CHAPTER 53

GRAIN-GRAIN INTERACTION IN OSCILLATING SHEETFLOW

by
W.T. Bakker[1], W.G.M. van Kesteren[2] and Z.H. Yu[3]

ABSTRACT

Viscous grain-grain interaction is an important aspect of the dynamics of oscillating sheetflow. This interaction between sand grains has been investigated qualitatively in a pulsating water tunnel. Furthermore, experiments concerning the interaction between neutrally buoyant spheres in a Couette flow have been carried out at a scale of 100:1 in a new developed ring shear apparatus, called " Carrousel."
With respect to the dynamics of sheetflow, in-situ measuring devices for the sand concentration in the sheetflow ("Harp") and the bed load ("Swan") has been developed; some preliminary results are shown.
For sand grains, the intrusion depth of sheetflow appears to be of the order of several mm. On high speed video recordings no lateral mixing between grain layers can be observed; for this some physical explanation is given. This supports the modelling of the sheetflow mechanism as moving grain layers.

1. INTRODUCTION.

For a good understanding of coastal behaviour and for accurate coastal field models, knowledge about sheetflow is indispensable.
From theoretical investigations (for instance Lofquist (1978), Mogridge (1972), Nielsen (1979) and Van Kesteren (1982)) and from visual observations from Dingler and Inman (1976) the impression arises that for normal beach sands ($D_{50} \cong 200$ μm) sheetflow occurs, when orbital velocities surpass an order of magnitude of 1 m/s. Fig. 1 shows visual observations of Yu (1987) made along the Dutch coast.
The impression exists, that generally sheetflow occurs at the seaward side of breaker bars and in the uprush zone.

This paper contains more a progress report on sheetflow studies than clear-cut solutions. It has to be seen in the context with former papers on the same subject (Bakker and Van Kesteren (1986) and (1987)) and with papers on near-bottom velocities (Bakker and Van Doorn (1978) and Van

[1]) Coastal Specialist, Tidal Waters Department Rijkswaterstaat; Principal Scientific Officer Delft University of Technology. Delft, The Netherlands.
[2]) Project Engineer Delft Hydraulics.
[3]) Researcher Forschungsstelle Küste Norderney.

Kesteren and Bakker (1984)), which finally are due to merge into an integrated model for the sediment transport under sheetflow conditions. The recent research is concentrated on two subjects, which are considered the main bottle-necks with respect to the solution of the sheetflow problem: the transmission of the shear stress from the turbulent boundary water layer to the sheetflow (treated in a preliminary way in Bakker and Van Kesteren (1987)) and grain-grain interaction, which is the subject of the present paper.
First the preliminary results of new laboratory experiments in the Large Pulsating Water Tunnel of Delft Hydraulics (ch. 2.1) and in the Carrousel of Delft University of Technology (ch. 2.2) are presented, as well as the results of some measurements in nature (ch. 2.3).
Furthermore, some theoretical considerations with respect to the importance of lift forces on grains in a high concentrated granular shear flow are given (ch. 3).
Chapter 4 gives the conclusions.

2. EXPERIMENTS.

2.1. PULSATING WATER TUNNEL.

In order to observe the sheetflowmechanism into detail some tests on sand with a mean diameter of 220 μm were performed in the Large Pulsating Watertunnel of Delft Hydraulics. The occurrence of sheetflow was observed in a harmonically oscillating flow with a period of 6 s and a maximum velocity of 1.6 m/s.
The behaviour of the sand near and in the bed was recorded with high-speed video (200 and 400 frames/s) (see photo 1). The camera was focussed on an area of 5x7 mm and 10x14 mm respectively. Although the velocities within this area exceeded 1 m/s the position of the top and bottom of the sheetflowlayer remained constant within a range of only a few grain diameters.
Fig. 2 shows an example of particle velocities within an area of 10x14 mm; the velocities are obtained from two sequential frames (time interval 5 ms) using the frame-freezing and overlay technique of the high-speed video equipment. Fig. 3 shows velocity distributions measured in this way at 6 equal time intervals of 1/10 of the wave period.
When the velocity distributions are compared with the velocity just outside the turbulent boundary layer (arrows in top of fig. 3) a very significant phase lag of more than 45 dgr. can be observed. This is consonant with the phaselag between shear stresses and velocities in the turbulent boundary layer (see Bakker and Van Kesteren (1986) and Horikawa et al. (1982)).
In fig. 4 the intrusion depth (i.e. the depth of the point of zero velocity) during half a wave period is shown. The maximum depth occurred before the time of maximum velocity outside the turbulent boundary layer (t=.2T). A phase lag of the same order was found by Horikawa et al. (1982).

