CHAPTER ONE HUNDRED FIFTY FIVE

VARIATION OF SEDIMENT SUSPENSION IN OSCILLATORY FLOW

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ABSTRACT

Different syphon type suspended load probes were used together with a newly developed 'carousel' sampler for measurements of the instantaneous sediment concentration in turbulent oscillatory flow over a sand bed. Shields parameters were well above the rippled/flat bed transition region, resulting in intense sediment transport over a flat bed. The measurements were performed at different levels in a large oscillating water tunnel. They showed some characteristic features of the temporal concentration variation and of the variation with height of the mean concentration. Also a pronounced effect of the orientation of the suction tube relative to the flow was observed.

1. INTRODUCTION

A large part of the sand in motion under waves on a sandy coast is carried in suspension. Thus, the suspended load plays an important rôle in the net transport of sediment.

Measurements of time-mean sediment concentrations have frequently been published during the last decades. In general, however, such information is not sufficient to determine the net sediment transport due to waves and currents. In a wave motion with a weak current (e.g. the onshore/offshore problem) the net sediment transport may be caused by the difference between large sediment movements in opposite directions due to the predominantly oscillatory nature of the water flow. Thus, to determine this difference between two large numbers with any accuracy it is necessary to have detailed information about the temporal variation of the sediment concentrations.

The aim of the present experimental study is to provide measurements of the time variation of sediment concentrations above a sand bed under high shear conditions ('sheet flow'). Thus, the sand bed is (almost) plane during the experiments.

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The Shields parameter is defined as

$$\theta = \frac{\tau_{b,max}}{\rho_g(s-1)d_{50}}$$

where $\tau_{b,max}$ is the maximum bed shear stress, ρgs is the specific gravity of the sand grains, ρ being the density of water, and d_{50} is the median grain diameter. When $\tau_{b,max}$ is determined by (2) and (3) (see Chapter 3) the situations studied correspond to θ -values of about 1.9 - 3.3 (with roughness $k_N = 2.5 \ d_{50}$, see comments in Chapter 3).

Measurements of time variation of sediment concentration have previously been reported by Nakato et al. (1977), Sleath (1982), and Bosman (1982). They all, however, measured the concentrations above a ripple bed corresponding to situations with smaller Shields parameters ($\sim 0.1 - 0.8$), and they used electro-optical equipment.

The measurements presented in the following were carried out in a large oscillating water tunnel, using wave periods of 9.1 s and 6.8 s. The sediment concentrations were measured by letting a syphon probe suck out a sand-water mixture from a fixed point in the tunnel. A horizontal wheel with 18 cups covering the circumference was rotating under the outlet of the syphon, and the rotation was synchronized with the oscillation in the water tunnel. The sand-water mixture in each cup thus represents the concentration averaged over (about) one 18th of the oscillation period, giving a phase interval of 20° .

A limitation of this method compared with electro-optical methods is that rapid concentration fluctuations will not be represented in the results. It also involves some rather complicated phase corrections of measurements.

In Chapters 2 and 3 is given a more detailed description of the experiments, and the test parameters are listed in Table 1.

In Chapter 4 we discuss and analyze the experimental data in order to obtain the results presented in Chapter 5. These include variations of concentration and corresponding variations of the average-over-depth velocity, as well as mean concentration profiles.

2. EXPERIMENTAL FACILITIES

The oscillating water tunnel, in which the measurements of sediment concentration were performed, has been described by Lundgren and Sørensen (1958) and Jonsson and Carlsen (1976), but has since been modernized. Briefly, it consists of two cylindrical vertical risers and a horizontal part comprising a 10 m long test section with plexiglass walls and with a rectangular cross section (height \times width = 36×39 cm²), see Fig. 1. In the experiments the bottom of the test section was covered with a 7 m long sand field. Thus, the inner height above the sand bed was about 30 cm. The water column was forced to oscillate by varying the air pressure above the water surface in the closed (southern) vertical riser. The air pressure was supplied by a hydraulically driven piston performing a sinusoidal oscillation under the control of an electric signal. The variation of the water level in the open (northern) riser was recorded by a capacitance-type wave gauge. From this record, the average-over-depth velocity, u, in the test section was determined by differentiating the record signal with respect to time.

(1)



Fig. 1. The oscillating water tunnel.



Fig. 2: Syphon probes with different types of intakes used in the experiments. Inner diameter of tubes is 1.6 mm. (Probe no. 6 has inner diameter 2.6 mm, see Table 1).



