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Size Gradation Effects in Sediment Transport

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Abstract

This paper presents the experimental results obtained at prototype scale in the Large Oscillating Water Tunnel (LOWT) facility of WL | Delft Hydraulics with graded sediment subjected to non-linear waves and linear waves plus current flows. The objective of this experiment is to increase our present understanding and physical insight of the basic mechanisms of bed-load and suspended load transport in oscillatory flow conditions when graded sediments are present in the bed. The sediment bed consists of a mixture of two well sorted sands (two fractions) that have been used before in the tunnel in order to make comparisons possible. Net sediment transport rates, time averaged suspended sediment profiles, time dependent concentrations in the suspension and sheet flow layers as well as time dependent velocity profiles are measured. Moreover, the sediment bed composition before and after each test is recorded in order to calculate the transport rate of each sediment fraction. Selected results are presented here. Full details are included in the data report (Hamm et al, 1998). The data will be used for the development of mathematical model formulations for graded sediment transport.

Introduction

The Large Oscillating Water Tunnel (LOWT) facility of WL | Delft Hydraulics in de Voorst, The Netherlands enables experiments at full scale including horizontal oscillatory flows with superimposed currents. The test section is 14 m long, 1.1 m high and 0.3 m wide. Most of the research in the tunnel during the last decade was carried out using unsieved dune sand with a median diameter of 0.21 mm and a narrow size distribution (Ribberink and Al-Salem,1994 and 1995, Ribberink et al., 1994, Katopodi

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et al., 1994). Two types of oscillatory flow conditions were generally used, namely regular second-order Stokes waves and sinusoidal waves with superimposed net currents. In the majority of the experiments the plane-bed regime with sheet-flow conditions was observed.

Since three years, specific attention is paid to the influence of the grain size in combined wave-current conditions. Experimental programmes were carried out with median diameters of 0.13 mm and 0.32 mm keeping the geometric standard deviation unchanged (Janssen and Ribberink, 1996, Dohmen - Janssen et al., 1998).

The flume is now also used to study sediment transport with sands containing heavy minerals with a density >2.9 kg/l which are naturally found in the field. These tests show that these heavy minerals, have clearly different transport properties than light minerals and induce armouring effects (Tánczos et al., 1997).

The present experiments actually include two Series named K and L. In Series L, the previous experiments of Tánczos et al. (1997) were completed by using mixtures of light sand and zircon with the same grain size but distinctly different density. These tests are reported by Manso et al.(1998). In Series K described in the present paper, a mixture of two sand types with median diameters of 0.13 mm and 0.32 mm has been used and the hydrodynamic conditions have been chosen in close connection with previous experimental series in the tunnel. This makes comparisons with available data possible and increases the scope and possibilities of the present work.

Experimental set-up and programme

Hydraulic conditions

The experimental programme consisted of 3 asymmetric wave conditions and 2 sinusoidal waves/net current conditions, which are summarised in Table 1. Two 2^{nd}-order Stokes waves conditions were chosen with different root-mean square velocities, u_{rms} (K1 and K2). The 2^{nd} order Stokes wave can be described with

(1) $u(t) = u_1\cos(\omega t) + u_2\cos(2\omega t)$,

the root-mean square velocity yields:

(2) $u_{rms} = \sqrt{0.5 * (u_1^2 + u_2^2)}$

Where u_1 and u_2 are the first- and second-order components of the horizontal velocity, respectively. ω is the angular frequency of the wave ($=2\pi/T$). The wave period T=6.5 s was the same for both conditions. The degree of asymmetry R, defined as $(u_1+u_2)/2u_1$ was 0.66.

Also a different asymmetric wave was used called the sawtooth wave (K3). The only difference between the sawtooth and the 2nd-order Stokes wave is a 90 degree phase shift of the second harmonic component. The sawtooth wave can be described by:

(3) $u(t) = u_1\cos(\omega t) + u_2\cos(2\omega t+\pi/2)$

Even when the values of u_1 and u_2 are the same, the third order velocity moment is very different, i.e. zero for the sawtooth wave and non-zero for the 2nd-order Stokes wave. It is therefore interesting to investigate the difference in net transport rates caused by a sawtooth wave and by a 2nd-order Stokes wave, with the same period and the same root-mean square velocity.

The last two conditions were combined sinusoidal waves/current conditions (K5 and K6). The net current velocity at 10 cm above the bed <u> and the amplitude of the sinusoidal velocity û were different for each condition. The oscillation period T=7.2 s. was the same for both conditions. All conditions correspond to the sheet flow regime and lie within the constrictions of the tunnel.

