).

The LDFM does not measure the horizontal and vertical components of the velocity directly, but two components, $v_A$ and $v_B$, at about 45° to the x-axis, in a vertical plane. Afterwards $v_A$ and $v_B$ are transferred to $u$ and $w$. Alternatively, the components $v_A$ and $v_B$ can be recorded in which case $u$ and $w$ can be calculated by hand afterwards. For the configuration of the velocity components $v_A$ and $v_B$ in the tunnel, see Figure 2.4.3.

In order to increase the range of velocities which can be measured by LDFM, the components $v_A$ and $v_B$, rather than the horizontal and vertical components $u$ and $w$ are recorded in the present experiments. This can be explained as follows: the voltage of the two output signals
is restricted to 10 Volts. If the horizontal and vertical components of the velocity are chosen as the output signals, the horizontal velocity range is equal to:

$$C_1 \left( \frac{m/s}{V} \right) \cdot 10(V) = 10C_1 \ (m/s)$$ (A.4)

In which $C_1$ is the calibration factor of the LDFM. However, if the components $v_A$ and $v_B$ are chosen as the output signals, the horizontal velocity range is equal to:

$$\left[ C_1 \left( \frac{m/s}{V} \right) \cdot 10(V) \right] \cos(45^\circ) + \left[ C_1 \left( \frac{m/s}{V} \right) \cdot 10(V) \right] \cos(45^\circ) = 10 \sqrt{2} C_1 \ (m/s)$$ (A.5)

This is possible because the velocity in the tunnel is purely horizontal.

The horizontal and vertical components are calculated afterwards by means of the following formula:

$$u = -v_A \cos(\alpha_A) + v_B \cos(\alpha_B)$$

$$w = v_A \sin(\alpha_A) + v_B \sin(\alpha_B)$$ (A.6)

in which $v_A$ and $v_B$ are determined from:

$$v_A = C_{1A} \cdot V_A - C_{0A}$$

$$v_B = C_{1B} \cdot V_B - C_{0B}$$ (A.7)

Here $C_{1A}$, $C_{1B}$ are the calibration factors (in m/s/V) and $C_{0A}$ and $C_{0B}$ the offsets (in m/s) of the components $v_A$ and $v_B$. $V_A$ and $V_B$ are the outputs (in Volts) for the two components.

The values of the variables are:

<table>
<thead>
<tr>
<th>Component A</th>
<th>Component B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ (°)</td>
<td>45.25</td>
</tr>
<tr>
<td>$C_1 \ (m/s/V)$</td>
<td>0.145</td>
</tr>
<tr>
<td>$C_s \ (m/s)$</td>
<td>-2.41 $\cdot$ 10$^{-3}$</td>
</tr>
</tbody>
</table>

**A4 ADV**

The ADV is based on the doppler principle to measure the three components of the velocity at a single point. The system includes three modules: a measurement probe, a signal conditioning module and a signal processing module.

The measurement probe consists of four ultrasonic transducers; a transmit transducer located at the bottom end of the stem and three receive transducers, slanted 30° from the axis of the transmit transducer and pointed at the sampling volume, which is located about 0.10 m below the probe tip. For a schematic diagram of the ADV probe, see Figure 2.4.6. The receive transducers record the signal, scattered by particles in the water. Because the frequency of
the received signal is shifted as a result of the velocity of the particles that scatter the signal (doppler-shift), the velocity of these particles can be determined. This implies that in practice the velocity of the particles in the water rather than the flow velocity itself is measured. However, for sediment transport measurements it is the velocity of the particles that determine the sediment transport rate. Therefore this is not a problem.

The size of the sampling volume depends on the number of pulses used for one measurement, one pulse corresponding to 3.5 mm, two pulses to 5 mm and three pulses to 9 mm sampling volume thickness. The horizontal dimensions of the sampling volume are determined by the diameter of the transmit transducer which is about 6 mm. The calibration coefficients of the ADV depend on the velocity range (vr). The values for the three different components are:

<table>
<thead>
<tr>
<th>vr = 2.5 m/s</th>
<th>vr = 1.0 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>v</td>
</tr>
<tr>
<td>C_u (m/s/V)</td>
<td>0.2503</td>
</tr>
<tr>
<td>C_v (m/s)</td>
<td>0.00005</td>
</tr>
</tbody>
</table>

In order to measure velocities by ADV, a set-up file is required, corresponding to the specific probe used in the measurements. This set-up file can be either in a binary or an ascii format. In the present experiments the binary set-up file "1135-3mm.pro", corresponding to a sampling volume thickness of about 3.5 mm was used, rather than the ascii set-up file, used in the fine sand experiments, because the binary set-up file seemed to produce less instrument noise than the ascii set-up file, in contradiction to the experience in the fine sand experiments. More information about the set-up files can be found in Janssen et al. (1996). For the processing of the ADV signal, in order to obtain the correct velocities, the water temperature and salinity should be measured to update the speed of sound in water.