The observations revealed the following important features of the sheetflow mechanism:

* No lateral mixing can be observed, even at high shear-rates (500 s^{-1}); this supports the modelling the sheetflow mechanism as moving grainlayers.
* As the name of the flow already indicates, the subsequent erosion of grain layers occurs in the way of the mobilisation of sheets of the paperfile in a foto-copier.

* The deposition of moving grains at the time of current reversal occurred uniformly in horizontal direction in a very short time (10 - 20 ms); because of the high concentration settlement can occur without much vertical motion.
* All over the wave period but especially at the time of current reversal a density wave within the sheetflow layer can be observed. These waves might indicate that, in accordance with Bakker and Van Kesteren (1986), the transfer and dissipation of the turbulent shear stress in the sheetflowlayer takes place by the means of viscous waves generated by the turbulent pressure wave caused by burst-fenomena in the boundary layer acting on the top of the sheetflow-layer.

2.2. CARROUSEL.

At the Delft University of Technology the grain - grain interaction is investigated by using a grain ring shear apparatus called Carrousel.
Fig. 5 shows a plan view; photo 2 shows the set-up.
In the annular space between two concentric cylindrical walls (ϕ = 1062 mm. resp. ϕ = 1198 mm.) and a bottom and a top ring, a mixture of polypropene spheres (ϕ=14 mm, ρ=870 kg/m^3), immersed in oil with the same density is contained. The viscosity of the oil is 10^{-4} m^2/s at 18^{0}C. The top ring can be adjusted with respect to its height. Four rings of half spheres are glued on both rings in a regular pattern (vide photo 3)
This mixture is sheared by rotating the top ring with velocities up to 4 m/s while the bottom ring is fixed.
Fig. 5b shows the way of measuring the forces on the bottom ring with 3 "gallow"-shaped metal bearings, provided with strain gauges.
Thus grain-grain interaction can be investigated at a scale 100:1.
The apparatus is in the stage of calibration; some first results are shown in photo 4a,b,c, which will be discussed in ch.3 .

2.3. MEASUREMENTS IN NATURE.

In cooperation with the Forschungsstelle Küste at Norderney (Dr.H.Niemeyer) a measurement project "Lohengrin" has started, involving the development of two measuring instruments, a "Harp" and a "Swan".
The Swan (vide photo 5) is dug into the sand (fig. 6) only its tail and neck rise above.
It feeds itself through its tail; the sediment comes to rest in its body and the water is discharged through its beak; the amount of it is measured with a flow meter (e).
When the current reverses, a repercussion valve (f) in the beak hinders an internal flow reversal.
Distance between tail and beak is so designed, that the own frequency of the water in the instrument allows an equal velocity in the extrance as in the sheetflow layer. The height of the opening in the tail can be adjusted; normally it is 12 mm. Also the height of the tail itself can be adjusted by a diver; it is essential, that it remains on the same level as the sand bottom.
Up to now, average concentrations over a height of 12 mm of 4 to 34 gr/l were measured (Yu (1987)). However, still more calibration should be done.
A very simple prototype of this instrument has been developed in 1983 by the first author and prof. dr.H.Krock of the Look Laboratory in Hawaii; since then it has been tested and developed by the third auther along

Dutch beaches and in the laboratory for Fluid Mechanics of Delft University of Technology (Yu (1987)) and, at present, in Norderney.