Table 1. Hydraulic conditions

Cond	**type**	**mean oscillatory flow (1)**	**mean net current (1)**		**number of runs**	
		U_{rms} (m/s)	**T (s)**	**<U> (m/s)**	**net sediment transport rate**	**detailed measurements**
K1	2nd order Stokes	0.84	6.5	0.04	7	
K2	2nd order Stokes	0.59	6.5	0.02	3	8
K3	sawtooth	0.70	6.4	0.01	3	
		û (m/s)	**T (s)**			
K5	sinusoidal	1.47	7.2	0.25	3	15
K6	sinusoidal	0.95	7.2	0.45	3	2

(1) measured at 0.10 m above the initial bed

Sediment properties

The sand used in the present experiments consisted of a 50%-50% mixture of the fine (D_{50} = 0.13 mm) and the coarse sand (D_{50} = 0.32 mm) with hardly any overlap as can be seen from the D_{90} of the fine sand (0.182 mm) and the D_{10} of the coarse sand (0.217 mm). The characteristics of the mixture derived from sieve-analyses (figure 1) are D_{10}= 0.097 mm, D_{50}= 0.194 mm, D_{90}= 0.406 mm with a density of 2650 kg/m^3. Analysis of the sand in the Visual Accumulation Tube (VAT) gives a median fall velocity of $W_{s,50}$ = 20.3 mm/s for the mixture.

Measurement programme and instruments

The measurement programme was designed as comprehensively as possible making use of several kind of instruments to measure time-averaged as well as time-dependent quantities. In order to achieve that goal, it was necessary to repeat the hydraulic conditions several times, each run being devoted to a particular instrument.

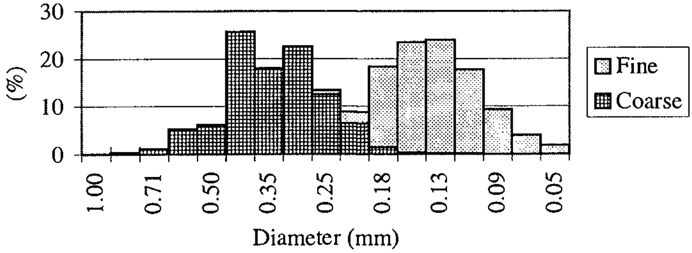

Figure 1. Grain-size distribution of the mixture

The measurements were especially delicate and more time consuming compared with previous measurements with uniform sand. For graded sand, the bed composition changes with time and thus replacement of the bed was necessary to restore the designed bed composition for the next runs. Thus, the upper layer of the sand bed (~5 cm) had to be removed from the tunnel and replaced with new sand every few tunnel runs. Considerable effort was also required for the extraction of the bed samples and their analysis in the settling tube.

The measurements required to obtain the net, time-averaged transport rates (global and per fraction) were performed first for the five hydraulic conditions. Then, the suction system was installed to measure the vertical profile of time-averaged concentrations in suspension for three hydraulic conditions (K2, K5 and K6). Finally, detailed time-dependent measurements over the the vertical were performed for two hydraulic conditions (K2 and K5) by installing successively four instruments described below.

Bed levels along the tunnel were measured before and after each run using a bed level profiling system. Additionally, the weight of the sand collected in the traps was measured underwater.

The upper layer of the sand bed in the test section was sampled using a siphoning system. A perspex cylinder (height about 12 cm) with a diameter of 100 mm was stuck into the sand bed for about 5 cm. Next the sand-water mixture within the cylinder was siphoned out of the tunnel, and the sand water mixture was collected in buckets. The grain size distribution and the percentage of the fine and the coarse fraction, present in each sample was determined by using a settling tube (Visual Accumulation Tube, VAT). Samples from the sand collected in the traps were also subjected to the same analysis.

The time-averaged concentration ⟨c(z,t)⟩ in the suspension layer was measured using a transverse suction system able to extract samples of a mixture of sand and water at ten locations over a vertical simultaneously. The concentration was determined and the sample was then put into the VAT to get the grain-size distribution of the suspended sediment.

Time-dependent sediment concentration c(z,t) was measured over the vertical both in the suspension layer (for $z > 0.01$ m) using an optical concentration meter (OPCON) and in the sheet flow layer using a conductivity concentration meter (CCM). The OPCON is based on the extinction of the infra-red light when concentrations are in the range 0.1-50 g/l. The CCM is able to measure large sand concentrations in the range 100-1500 g/l on a sensing volume with a height of 1 mm.