Fig. 3: The 'carousel sampler'. Two sets of cups placed on a horizontal wheel, 18 cups at each level. The outlets from the syphons are seen to the left.

'Wave' periods (T) were 9.1 s and 6.8 s, and amplitudes in the test section (α) 1.8 to 2.1 m. Maximum flow velocities (u_{max}) were 1.3 to 1.9 m/s.

The probe for the concentration measurements was installed almost at the middle of the test section, see Fig. 1. A number of different probes were used in the experiments. Some of them are shown in Fig. 2. Each probe includes a stainless steel pipe supplied with an extension of plastic tubing with its outlet over the 'carousel sampler', as the horizontal wheel in Fig. 3 has been termed.

During an experiment the excess pressure in the tunnel continuously forced out a sand-water mixture through the probe. The 'carousel sampler' (Fig. 3) actually consists of two levels, each with 18 cups mounted along the circumference and rotating under the outlets of the double syphons used in most of the experiments. The rotation of the wheel was synchronized with the oscillation in the water tunnel. The revolutions of the wheel were recorded by a photo-electric cell, and corrections were made by a feed-back mechanism adjusting the velocity of rotation once every wave period.

Two different types of sand were used with median diameters 0.19 mm and 0.38 mm. Settling velocities at 18° C are about 0.021 m/s for d_{50} = 0.19 mm, and 0.050 m/s for d_{50} = 0.38 mm.

PROCEDURE

Before each test the level of the sand bed along the test section was measured. Sampling of suspension was begun a few minutes after the start of the oscillations to allow initial disturbances of bed and suspension to vanish, and each test then lasted for 6-13 minutes (Table 1). After each test the concentration of sand in the cups was determined by drying and weighing.

Ripples were not observed, but quite often some deviation from a plane horizontal bed was found. However, the associated bed slopes never exceeded 2° and usually were much gentler. The configuration was apparently caused by small irregularities in the flow conditions, perhaps partly related to the asymmetrical way in which the flow was driven. Variations of the bed level in the lateral direction were also recorded and found to be only a few millimetres.

Since the bed level sometimes changed during an experiment, the probe was not exactly at the same height above the sand bed during the whole test. Therefore, the bed level was measured before, during, and after each test, and an 'effective probe elevation' during the test was determined by averaging these three elevations. Both the average value and the range of variation are shown in Table 1 for each test. See also Figs. 8 and 9.

It may also be worth mentioning that there was no observation of local scour in cases where the probe was positioned close to the bottom.

The column 'probe pointing' in Table 1 shows the directions of the probe intakes - which are opposite to the directions of suction velocities. In most of the tests with the coarsest sand wider suction pipes were applied in order to avoid effects of partial or momentaneous blocking of the pipe. However, comparison of results obtained with wide and narrow suction pipes showed no such tendency. In some cases, however, clogging was observed, as demonstrated in the table. Table 1.