A second instrument in developing stage, to be tested at the Forschungsstelle Küste, is the Harp.
It consists of 3 concentration probes, sensoring at a different level in the sheetflow (fig. 7). The probes are mounted in upward direction on a lower bar under the sand, which is connected to a frame, consisting of 2 poles driven into the beach sand and an upperbar between. The whole lower bar can be lifted, as it is connected with screws to the upper bar of the frame.
The concentration probes consist each of 4 electrodes of 1 mm. protruding from a probe head of 10 x 2 mm (fig. 8). A 2 kHz AC is generated between the outer electrodes and the voltage difference (electral resistance) between the inner electrodes is measured.
Fig. 9 gives the calibration curve between the relative resistance and the volumetric concentration (from Mastbergen and Bezuijen (1988)).
Fig.10a,b shows the situation in Norderney where the instruments are tested, in the swash zone between the groyne fields D and E.
Up to present, no three-level measurements are available; fig.11 and 12 show measurements resulting from 1 sensor.
In fig.11 showing concentration versus time, one probe is driven into the bottom, thus giving a concentration of about 50%, but still reacting on the waves. At arrow "A" the probe is lifted over 2 mm. The lifting causes a hole (lower concentration) which fills up quickly again. After some waves the whole bottom lowers obviously, thus causing a low concentration at the instrument. Now wave motion causes an increase in concentration.
After ca. 15 seconds the old situation is restored, more or less and later on again the concentration decreases. Lifting the probe again 2 mm (arrow B) leads to analogeous results, however now with a lower mean concentration. The next lifting of the probe (arrow C) brings it out of the sheetflow area. Now only accidently high concentrations occur.
The local range of the sheetflow layer (from maximum concentration up to suspended load concentrations) thus shows to be of the order of 6 mm.
Fig.12 shows an interrelation between sheetflow concentration and orbital velocities measured ca. 20 cm. above the bottom. Here the probe is kept stationary at a rather high level.
There is shown respectively: the concentration, the cross-shore and longshore component of an electromagnetic current meter and the wave height, measured with a pressure meter. Averaged concentrations of about 3% are found.

3. THEORETICAL ASPECTS.

Little grains love physical law and order. This is confirmed by observations during preliminary tests in the grain Carrousel (photo 4a,b,c). When the distance between the upper and bottom ring is decreased, the neutrally buoyant spheres do not only center themselves between the rings, but also show a preference for equally mutual distance and for the same orbit, situated halfway the outer ring of spheres glued on the steel rings and the adjacent ring of spheres.
Sometimes a rebel grain, deviating too much from neutral buoyancy, disturbes the order causing some rattling in the Carrousel, but mostly the order is restored quickly.
The number of 'free' grains in the tests was half the number of glued grains on one ring.

Experimentally and theoretically, the centering force has been investigated by quite a school of investigators, from which will be mentioned : Halow and Wills (1970), Vasseur and Cox (1976) and Ho and Leal (1974).
The last two papers deal with theory concerning a neutrally buoyant sphere in a Couette flow between two (flat) plates. The first one gives as well theory as experimental results concerning radial migration of a sphere in the annular region between two concentric cylinders, of which the outer one was in rest and the inner one was rotating. The theoretical considerations of the last two papers seem more adequate than the ones of Halow and Wills (1970), as a confined space is considered, where Halow and Wills use Saffman's theory (1965), valid for Couette flow in an unconfined space.
From Vasseur and Cox (1976) a velocity $\dot{x}$ of a neutrally buoyant sphere in the vicinity of the central position can be derived, equal to:

$$\dot{x} = - \frac{x\, r^3\, S^2}{3.5\, h\, \nu} \qquad (1)$$

where x is the deviation from the central position, h is the distance between the plates, r is the radius of the sphere, S is the vertical velocity gradient and ν is the kinematic viscosity of the fluid.
Reading (1) as a differential equation (neglecting the inertia of the grain itself), one finds for the 'neperian' time T_e, in which the distance to the central position reduces with a factor e:

$$T_e = 3.5 \frac{h\, \nu}{r^3\, S^2} \qquad (2)$$

Neperian times T_e of 4 and 9500 s, found in this way for two experiments of Halow and Wills (1970), (their fig. 4 and 5) are not inconsistent with their results. For the Carrousel experiments neperian times of 0.3 s or less are found.
For natural grains (for instance a velocity gradient $S = \Delta u/\Delta z = 100\ s^{-1}$ (velocity difference Δu of 0.5 m/s over a layer thickness Δz of 0.05 m); $r = 10^{-4}$ m, $h/r = 4$, $\nu = 10^{-6}$ m^2/s one finds $T_e = 0.14$ s.
Deriving the maximum lift velocity from Vasseur and Cox (1976) and using (1) one finds the order of magnitude of 1 mm/s, i.e. small with respect to the unhindered settling velocity of grains, but essential when using mechanism, exposed in by Bakker and Van Kesteren (1986).
However, the self-centering capacity of grains did not show to be so dominant, that a total layer of grains in the Carrousel pops into position (i.e. in an experiment similar to that shown in photo 6, but with a higher concentration of grains).
The reason for this (too much density differences?) is subject of future research.

