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SHEET FLOW AND SUSPENSION UNDER WAVE GROUPS IN A LARGE WAVE FLUME (SISTEX99)

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Abstract: Detailed measurements of sediment concentrations in the sheet flow layer and in the suspension layer for flat bed conditions under prototype wave groups are presented. These measurements are part of experiments on near-bed sand transport processes, carried out in the Large Wave Flume in Hannover, Germany (SISTEX99). The results show that concentrations in the sheet flow layer are highly coherent with the instantaneous near-bed velocity. In the suspension layer, however, concentrations respond much slower to changes in near-bed velocity: at some distance from the bed concentrations increase and decrease on the time scale of the wave group, with a time delay relative to the peak wave within the wave group.

INTRODUCTION

Near-bed sediment transport processes play an important role in cross-shore morphology. This is especially the case in sheet flow conditions, when ripples are washed out and large amounts of sand are transported in a very thin layer (a few mm to one or two cm) close to the bed. Sediment transport in oscillatory sheet flow has mainly been studied in oscillating water tunnels (e.g. Dohmen-Janssen, 1999). It is important to investigate whether these results are representative for the situation in the field. Thereto, experiments on near-bed processes are performed under prototype surface waves in the large wave flume of the ForschungsZentrum Küste (FZK) in Hannover, Germany (SISTEX99: Small-scale International Sediment Transport Experiments 1999, see also Ribberink et al., 2000).

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This paper focuses on the experiments with repetitive wave groups of large wave heights over a flat bed (sheet flow conditions). In the past, field observations showed that suspension events are strongly related to wave groups: during the first few waves in the group sediment is stirred up from the bed, followed by "pumping up" of sediment to progressively greater heights during later waves (e.g. Hanes, 1991; Hay and Bowen, 1994). This phenomenon would not be expected in the sheet flow layer, which is located so close to the bed that sediment is expected to react nearly instantaneously.

It has only recently become feasible to measure sediment concentrations and grain velocities inside the sheet flow layer under prototype waves using a new Conductivity Concentration Meter system (CCM-system). At the same time, time-dependent profiles of suspended sediment concentration have been measured using acoustic backscatter sensors. These data have been used to analyze pumping up processes in the suspension layer and to investigate whether these processes are indeed not important in the sheet flow layer.

EXPERIMENTAL SET-UP

Wave Flume and Test Section

Experiments were performed in the large wave flume of the University of Hannover, Germany. The flume has a total length of 300 m, a width of 5 m and a depth of 7 m with a wave paddle on one end and a 1:6 sloping dike on the other end. Measurements were carried out in the middle of a 75 cm thick, 45 m long horizontal sand bed in the central part of the flume, consisting of well-sorted sand with a median grain size of 0.24 mm. A 1:10 sloping beach consisting of somewhat coarser sand (D_{50} = 0.3 mm) was placed against the dike in order to dissipate the wave energy. Figure 1 shows the outline of the flume with the test section.

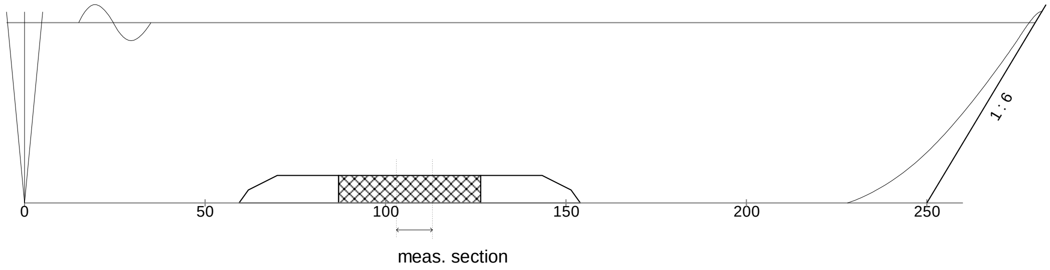

Figure 1: Outline of the wave flume with the test section

Measuring Techniques

Sediment concentrations and grain velocities at different elevations inside the sheet flow layer were measured using a new CCM-system that was specifically developed for the present flume tests. The system consists of two Conductivity Concentration Meters (developed by Delft Hydraulics), installed in a waterproof enclosure that was buried under the sand bed, such that the CCM-probes penetrated the sheet flow layer from below. The probes could be moved up and down using a remotely controlled vertical positioning system.