TEST No.	PROBE POINTING	PROBE TYPE(NO)	PERIOD T(s)	EXCURSION 2α (m)	MAX.VEL. u _{max} (m/s)	SHIELDS PARAMETER O(C)	MEDIAN GR.SIZE (mm)	HEIGHT OF PF AVERAGE(cm)	RANGE (a) (cm)	WATER TEMP(°C)	TEST DURATION(s)
820 823 825A 825B	S E S N	10 L	9.1	3.6 3.6 3.6 3.6 3.6	1.3 - -	1.85 - - -	0,19	(2.2) 2.3 2.5 2.7	$(2.0) \sim 2.4$ 2.1 - 2.5 2.3 - 2.7 2.7		634 751 724 724
1 2 3 4 5 6	S+(W) S+(W) W+(S) W+(S) N+(E) E+(N)(c)	2 JL 90°	9.1 - - -	3.64 3.68 3.64 3.64 3.72 3.72	1.26 1.27 1.26 1.26 1.28 1.28	1.87 1.90 1.87 1.86 1.93 1.93	0.19	2.0 2.3 1.6 2.0 1.9 1.8	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$		581 719 726 729 729 729 729
7 8 9 10 11	N+S N+S N+S N+S N+S	3_L	9.1	3.72 3.78 3.68 3.76 3.80	1.29 1.31 1.28 1.30 1.32	1.96 2.02 1.92 1.99 2.03	0.19	2.4 1.9 1.4 1.7 1.2	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$		606 724 724(346)(b) 725 734(430)
12 13 14	E+N E+N E+N	©	9.1	3.78 3.80 3.76	1.31 1.32 1.30	2.01 2.03 1.98	0.19	1.3 1.8 0.9	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$		726 725 727
15 16	-	© ⊥ Disc	9.1	3.74 3.78	1.29	1.97 2.01	0.19	2.0 1.0	1.6 - 2.3 0.8 - 1.2		726 726
17 18 19 20 21	N+S N+S N+S N+S N+S	③ _IL	6.8 - -	3.62 3.62 3.62 3.62 3.62 3.62	1.68 1.68 1.68 1.68 1.67 1.68	3.33 3.33 3.33 3.30 3.30 3.33	0.19	2.1 1.6 1.9 2.6 1.2	1.6 - 2.6 1.3 - 1.8 1.7 - 2.1 2.5 - 2.7 1.0 - 1.3	18.6 18.0	678(202 678(153) 678 681 678
22 23 24 25	N-S N-S N-S N-S	⊛ ⊥	9.1 - - -	3.72 3.72 3.72 3.72 3.78	1.28 1.29 1.29 1.30	1.93 1.94 1.94 2.00	0.19	1.7 2.3 1.6 1.4	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	16.1 16.1 16.4 16.4	729 727 727 553
26 27	N+S N+S	∟لہ 3	9.1	3.72 3.74	1.29	1.86 1.96	0.19	1.7	1.3 - 2.1 0.7 - 1.2	13.0 18.7	727 727
28 29	N+S N+S	3_1_	6.8	3.58 3.54	1.66	3.26 3.19	0.19	1.0 2.7	0.8 - 1.1 2.6 - 2.7	18.6 18.9	678 682
31 32 33 34	N+S N+S N+S N+S	³ _ا_	6.8 - - -	4.06 4.08 4.08 4.06	1.88 1.89 1.89 1.88	2.37 2.39 2.37	0.38	2.D 1.9 2.4 2.8	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	16.6 13.8 14.9 16.4	678 475 475 678
35 36 37 38 39 40 41	N+S N+S N+S N+S N+S N+S N+S	©_ <u> </u> _	6.8 - - - - -	4.06 4.06 4.12 4.12 4.14 4.14 4.12 4.12	1.88 1.88 1.90 1.92 1.92 1.91 1.92	2.36 2.36 2.42 2.44 2.44 2.43 2.44	0.38	2.1 1.1 1.3 1.7 1.3 2.8 0.8	$\begin{array}{rrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrrr$	13.2 15.7 17.7 15.1 18.7 18.3 19.0	476 476 340 406 476 509 406

PROBE TYPE NOS. 1-5: $\phi_i = 1.6$ mm PROBE TYPE NO. 6 : $\phi_i = 2.6$ mm

(a) Estimated variation of probe level. (b) One suction tube clogged after time interval in parenthesis. (c) Directions in parenthesis means that only time-mean concentrations were measured. (d) Based on roughness $k_N \neq 2.5 d_{50}$, see text.

Tabel 1: Test parameters for suspension measurements. Re directions $N\left(\text{orth}\right)$ and S(outh), see Fig. 1. Re details of probes, see Fig. 2. The Shields parameter listed in the table is defined by (1), where maximum bed shear is determined by

$$\tau_{\rm b,max} = \frac{1}{2} f_{\rm w} \rho u_{\rm max}^2$$
(2)

The wave friction factor is determined from Swart's approximate formula based on the measurements by Jonsson and Carlsen (1976)

$$f_{w} = \exp\{-5.977 + 5.213 (\alpha/k_{M})^{-0.194}\}$$
(3)

with the bed roughness $k_{\rm N}$ = 2.5 d_{50}. Quantity α is the water particle amplitude of the oscillation.

The Shields parameters thus determined (Table 1) must be regarded with some reservation. Recent interpretations of the experiments by Carstens et al. (1969), see Grant and Madsen (1982), indicate much higher values for $k_{\rm N}/d_{50}$ than 2.5, for oscillatory flow associated with intense sediment transport over a flat bed. From their work one can quote figures as high as 210 - 240 for $k_{\rm N}/d_{50}$. In this context note that the Shields parameter in Grant and Madsen's work is based on a wave friction factor, where roughness equals grain diameter; thus their Shields parameters - like the ones in Table 1 - are more formal than physical quantities. In conclusion, the 'real' Shields parameters must be expected to be much higher than listed in Table 1.

4. INTERPRETATION OF MEASUREMENTS

The experimental data do not directly provide the information about sediment concentrations which we are aiming at. In the following it is described how the data were analyzed to obtain the experimental results presented in Chapter 5.