4. CONCLUSIONS.

As well in the field as in the laboratory (Pulsating Water Tunnel) the result of Horikawa et al. (1982), that the intrusion depth of sheetflow is of the order of several mm has been confirmed.

High Speed Video recording reveals that layers of grains shear with respect to each other, without lateral mixing. Theoretically, shearing grain layers in a viscous medium should show the tendency to centering themselves with respect to adjacent layers. This effect is also observed

in tests with neutrally-buoyant grains sheared in a ring shear apparatus (Carrousel). This self centering effect can be explained by lift forces caused by inertia of the fluid surrounding the grains.

ACKNOWLEDGMENTS.

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The Carrousel would never have delivered results without the designing of ir. H. Havinga, the construction by mr. Groeneveld and the experiments carried out by mr. W. Klomp (all Delft University of Technology).
Hi-Speed video was made possible by courtesy of mr. Reinders of Reinka B.V.

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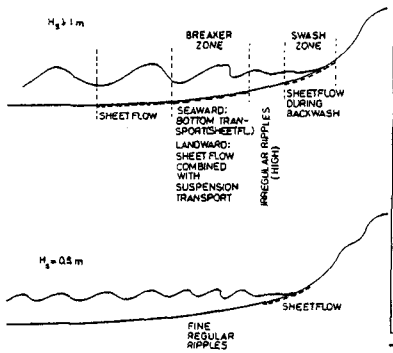


Fig. 1
Visual observations concerning sandtransport mechanisms along Dutch coast.

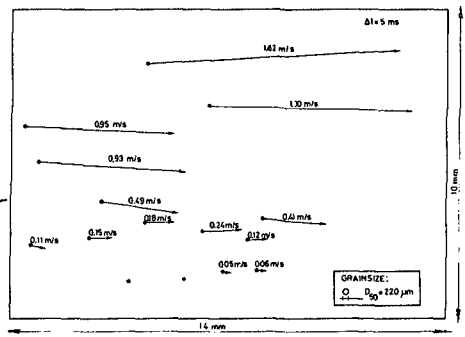


Fig. 2
Particle velocities within sheetflow layer measured in the the Delft Hydraulics Pulsating Water Tunnel

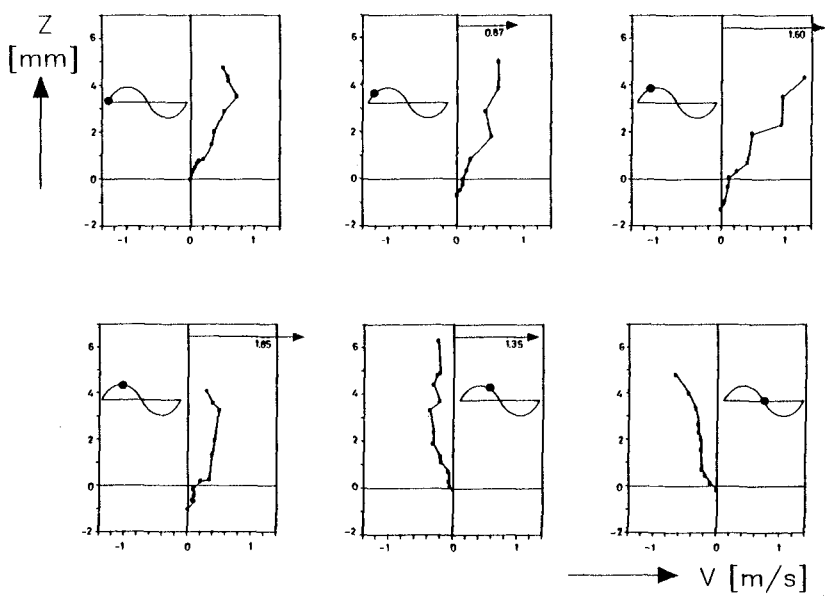


Fig. 3 Velocity distributions in sheetflow layer at 6 successive times (arrows indicate water velocities, measured above the boundary layer).