The CCM is designed to measure high sand concentrations (≈ 100 - 1900 g/l or .04 to .7 by volume). It measures the electro-conductivity of the sand/water mixture, which is related to the volume concentration of sand. The height of the sensing volume is approximately 1 mm (see Ribberink and Al-Salem, 1995). In the present experiments two CCM probes were used at the same vertical elevation but separated by 15 mm in the horizontal (flow) direction in order to determine grain velocities by cross-correlation of the two concentration signals.

Time-varying suspended sediment concentration profiles were measured using several Acoustic Backscatter Sensors (ABS, see Thorne and Hanes, 2001). Near-bed flow velocities (outside the wave boundary layer) were measured using three Acoustic Doppler Velocimeters, one near the location of the CCM at about 0.1 m above the bed and 2 near the location of the ABS's, at about 0.08 and 0.14 m above the bed. The one near the CCM was also used to determine the height of the sand bed during the run.

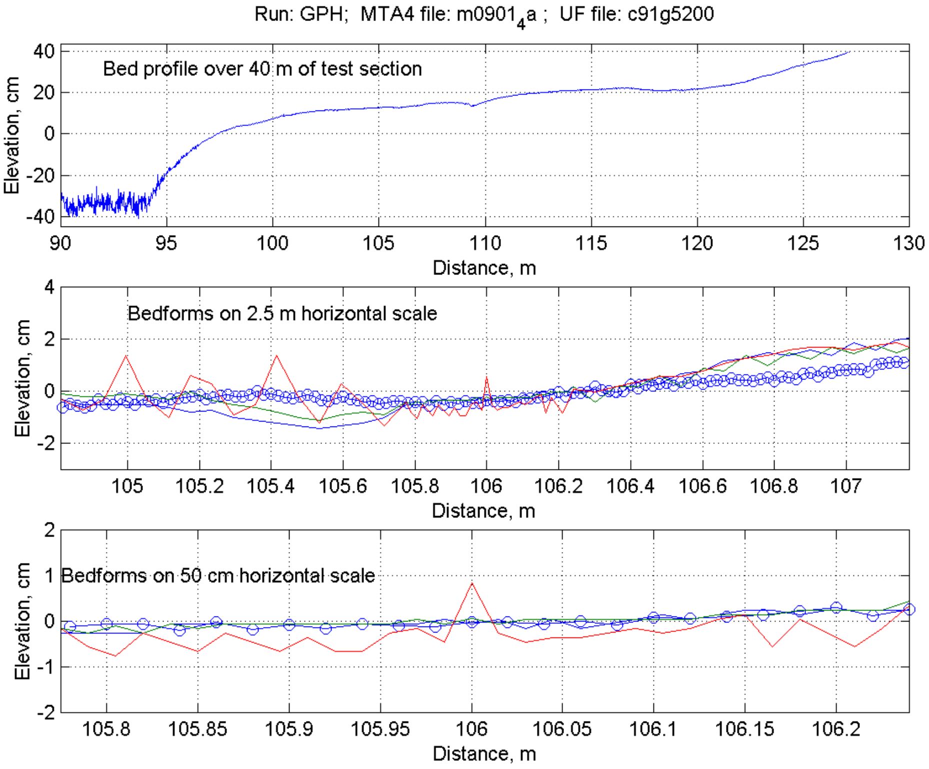

Figure 2: Seabed profile during run gp

Test Conditions

Experimental conditions consisted of repetitive 'natural' wave groups. The wave groups were generated by selecting one wave group from a narrow-banded Jonswap spectrum ($\gamma = 10$) and repeating this wave group about 20 times in each experimental run. In this paper we focus on one series of the flat bed sheet flow conditions called gp. During this series of experiments the wave group period, T_{gr}, was 90 seconds.