The sand-water mixture takes some time to pass through the suction system to the carousel. This phase shift or 'delay' must be accounted for when relating the concentrations to the water velocities in the test section. Also the effect of a varying sand-water mixture velocity in the suction system at T = 6.8 s was considered, and the measurements were corrected accordingly.

Furthermore, the phase shift we are looking for is not just the delay of the water particles, but that of the sediment grains. These two phase shifts are not quite the same because on the non-uniform velocity distribution over the cross section of the pipes and tubes. The centre of the grains cannot get closer than half a grain diameter to the pipe walls where the velocities are lowest. Thus, if the sand grains are uniformly distributed over the remaining pipe cross section the average velocity of the sand through the suction system will be higher than the average velocity of the water. For a quantitative evaluation of this effect, however, we must estimate the velocity profile. From a few simple experiments the 'quickest' sand grains are found to pass through the suction system about 20% faster than the water, that is the maximum sand velocity is approximately 20% larger than the average water velocity. The experiments also indicated that this could be explained by introducing the velocity distribution

$$v = v_{max} \left(1 - \frac{r}{R}\right)^{\frac{1}{7}}$$

(4)

where v is the velocity, r is the distance from the centre line, and R is the inner radius of the pipe (or tube). This well-known expression meets the requirement of a maximum velocity approximately 20% higher than the average velocity. In the tests we have used $d_{50}/D = 0.10 - 0.13$, D being the inner diameter of the suction system. With the velocity profile given by (4), the difference between the delay of the sand and the delay of the water was found to be between 2° and 10° .

The average velocity, u, in the test section was determined by differentiating the wave-gauge registrations of the water level in the open vertical leg of the tunnel. As expected for a period of T = 9.1 s, which is close to the natural period of the water column, u varies nearly sinusoidally (Fig. 4).

At a period of T = 6.8 s, however, the deviation from a sinusoidal velocity variation is appreciable (Figs. 5 and 6). The wave motion corresponding to the flow in the tunnel is defined so that $\omega t = 0$ ($\omega = 2\pi/T$) at maximum velocity northwards (i.e. towards the open riser).

5. RESULTS

Some examples of the measured instantaneous concentrations, C_m , and the corresponding time variations of water velocities in the tunnel are shown in Figs. 4-6. All are tests with twin suction intakes oppositely directed and parallel to the flow (type 3 in Fig. 2), but located at the same level above the bed. The concentration variation curves are drawn through the measurement points, each corresponding to the sand concentration in one cup. The phase distance between these points is rather variable in Fig. 5 (test no. 28) due to a large variation in suction velocity in this particular test.

As expected the measured concentrations have two maxima during an oscillation period, one for each extreme in velocity. However, there is a considerable difference in magnitude between the two measured concentration maxima. Figs. 4-6 clearly show that the concentration measurements are very sensitive to the direction of the oscillatory flow (typically ± 1.3 to ± 1.9 m/s) relative to the suction velocity (typically 0.9 m/s). The effect is probably due to the fact that the heavier sand particles cannot quite follow the water in the large accelerations immediately around the intake of the probe.

Calibration tests for different types of suction probes in a stationary current have been made by Bosman (1982). These calibrations show that for a current directed towards the opening of the probe the true concentrations are up to about 30% larger than the measured concentrations, depending on the ratio between suction and flow velocity. None of Bosman's calibrations, however, were made with the opposite current direction. Qualitative considerations show that in this case concentrations and this is believed to be the reason for the above-mentioned differences between the two measured concentration maxima.

Therefore, in the following we consider measurements made when the current velocity opposes the intake velocity to be unreliable. In the tests with twin suction intakes we consider the at any instant highest of the two C_m -curves to be the best approximation to the actual concentrations, i.e. we change from one curve to the other one as soon as the

SEDIMENT SUSPENSION VARIATION



Pig. 4: The temporal variation of the sand concentration C_D, and the average-over-depth velocity u, in Yest no. 10 (two oppositely directed southon pipes paxallel to the flow, type 3 in Fig. 2). That parameters in Table 1. H and S are North and South.