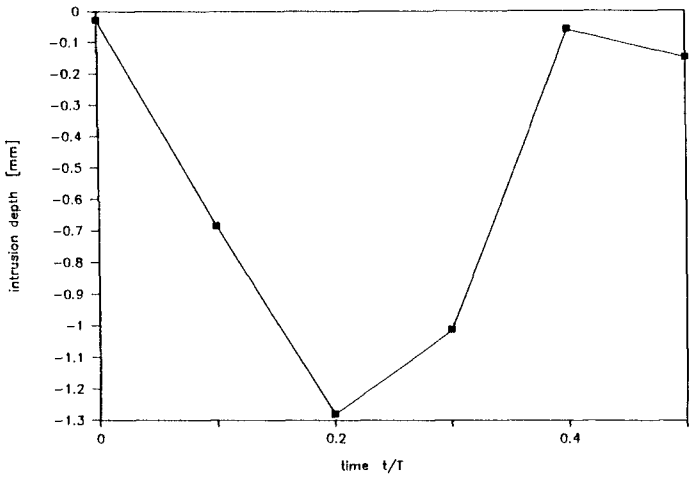


Fig. 4 Intrusion depth as function of time.

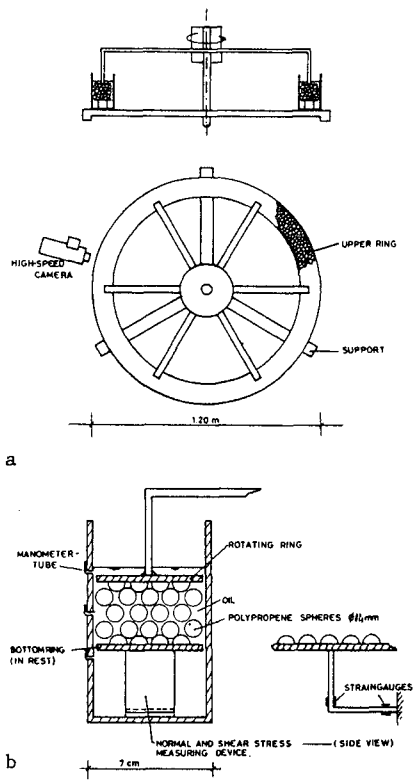


Fig. 5
Carrousel; a) cross-section and top-view, b) detail cross-section.

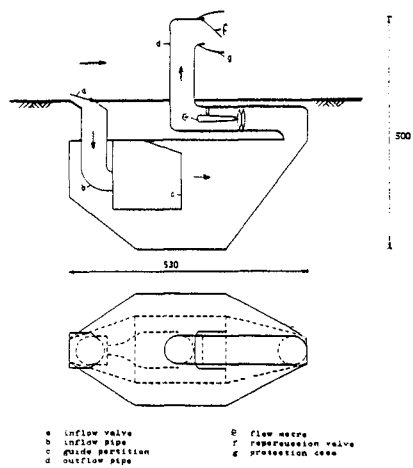
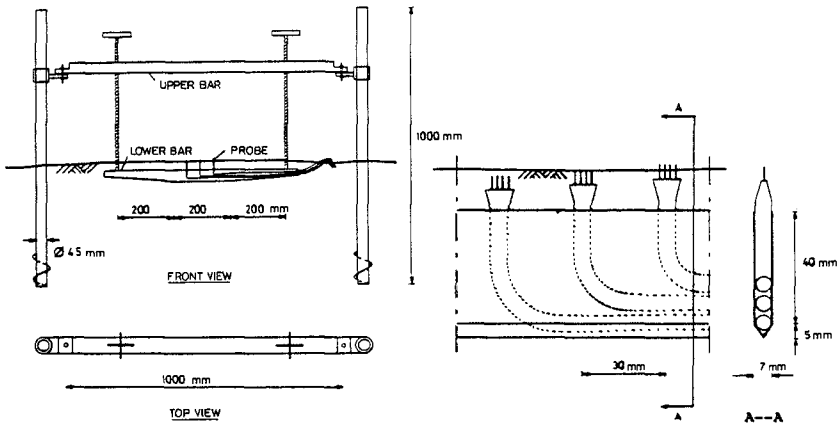


Fig. 6
Cross-section Swan.



a b

Fig. 7 The "Harp"; a) front- and top-view, b) detail position probes on lower bar.