The peak wave period, T_p, was 9.1 seconds, and the (design) significant wave height at the wave paddle, H_s, was 0.9 meters. The water depth at the wave paddle was 3.75 m, corresponding to a water depth above the sand bed of 3.0 m. The seabed was relatively flat during these wave conditions. Figure 2 shows the seabed profile over three different length scales: a) the entire test section, b) a 2.5 meter section, and c) a 50 cm section.

EXPERIMENTAL RESULTS

Sediment Concentrations

Figure 3 shows ensemble-averaged flow velocities and sediment concentrations for condition gp. The upper panel presents the concentrations at different levels inside the sheet flow layer, i.e. just below and above the initial bed level ($z = 0$). The elevations with respect to the initial bed level are given by the numbers to the right of the figure (in mm). The measurements are ensemble-averaged over several wave groups. The numbers between parentheses present the number of wave groups over which the ensemble-average is determined. This number varies because the sensor is moved vertically but not uniformly over the course of the experiment in order to obtain measurements at different elevations within the sheet flow layer. The middle panel shows the ensemble-averaged suspended sediment concentrations at two different elevations. The lowest obtainable measurement of suspended sediment concentration, which is approximately 5 mm above the bed, is shown as well as the concentration 74 mm above the bed. The lower panel presents the measured flow velocity just outside the wave boundary layer (at $z = 0.1$ m). These measurements show that the near-bed velocities are very asymmetric, with maximum crest velocities of about 1.5 m/s and maximum trough velocities of about 0.8 m/s. This asymmetric behavior is clearly reflected in the sediment concentrations.

From the concentration measurements in the sheet flow layer two different layers can be identified: a pick-up layer located below the initial bed level (i.e. $z < 0$) and an upper sheet flow layer located above the initial bed level (i.e. $z > 0$). This two-layer system is very similar to what was observed in the past in oscillating water tunnels. At the lowest elevation ($z = -1.9$ mm), the concentration during most of the wave group is equal to the concentration of the sand bed. Only under the crest of the largest waves (largest near-bed velocities) sediment is being picked up from the bed, resulting in a decrease in concentration at the moment of maximum (crest) velocity. At a slightly higher elevation ($z = -0.6$ mm), sediment is also being picked up under the crest of smaller waves and under the trough of the waves. The decrease in concentration is strongest under the largest wave and the decrease in concentration under the crest of the wave is much stronger than under the trough of the wave. This indicates that the concentration in the pick-up layer is directly and nearly simultaneously related to the near-bed velocity.

Above the initial bed, in the upper sheet flow layer ($z = +0.6$ mm; $z = +2.4$ mm) concentrations increase when the near-bed velocity increases; grains that are picked up from below the still bed level are entrained into the flow just above the still bed level. Again, the peak in concentration is largest under the crest of the largest wave. Decreasing velocities under the following smaller waves lead to lower concentration peaks. The concentration peaks under the wave troughs are much smaller than under the wave crests, corresponding to the much smaller trough velocities compared to the crest velocities. Thus the sediment concentrations in the upper sheet flow layer also seem to be highly coherent with the near-bed velocity.

