CHAPTER 68

SAND TRANSPORT BY WAVES

by

E.W. Bijker*), E. van Hijum**) and P. Vellinga***)

1 Summary

Sand transport parallel to the direction of wave propagation by waves of arbitrary form over a rippled bed has been investigated in a flume, at the Laboratory of Fluid Mechanics of the Dept. of Civ. Eng. of the Delft Univ. of Techn. The transport has been measured by means of a special procedure which does not disturb the process. The measured sand transport is related to the measured wave form parameters. The results indicate that the direction of net sand transport depends upon the form of the waves.

2 Introduction

This study has been carried out with the aim to understand the onshore and offshore movement of sand which determines the development of beach profiles. From movable bed model tests it has become clear that beach profile formation may be severly affected by secondary waves which, together with the primary wave always originate from a sinusoïdally moving wave-board. Even a hardly measurable second harmonic free wave can cause bar formation over a horizontal bottom. Since secondary waves are present in nature the study of the effect is of great interest in the understanding of beach profile development.

3 Description of the tests

To obtain insight into the transport phenomenon 27 tests have been conducted in a flume (see Fig. 1) with a horizontal sand bed with a mean particle diameter of 250 µm with different combinations of water depths, wave periods and wave heights as shown in Table 1. The Ursell parameter ($Ur = HL^2/d^3$) ranged from 12 to 57. Since the presence of secondary waves results in a spatially varying wave form, the wave form parameters and the resulting sand transport have been measured at 0.50 m intervals along the flume.

*) Professor of Coastal Engineering, Delft University of Technology, Department of Civil Engineering, The Netherlands.

**) Project Engineer, Maritime Structures Branch, Delft Hydraulics Laboratory, Laboratory de Voorst, The Netherlands.

***) Project Engineer, Harbours and Coasts Branch, Delft Hydraulics Laboratory, Laboratory de Voorst, The Netherlands.

water depth	d	m	0.20	0.25	0.30
wave period	T	sec	1.50	1.70	1.90
relative wave height	Hd^{-1}	-	0.2	0.3	0.4

Table 1

4 Measuring procedure

It is very difficult to measure sand transport under undisturbed conditions. The use of sandtraps usually causes such a discontinuity that the upwave as well as the downwave sandtrap is filled with sediment. An uncovered part in the flume bottom however causes hardly any discontinuity and creates an excellent boundary condition for the balance of sand volume (see Fig. 1).

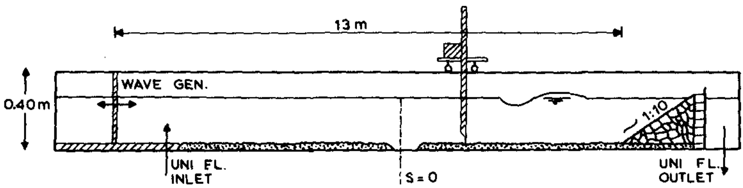


Fig. 1 A schematic illustration of the model

An electronic bottom-profile indicator together with a recorder was used to measure the bottom profile along the flume. By integrating the measured profiles before and after the test, the sediment transport through any cross-section is known. The essence of this procedure is that it is assumed that the transport across the uncovered part is zero. To eliminate the initial effects, the t - 0 measurements were done only after ripples of the equilibrium form were developed. Also the tests were finished before any secondary interaction processes influenced the results: disturbing processes may originate from the discontinuity at the uncovered part, while also bottom deformation may cause interaction effects on the wave parameters. Taking this into account, it was decided to use test durations between 20 and 60 minutes, depending on the transport intensity. During this period usually bottom elevation variations of the order of 1 mm had occurred. The accuracy of the measuring procedure is of the order of 0.1 mm.

As the bottom profile measurement was done along the length of the flume and as the width of the flume was 0.50 m, the bottom profile was measured along the center line and the quarter lines and the volume change between two cross-sections was found by taking the average of the three quantities.

The sand transport rate was computed at intervals of 0.50 m. At the same cross-sections the wave parameters were measured: the velocity profile was measured with a micro propellor 1/3 d above the bottom, d being the waterdepth, and the wave heights were measured using a resistance type wave gauge.