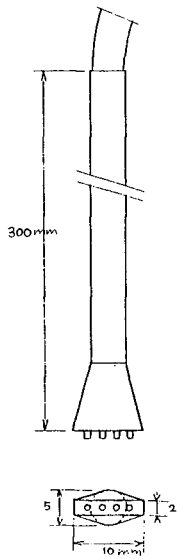


Fig. 8
Detail probe used in "Harp" (electrical conductivity meter, developed by Delft Hydraulics).

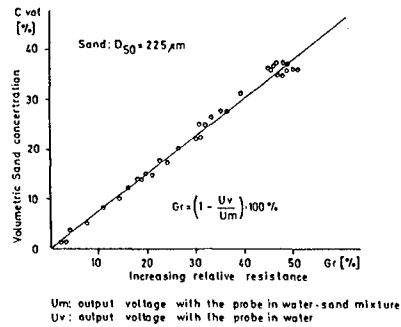
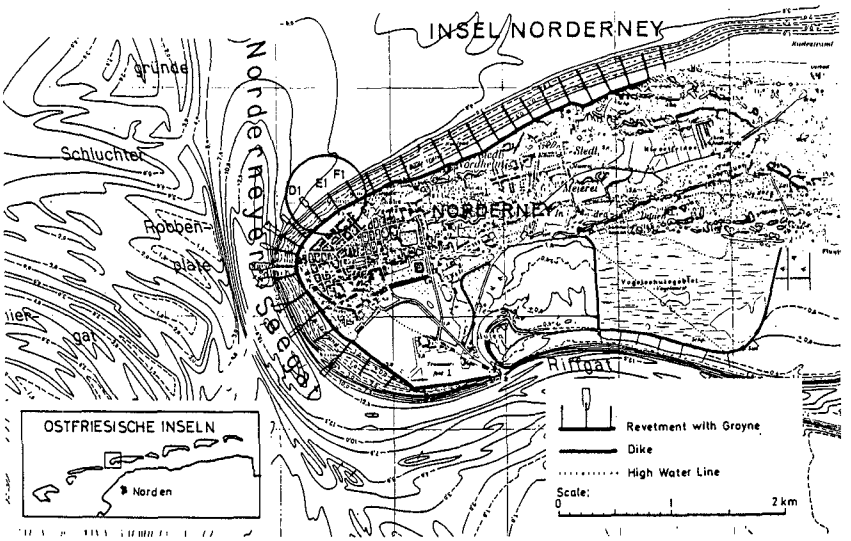
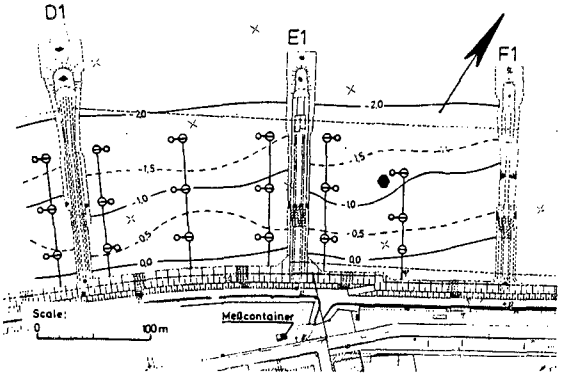


Fig. 9
Relation between measured increase of relative resistance and volumetric concentration.



a



b

Fig.10 Measuring site of the Forschungsstelle Küste at Norderney.