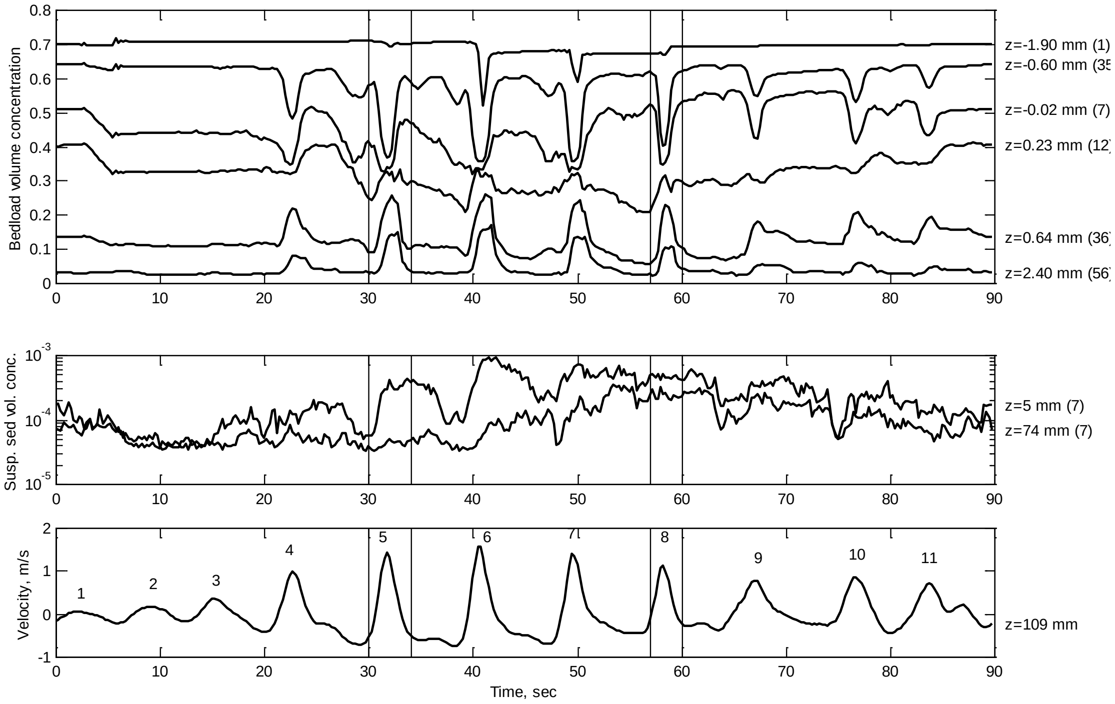

Figure 3: Ensemble-averaged concentrations in the sheet flow layer (upper panel) in the suspension layer (middle panel), together with ensemble-averaged near-bed velocities outside the wave boundary layer (at 0.1 m above the bed, lower panel).

The suspended sediment concentrations indicate a temporal response quite different from the bedload, particularly as the distance above the bed increases and as the waves occur later in the group. Very close to the bed there is an increase in suspended sediment concentration that corresponds to the increasing velocity under the crest of each of waves 3-7. There is also a decrease in concentration during the subsequent wave trough, but this decrease occurs over a longer time scale than the response of the bedload concentrations. Further into the wave group this response to the individual waves becomes progressively weaker, with the suspended sediment concentration remaining elevated during the small waves at the end of the wave group. Higher above the bed, the slow time response of the suspended sediment is more obvious. Here the response to individual waves is relatively small, but the concentration increases and then decreases on the time scale of the wave group, with a time delay relative to the peak wave within the wave group.

The direct relation between the near-bed velocity and the concentration inside the sheet flow layer is illustrated in a different way in Figure 4, which shows the crest velocity of the different waves in the group and the corresponding instantaneous value of the concentration at the various elevations inside the sheet flow layer. This figure shows that the concentrations inside the sheet flow layer follow the near-bed velocities: the highest concentration in the upper sheet flow layer and the strongest decrease in concentration in the pick-up layer occur under the highest wave (i.e. wave 6, highest crest velocity). When the waves decrease again (wave 7, 8 and 9) concentrations in the upper sheet flow layer decrease again and similarly, concentrations in the pick-up layer increase again. Thus, no time history effects on the time scale of a wave group seem to be present in the sheet flow layer.