A5 opcon

The OpCon is an instrument, developed by DELFT HYDRAULICS, for the measurement of (sand) volume concentration, based on the extinction of infrared light. The range of concentrations is approximately 0.005 - 2 volume percent (sand: 0.1 - 50 g/l). Figure 2.4.8 and 2.4.9 show the opCon configuration in the tunnel and a schematic diagram of the OpCon probe. The light beam has a thickness of 2.6 mm (= height of sensing volume). The distance between the optical transmitter and the receiver is 30 mm (= length of sensing volume).

The calibration factor of the OpCon K_1 is defined as follows:

\[
K_1 = \frac{\rho_s}{(a_s a_e \gamma)}
\]  

(A.8)

Where:

\( \rho_s \) = sediment density

\( a_s \) = amplification factor of electronic amplifier (factor 1 or 10)
\[ a_e = \text{electronic conversion factor for the log-amplifier} \]
\[ = 3(\log(e) = 1.303 \text{ for the applied OpCon}) \]
\[ \gamma = \text{calibration factor for the OpCon probe (grain-size dependent)} \]

As can be seen from Eq. (A8), the calibration of the OpCon depends on an amplification factor \(a_e\), which can be set during the measurement at 1 or 10, and on the grain diameter. Bosman (1982, 1984) developed the OpCon probe and calibrated it extensively (in a calibration vessel), for different unsorted and sorted sand types. The relation between \(D_{50}\) (in mm) and the calibration factor \(K_1\) (in g/l/Volt) is given in Figure A3.2 of Katopodi et al. (1994) and can be written as:

\[
K_1 = 84.1 \ (D_{50} - 0.05325) \quad \text{for} \quad a_e = 1 \\
K_1 = 8.41 \ (D_{50} - 0.05325) \quad \text{for} \quad a_e = 10
\]

From this relation it is found, that the calibration factor \(K_1 = 2.21 \text{ g/l/Volt} \ (a_e = 10)\), for sand with \(D_{50} = 0.32 \text{ mm}\). However it can be expected that the \(D_{50}\) of the suspended sediments is somewhat smaller than 0.32 mm. In the earlier experiments with unsieved dunescrub (\(D_{50} = 0.21 \text{ mm}\), Katopodi et al., 1994) and fine sand (\(D_{50} = 0.13 \text{ mm}\), Janssen et al., 1996) it was found that the grain diameter of the suspended sediments was about 75 - 80% of the \(D_{50}\) of the bed material. This was determined from samples collected by the Transverse Suction System. Because in the present experiments, no measurements were performed with the Transverse Suction System, it was decided to use a \(D_{50}\) equal to 75% of 0.32 mm = 0.24 mm to calculate the calibration factor of the OpCon. This results in \(K_1 = 1.5 \text{ g/l/Volt} \ (a_e = 10)\). However, there remains some uncertainty about the grain diameter of the suspended sediments and the results should be treated with care.

**A6 CCM**

The CCM is an instrument, developed by DELFT HYDRAULICS, for the measurement of large sand concentrations (5 - 50 volume percent, 100 - 1500 g/l) with a four-point electro-resistance method. Figures 2.4.10 and 2.4.11 show the CCM configuration in the tunnel and a detailed plot of the CCM probe. The distance between the electrodes is 0.6 mm and the electrodes have a thickness of 0.3 mm. The length of the sensing volume is approximately 2 mm. According to Ribberink & Al-Salem (1992), the height of the sensing volume (above the ends of the electrodes) is approximately 1 mm. This is confirmed by Koelewijn (1994). A constant (AC) current is generated between two outer electrodes and the voltage between the inner electrodes is measured. The measured voltage is proportional to the electro-resistance of the sand-water mixture in a small sensing volume directly above the electrodes. The electro-resistance increases (or the conductivity decreases) for increasing sand concentrations.

The output of the CCM can be transferred to concentrations, using the calibration factor \(Gr\):

\[ C(\text{g/l}) = Gr \ (\text{g/l/Volt}) \times U_m (\text{Volts}) \]
The conductivity of water can vary considerably. Therefore a relative conductivity $G_r$ is used for the calibration, defined as:

$$G_r = 1 - \frac{U_0}{U_m}$$ (A.9)

Where:

$U_0 =$ output voltage of the probe for 'clear water'

$U_m =$ output voltage of the probe for the sand-water mixture

The CCM was calibrated before by Ribberink & Al-Salem (1992), Koelewijn (1994) for the 0.21 mm sand and by Van der Wal (see Janssen et al., 1996) for the 0.13 mm sand. The results agreed very well and were not grain size-dependent. Therefore no new calibration was performed for the present experiments. The calibration factor $G_r$ is equal to 1.1.
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