During the analyses of the test results, only the velocity profile was used when relating the wave parameters to the resulting sand transport, because for sand transport, the velocity profile is of more direct interest than the surface wave form, especially since in latter tests a uniform current was superimposed on the oscillatory motion. Furthermore with waves only the form of the velocity profile is about the same as the form of the wave.

During the analyses no specific attention has been paid to the ripple pattern since the aim of the study is to find a relation between the wave parameters and the resulting transport; the ripple pattern is not an independent variable in this relation and as such not of direct interest in finding this relation. However, the ripple patterns were measured to enable comparisons with other experiments to be carried out on a different scale.

5 Test results

As described by Hulsbergen [1] and Buhr Hansen [2] the wave form varies along the length of the flume. When the velocity variation is analysed in harmonic components it appears that the variation is repititive in the same form at certain distance intervals. The distance is equal to the distance which is required for the primary wave (period T) to overtake the secondary wave (period T/2). The repetition especially appears in the variation of the second harmonic component (see Fig. 2). To see how this overtake length is related to the measured overtake length by Hulsbergen [1] and the theoretical overtake length according to Miche, the distance between two places where the second harmonic component $\hat{u}_2$ reaches it's maximum (L_{ov-2}) is plotted against the waterdepth (see Fig. 3).

Because of the similarity it may be assumed that the wave form variation in these tests agrees with the theory as described by Hulsbergen [1] and Buhr Hansen [2]. According to Hulsbergen [1] one may separate the $\hat{u}_2$ component into a contribution from the second order Stokes wave and a contribution from the secondary wave. These contributions can be found by taking the average of $\hat{u}_2$ over an overtake length as the $\hat{u}_{2-stokes}$ and the amplitude of the variation as the $\hat{u}_{2-fontanet}$ (see Fig. 2).

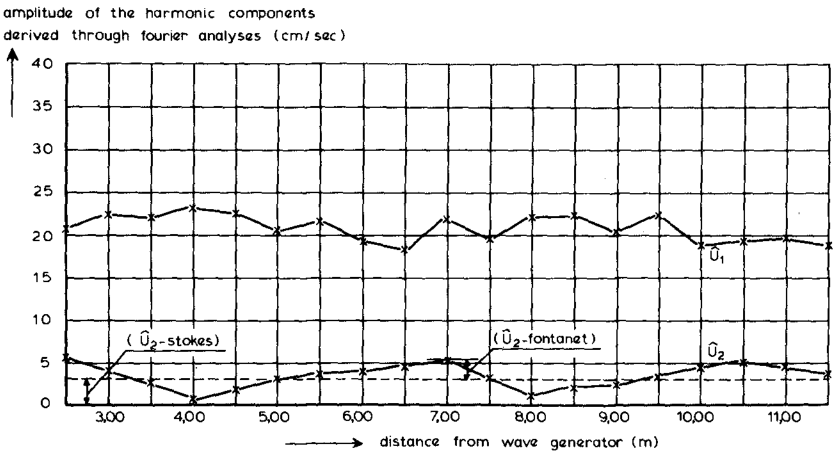


Fig. 2 Variation of the amplitudes of the harmonic components of the orbital velocity with the distance from the wave generator (T = 1.70 sec, d = 0.30 m, Hd^{-1} = 0.3)

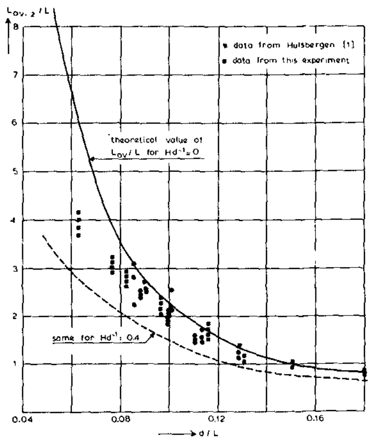


Fig. 3 Dimensionless overtake length

Sand transport variation

From the experiments it is clear that the sand transport varies with the distance from the wave generator. Along the length of the flume sand transport in the direction of wave propagation alternates with sand transport opposite to the direction of wave propagation. For further analyses the sand transport along the flume is divided into the average $\bar{S}$ and the amplitude of the variation $\hat{S}$ (see Fig. 4).