Finally, time-dependent flow velocity components over the vertical were measured thanks to an acoustic doppler velocity meter (ADV) able to work even in high concentrations of sediment and a laser doppler flow meter (LDFM). In total, 41 runs were performed to achieve the measurement programme. The number of runs per hydraulic condition is provided in table 1.

Experimental results

Net sediment transport rate

The net sediment transport rates were measured for all five flow conditions. The sediment continuity equation was solved twice (starting either from the left or the right-hand-side) using as boundary conditions the sand volumes collected in the sand traps (given the sand porosity). This gives two estimates of the actual occurring transport rate in the middle of the tunnel for a specific test and the mean value is used. Figure 2 gives an example of such a result for test K5. In table 2, the net transport rates averaged over several runs are presented. Moreover, the standard deviation and the relative error are provided. They are comparable to the previous experiments (see i.e. Katopodi et al., 1994).

Table 2. Net sediment transport rate, averaged over all tests per condition

Test	$<q_{savg}>$ (10^{-6} m^2/s)	σ (10^{-6} m^2/s)	$r=\sigma/<q_{savg}>$ (%)	$\frac{r}{\sqrt{N}}$ (%)
K1	34.53	2.87	8.30	4.79
K2	17.03	0.17	1.00	0.58
K3	18.03	1.82	10.07	5.81
K5	78.80	9.03	11.46	6.61
K6	72.70	5.20	7.15	5.06

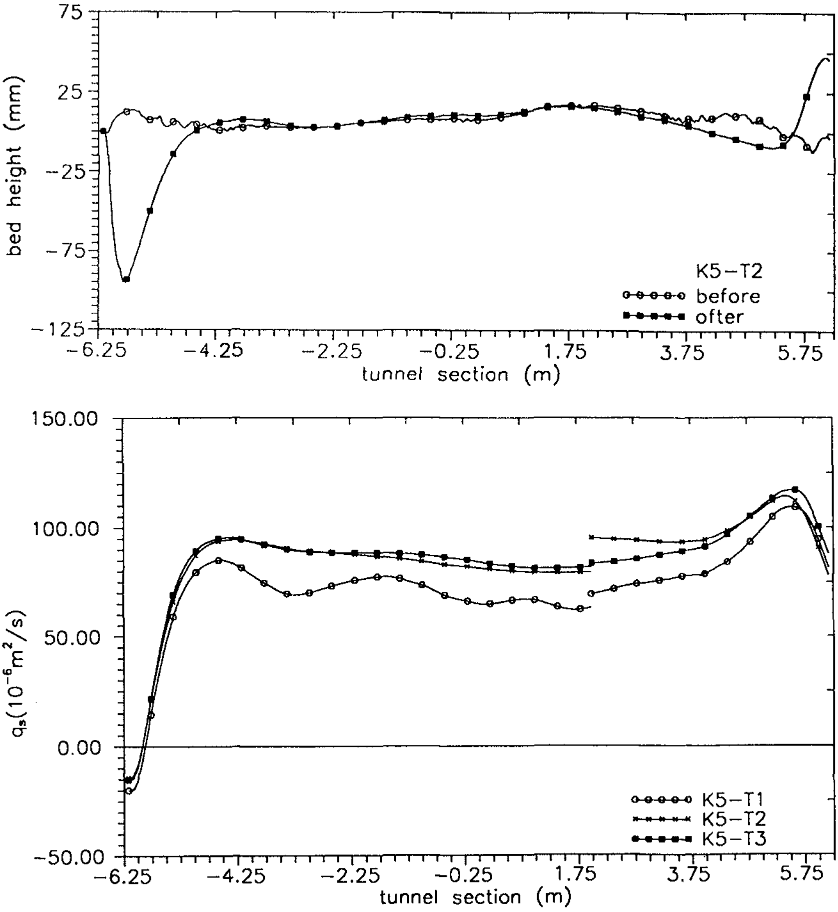

Figure 2. up: bed level before and after run K5-T2
down: net sediment transport along the test section for the three runs of test K5.

Cloin (1998) compared these results with available previous experiments performed with uniform sand (Katopodi et al., 1994, Janssen and Ribberink,1996 and Dohmen-Janssen et al., 1998) and with similar hydraulic conditions (see figure 3). She also performed an analysis of the sediment transport per fraction, which is presented hereafter, in order to understand the main features of this comparison.