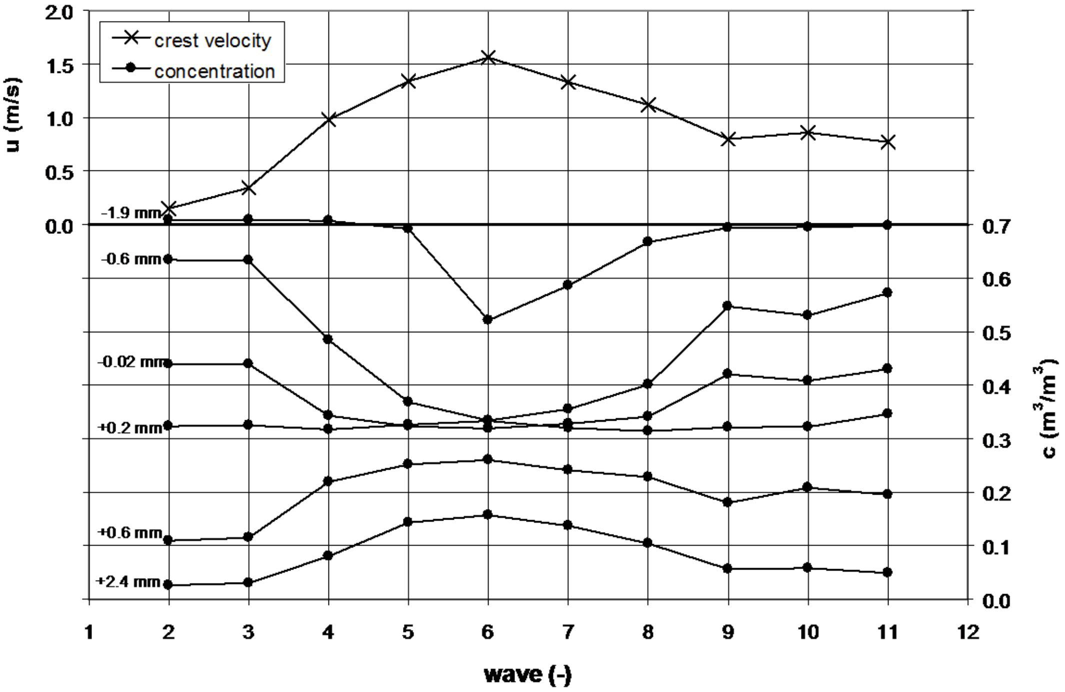

Figure 4: Concentrations at different elevations inside the sheet flow layer under the wave crest, in relation to the near-bed velocity, for different consecutive waves in the wave group.

Vertical Concentration Profile and Sheet Flow Layer Thickness

Figure 5 shows the vertical profile of sediment concentration in the sheet flow layer under the crest and the trough of the highest wave in the group (wave 6). The measurements are given by the symbols. The dotted line indicates the expected shape of the concentration profile beyond the measurement points.

Under the trough of the wave the concentration at 1.9 mm below the initial bed is equal to the still bed concentration. Above this level the concentration shows a very sharp vertical gradient going from a volume concentration of 0.68 to 0.1 over less than three mm.

Under the crest, more sediment is being picked up due to the larger near-bed velocity and the concentration at the lowest elevation (z = -1.9 mm) is smaller than the still bed concentration. The concentration gradient under the crest of the wave is somewhat smaller than under the trough of the wave.