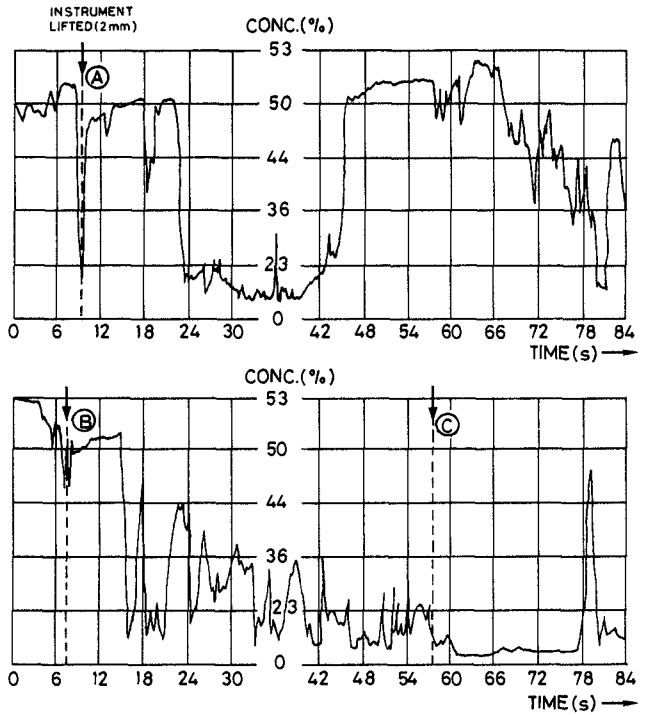


Fig.11 Concentration measurement Norderney, 11 december 1987 (swash zone).

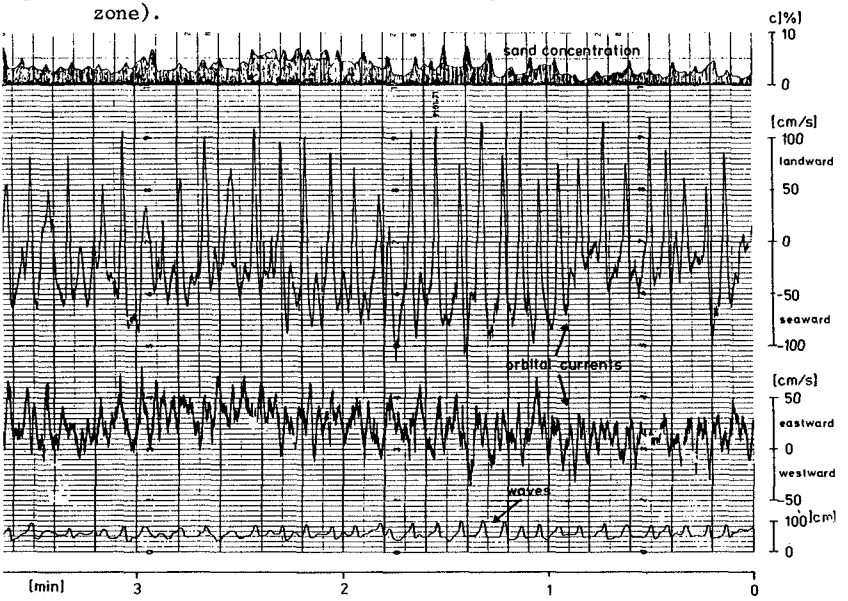


Fig.12 Concentration measurement Norderney, 16 june 1988 (waterdepth ≅ 1.2 m.)

Photo 1 Set-up High Speed Video at Delft Hydraulics Pulsating Water Tunnel.

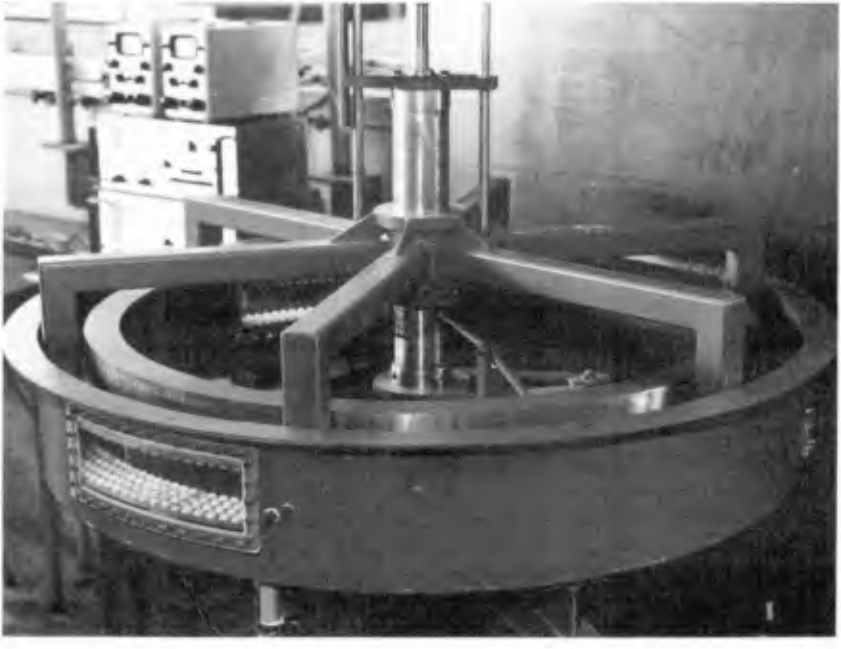


Photo 2 Set-up grain ring shear apparatus "Carrousel".