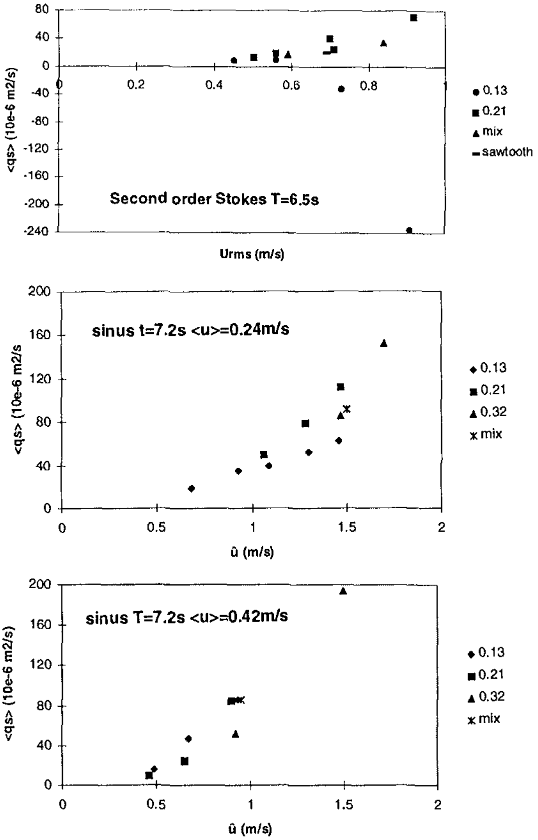

Figure 3. Comparison of the net sediment transport rate with previous experiments using uniform sediment. up: test K1, K2 and K3, middle: test K5 and down: test K6

Bed composition

An important part of the experiment was the estimation of the bed composition before and after each test. This information was necessary to estimate the transport rate per fraction and also explain the suspended sediment behaviour. Unfortunately, large scatter was observed in the bed composition data. The bed composition before the test was not completely uniform along the tunnel owing either to non uniform mixing of the two sand fractions or to inaccuracies of the sampling method. The bed composition after the tests did not show the same trends for all the tests of each condition. This might be again due to the sampling method or due to the fact that the upper layer of the bed was not changed after each test.

A detailed analysis of the bed composition data as well as an evaluation of the sampling method can be found in Cloin (1998). Despite of the large scatter of the data, she was able to calculate the transport rate per sediment fraction for all flow conditions. Figure 4 shows the result obtained for test K5.

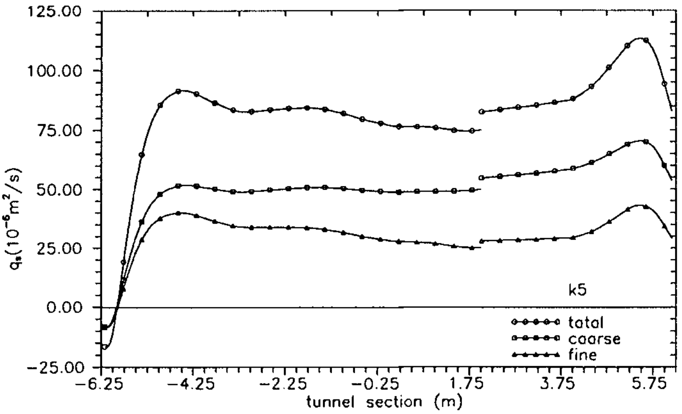

Figure 4: Net sediment transport per fraction along the test section for the test K5.

Then, she compared the measured sediment transport per fraction with the previous measurements with uniform sand (figure 3) by attaching to each fraction an estimated , uniform-based sediment transport. This estimation was computed by multiplying the volume percentage of occurence of the fraction considered in bed material with the transport rate of the fraction assumed to be alone, this transport being derived from the measurements with uniform sands. She was thus able to show that for sinusoidal waves with a net current, the fine fraction is hidden by the coarse fraction and the coarse fraction is more easily transported than in the case of uniform coarse bed material. The hiding is larger in case of higher mean velocity and smaller oscillating velocity. For second-order wave conditions, the fine fraction is also hintered by the coarse fraction for the strongest case (K1) but the coarse fraction is not influenced by the fine fraction in both cases.