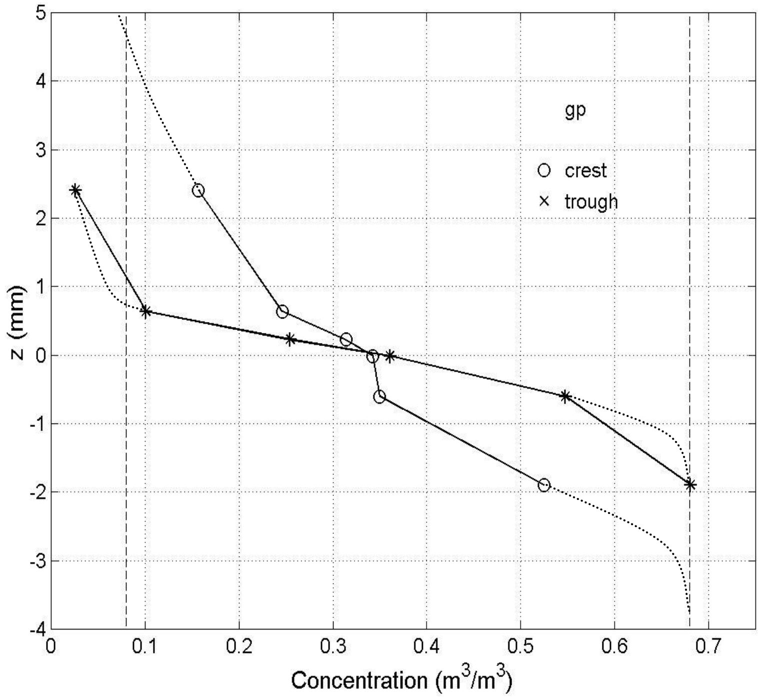

Figure 5: Vertical concentration profile in the sheet flow layer under the crest and the trough of the highest wave in the wave group of condition gp.

In general, the sheet flow layer is defined as the layer where concentrations are so high that intergranular forces are important. Therefore, in this study, the top of the sheet flow layer is defined as the level where the concentration reaches a value of about 0.08. This is the concentration for which the distance between particles is on average equal to the grain diameter. It can be expected that for higher concentrations intergranular forces become important. It is reasonable to assume that the bottom of the (mobile) sheet flow layer is located at the level where the sediment concentration reaches the value of the still bed concentration ($c \approx 0.68$).

These two limiting concentration values are indicated in the figure by the vertical dashed lines. They can be used to estimate the thickness of the sheet flow layer under the crest and under the trough of the wave. For example, for the concentration profiles presented in Figure 5 this yields the following results:

At the time of the wave trough:	δ_s = 2 mm (1.5 mm – 3 mm)
At the time of the wave crest:	δ_s = 8 mm (7 mm – 10 mm)

The same is done for all the waves in the group, for two flat bed sheet flow conditions, i.e. gp and gi (T_{gr} = 100 s, T_p = 6.4 s, H_s = 1.0 m and a water depth above the sand bed of 3.0 m). In addition, values of sheet flow layer thickness have been determined for 6 monochromatic wave conditions (see Ribberink et al., 2000). The values of the sheet flow layer thickness derived in this way are normalized by the mean grain size and plotted against the Shields parameter θ in Figure 6. This figure also shows an expression for non-dimensional sheet flow layer thickness as a function of θ, derived by Sumer et al. (1996) for steady flow. For the measurements, the value of θ is calculated using a wave friction factor (i.e. Swart, 1974) and a mobile-bed roughness height, according to the expression of Sumer et al. (1996), which is a function of the Shields parameter and the ratio of settling velocity to friction velocity.