- Fig. 5: The temporal variation of the sand concentration C_u, and the average-over-depth velocity u, in Test no. 28 (two oppositely directed suction pipes parallel to the flow, type 3 in Fig. 2). Test parameters in Table 1. N and S are North and South.
- Fig. 6: The temporal variation of the sand concentration $C_{\rm pr}$, and the average-over-depth velocity u, in Test no. 41 (two oppositely directed suction pipes parallel to the flow, type 6 in Fig. 2). Test parameters in Table 1. N and S are North and South

latter exceeds the former one⁴. This observation puts a question mark to the reliability of time-mean concentrations found in conventional experiments with single, longitudinally directed probe intakes. These should, according to the present experiments, be increased by at least 25-80% to get the actual mean concentrations in the flow (see, e.g. Figs. 4-6). Fig. 7 compares - for all three groups of test parameters - the time-mean concentration, \overline{C} , determined by time-averaging the highest of two measured concentrations. In the following only \overline{C} is considered.

In general, the time variation of concentration was 'peaky', with narrow maxima and broad minima, especially so for the coarse sand.

Mean concentration profiles are shown in Figs. 8 and 9. The range of variation of the height of the probe above the bed during each test is shown as a full line through the measurement point. A special procedure has been applied to determine the mean concentration in the tests with only a single suction tube directed parallel to the flow. The measured concentration variation was shifted 180° to simulate an oppositely directed probe, and the mean concentration was then determined from the at any time highest of the two concentration curves.

In addition to the grain size distribution of bed material a number of samples of suspended sand were analyzed. The median grain sizes for these are plotted in Fig. 10 versus the height of the probe above the sand bed. For the finer sand type, there is a clear tendency towards decreasing grain size at increasing height above bed, whereas no such variation appears in the results for the coarser sand.

6. CONCLUSIONS

- a. The time variation of sediment concentration at different heights over bed was measured in a large oscillating water tunnel (Fig. 1). Two types of sand were used with median diameters 0.19 mm and 0.38 mm. 'Wave' periods were 9.1 s and 6.8 s, and amplitudes were 1.8 to 2.1 m. Maximum velocities were 1.3 to 1.9 m/s corresponding to intense sediment transport over an approximately plane bed without ripples.
- b. The 'carousel sampler' (Fig. 3) with the probes in Fig. 2 proved to be well-suited for measuring 'instantaneous' sediment concentration in oscillatory flow (Figs. 4 - 6), although problems arise with phase corrections and calibration.
- c. The influence of the direction of probe intake relative to the flow on directly measured instantaneous concentration was large (Figs. 4 -7). In situations where the flow direction opposed the direction of flow into the probe, the measured concentrations were found to be too small. This was accounted for by using probes with two oppositely directed intakes.

⁴ Recently, C.H. Hulsbergen, Delft Hydraulics Laboratory, has performed experiments to determine the influence of suction velocity and probe direction on measured concentration (Bosman, 1984). When the report is published, the results will be used in a further adaptation of our measurements.



Fig. 7: Comparison of two methods to determine time-mean concentration \tilde{C} in tests with two separate longitudinally directed (N-S) suction intakes. x: \tilde{C} determined as the mean concentration for the actually measured suspension sample (= \tilde{C}_m). o: \tilde{C} determined as the mean value of the at any time highest measured concentration. —: $d_{50} = 0.19 \text{ mm}, \text{ T} = 9.1 \text{ s}.$ —:: $d_{50} = 0.19 \text{ mm}, \text{ T} = 6.8 \text{ s}.$



Fig. 8: Time-mean concentrations \overline{C} , determined from the at any time highest measured concentration. $d_{50} = 0.19$ mm, T = 9.1 s and 6.8 s. Specifically for single longitudinally directed intakes: \overline{C} is determined from the at any time highest of curves $C(\omega t)$ and $C(\omega t + 180^{\circ})$. The range of variation of the bed level during the tests is marked by a full line through each test point. Δ : intake pointing N; ∇ : intake pointing S; \triangleright : intake pointing E; \triangleleft : intake pointing W; \Diamond : two intakes pointing N-S; \times : T-shaped intake; o: disc-shaped intake.



Fig. 10: Median grain diameters of suspended sediment versus height above sand bed. o: d_{50} (bed) = 0.19 mm, T = 9.1 s. +: d_{50} (bed) = 0.19 mm, T = 6.8 s. \Box : d_{50} (bed) = 0.38 mm, T = 6.8 s.

- d. Also time-mean concentration profiles were found (Figs. 8 and 9).
- e. For the finer sand, grain size was found to decrease with height (Fig. 10).
- f. The time variation of concentration was 'peaky' with narrow maxima and broad minima, especially so for the coarse sand.
- g. The time variation of relative concentration was larger in experiments with coarse sand than with fine sand.

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