Vertical sorting of the grain sizes

The sand samples extracted from the flow (suspension layer) with transverse suction present a strong reduction of the median diameter with elevation for all three conditions examined (K2, K5 and K6). The coarsest sand found near the bed has a D_{50} of only 0.13mm while the D_{50} of the original sand in the bed was 0.21 mm. This shows that only sand belonging to the finer fraction was set into suspension. The median diameter for all conditions decreases with elevation reaching a minimum of 0.08mm. The two tests per condition give similar results, except for K2 where the two tests are considerably different for elevations higher than 2 cm. The sand of the first test is much finer than of the second. It is clear that for the two tests the bed composition was not the same.

Sediment concentrations

a) Time-averaged concentrations

Time-averaged suspended sediment concentrations were measured with transverse suction for K2, K5 and K6. The concentrations for all conditions follow a power law (straight best fit lines), as has been found for all previous measurements in the tunnel under sheet flow conditions. For all cases the concentrations are larger than the concentrations measured previously with well sorted sand of D_{50}= 0.21mm for the same flow conditions. Time-averaged suspended sediment concentrations were also computed from the time dependent OPCON signal for K2 and K5. The two tests of K2 give somewhat different results, with the first test showing larger concentrations than the second. This indicates different bed composition during the two tests. For K5 the different tests show a rather good agreement. Comparison with transverse suction concentrations shows a satisfactory agreement for K5, differences for K2. Again, the rather variable bed composition for K2 may have played a role. The time-averaged concentrations computed from the CCM time dependent signal show an almost constant value of about 1350 g/l in the pick-up layer below the bed level. Above the bed the concentration decays rapidly to values less than 100 g/l in a distance of 3-5 mm (thickness of the sheet flow layer).

The vertical profile of the concentrations measured with the three instruments spans a distance from ~ 1cm below the bed up to ~ 25 cm above the bed and covers the pick-up, the sheet flow and the suspension layers. For both conditions (K2 and K5) the concentration profile shows a transition from a convex shape (pick-up layer) to a concave shape (suspension layer), reflecting the presence of different mechanisms in the mixing process. The profile obtained during test K5 is shown on figure 5.

b) time-dependent concentrations

The time-dependent concentration was measured at different elevations with OPCON (suspension layer) and CCM (sheet flow and pick-up layers) for K2 and K5. In the sheet flow layer the concentration is in phase with the free stream velocity. The same also holds for the suspension layer although a phase shift growing with elevation can be observed. In the pick-up layer the concentration follows the opposite behaviour (i.e. min concentrations at max velocities and max concentrations at zero velocities). The concentration in the sheet flow layer shows sharp peaks at the moments of the flow reversal a feature found before in measurements with uniform sand. In general the shape of the time dependent concentrations was the same as with well sorted sand with the same D_{50} . Figures 6 and 7 show the results obtained for test K5.

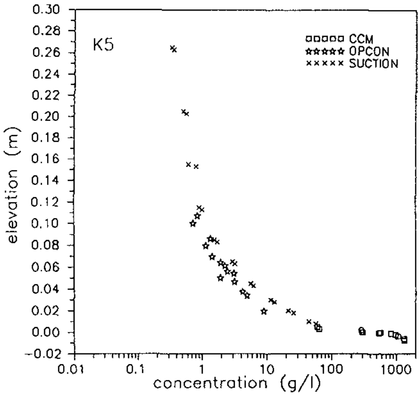

Figure 5: Time-averaged concentration profiles - test K5

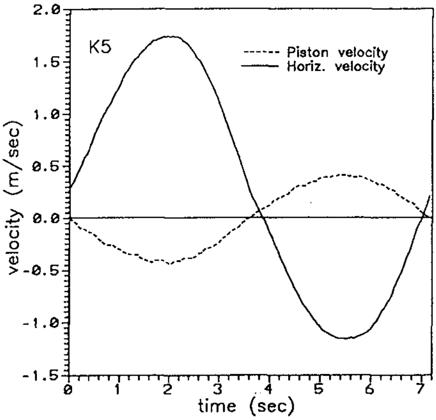

Figure 6: Time-dependent horizontal velocity at 10 cm above the initial bed (test K5)