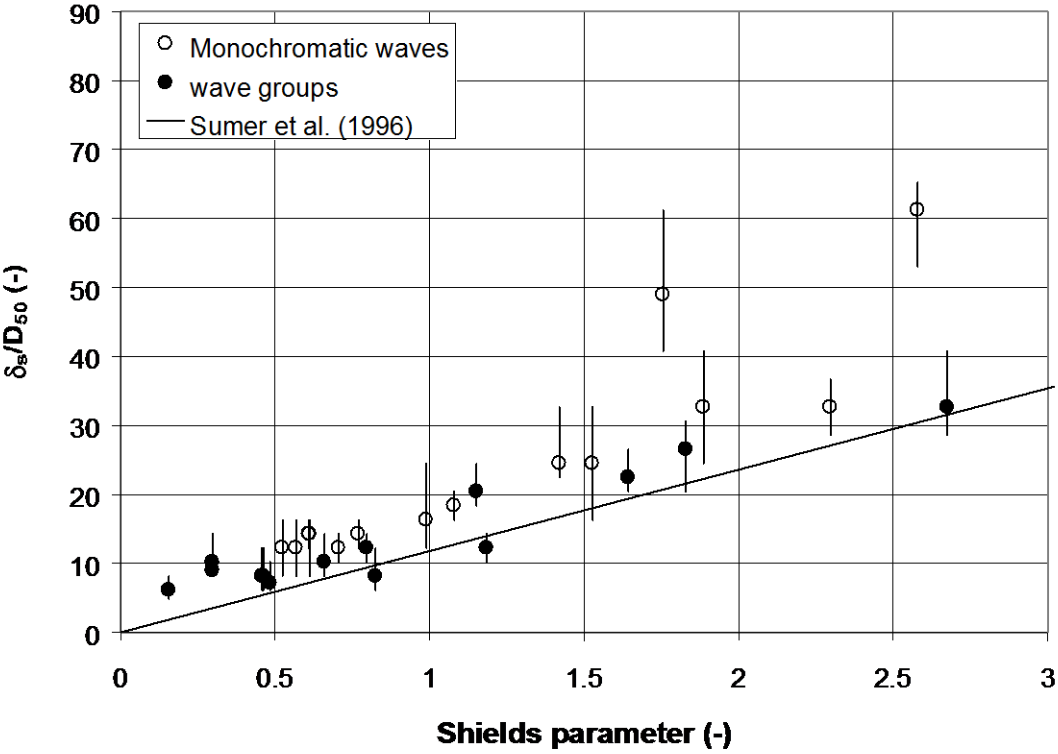

Figure 6: Non-dimensional sheet flow layer thickness under crests and troughs of monochromatic waves and waves in two different wave groups against Shields parameter

Figure 6 shows that the sheet flow layer is several grain diameters thick (10 – 40). The measurements of non-dimensional sheet flow layer thickness seem to follow the linear relation with Shields parameter, as suggested by the expression of Sumer et al., although the sheet flow layer thickness under waves seem to be somewhat larger than in steady flow.

Moreover, the values of sheet flow layer thickness under individual waves in a wave group are very similar to those under monochromatic waves. This confirms the idea that the concentrations in the sheet flow layer are nearly instantaneously related to the near-bed velocity and do not depend on the wave history.

CONCLUSIONS

Detailed measurements of sediment concentrations in the sheet flow layer and in the suspension layer have been presented. The measurements were carried out under prototype waves in the Large Wave Flume in Hannover, Germany. The present paper focuses on the tests with repetitive wave groups in the flat bed sheet flow regime.

The following conclusions can be drawn from the measurements:

- Concentrations in the sheet flow layer are highly coherent with the instantaneous near-bed velocity: concentrations show (relatively sharp) peak values under the crests of the waves and these peak values increase for increasing wave heights (increasing crest velocities). When the waves decrease again (further into the wave group), the peak values of the concentration decrease too.
- Concentrations in the suspension layer respond much slower to changes in near-bed velocity: the decrease in concentration during flow deceleration occurs much slower than in the sheet flow layer. Further away from the bed the concentration continues to increase when the waves start to decrease again: the concentrations increase and decrease on the time scale of the wave group, with a time delay relative to the peak wave within the wave group.
- The thickness of the sheet flow layer under a certain wave is related to the velocity under that wave and does not depend on the preceding wave. This confirms the instantaneous behavior of the concentrations in the sheet flow layer.
- The non-dimensional sheet flow layer thickness (normalized by the grain diameter) under the crest and the trough of the wave is linearly related to the Shields parameter and agrees reasonably well with the expression of Sumer et al. (1996) that was derived for steady flow.

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