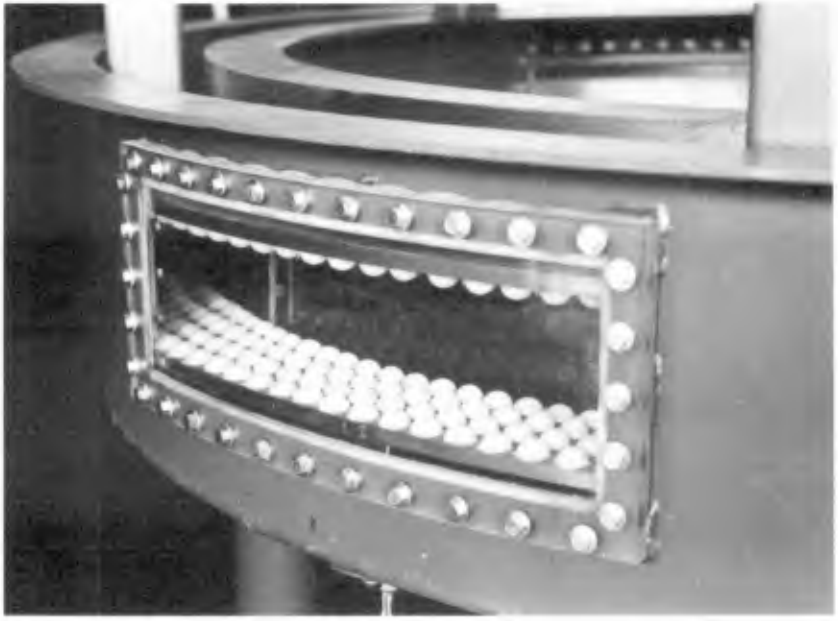


Photo 3 Detail Carrousel: 4 rings of half spheres are glued on the top and bottom ring.

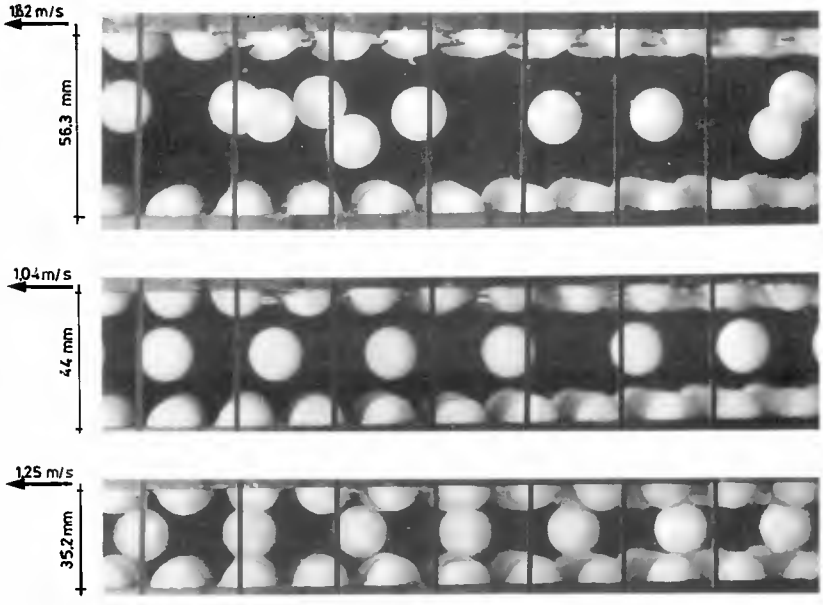


Photo 4 Neutrally buoyant spheres in Couette-flow in the Carrousel showing self-centering capacity.

Photo 5 Swan.