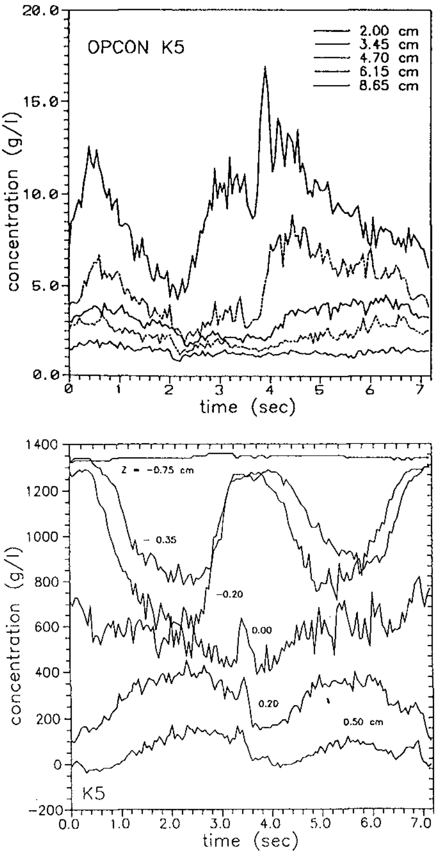

Figure 7: Time-dependent measurement of concentration - test K5. up: OPCON measurement and down: CCM measurement.

Flow velocities

Time dependent velocities were measured at different elevations for K2 and K5 with ADV and laser (LDFM). Velocity profiles could not be measured satisfactorily with laser for condition K5 because the suspended concentration was large and was blocking the laser beams almost for the entire depth.

The ADV signal in general was disturbed but we could measure close to the bottom (see figure 8 illustrating a typical result). Although the net ADV profile data present

The ADV signal in general was disturbed but we could measure close to the bottom (see figure 8 illustrating a typical result). Although the net ADV profile data present much scatter, for the second order Stokes condition K2 a small net current in the crest direction was distinguished as well as the asymmetry induced boundary layer streaming in the opposite direction. For the wave and current condition K5 the profile was logarithmic. These findings are in accordance with previous measurements in the tunnel.

Comparison of ADV and laser measurements for K2 showed a systematic difference which is small in the time dependent values but significant when averaged over the wave period. In Katopodi et al (1994), a similar mismatch was found when comparing laser and EMF (electromagnetic flow meter) measurements for waves and currents. Although the two cases are not directly comparable, they both concern asymmetric flows (K2 second order Stokes, series E current and sinusoidal waves).

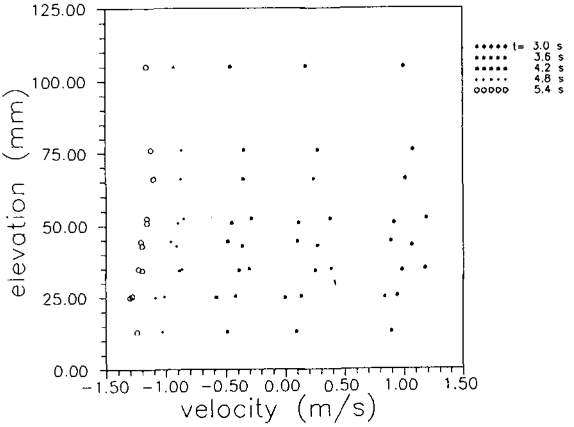

Figure 8: Time dependent velocity profiles measured by ADV test K5 between 3.0 and 5.4 secs.

Conclusions

An experimental investigation of graded sediment transport was conducted in the Large Oscillating Water Tunnel of WL | Delft Hydraulics under various hydraulic conditions with plane bed. The sediment bed consisted of a mixture of two well sorted sands (two fractions) that have been used before in the tunnel. The experiment concerned measurements of net sediment transport rates, bed composition change, time averaged suspended sediment profiles, time dependent concentrations in the suspension and sheet

flow layers and time dependent velocity profiles. A detailed presentation of the measurements and results is presented in the data report (Hamm et al, 1998).
Furthermore, net transport rates per sediment fraction were calculated by Cloin (1998) based on the bed composition data.

The data set has then been used by Cloin (1998) to compare with previous experiments using uniform sands. She also used it for the experimental verification of various transport formulae as well as time dependent models of sediment transport of graded sediment in sheet-flow conditions. This work is being extended to enlighten the influence of size and density in selective transport mechanisms. The examination of the gradation characteristics of the suspended sand samples and their linking with the characteristics of the bed samples is also scheduled (Katopodi et al., 1999).

As seen from the bed composition results, the used bed sampling technique did not prove very accurate and should be improved, possibly by taking cores out of the bed or colouring one of the fractions. Moreover, it would be very useful if the measurements concerning the two well sorted sands that constitute the sediment mixture of this experiment were completed such that all the quantities measured for series K could be compared with measurements of sand consisting out of one fraction only (see Hamm et al, 1998).

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