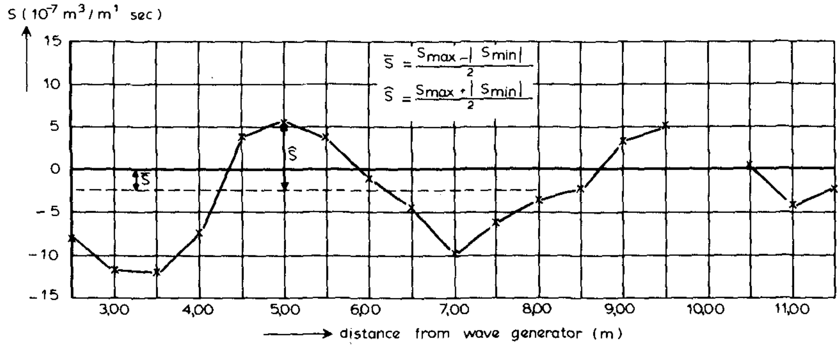


Fig. 4 Variation of the sand transport with the distance from the wave generator

Relation between sand transport variation and wave form variation

To demonstrate that the variation of the sand transport corresponds with the behaviour of secondary waves, the overtake length (L_{ov-2}) is plotted against the distance over which the variation in sand transport is repeated (see Fig. 5). From this figure it is clear that the distances are about equal, hence it may be concluded that the variation in sand transport is caused by the occurrance of secondary waves.

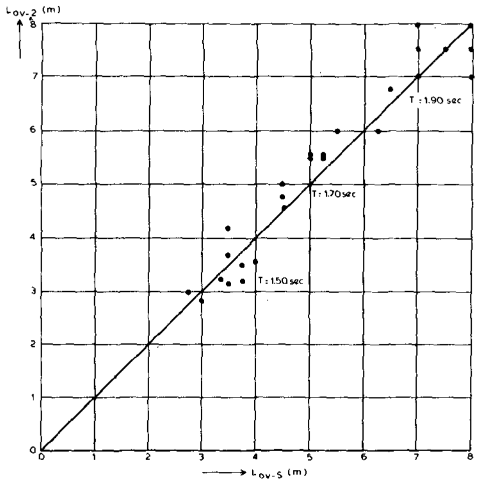


Fig. 5 Overtake length of the secondary wave against the repetition distance of the sand transport variation

6 Analyses of the results

Mechanism of sand transport by waves

The sediment movement under a wave can be described as follows (see Fig. 6): a vortex is generated behind the ripple crest at t_1. From t_1 to t_2 this vortex is filled with sediment. At t_3 the sediment of this vortex is brought into suspension and is carried backwards by the negative orbital velocity to the preceding ripples. At t_3 at the other side of the ripple crest, a new vortex is formed. At t_5 the sediment of this vortex is brought into suspension and is carried forwards by the positive orbital velocity, etc.

This way a big quantity of sand is in oscillatory motion. A resulting transport can be caused by a small asymmetry in the orbital motion.
In further analyses the following assumptions have been made:

- the quantity of sand moving back and forth under oscillatory motion is proportional to $\hat{u}_1^2$.
- the difference between the two quantities is proportional to $\hat{u}_2$.
- the resulting sand transport is related to the product of $\hat{u}_1^2$ and $\hat{u}_2$.

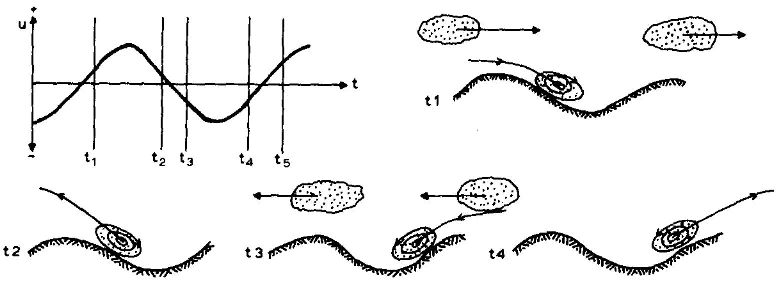


Fig. 6 Sand movement over sand ripples

Relating sand transport to the second harmonic component of the velocity profile

Fourier analyses of the velocity profile shows that the value of the second harmonic component varies with the distance from the wave board. This variation can be described by the average and the amplitude of the variation. Also the sand transport variation with the distance from the wave board can be described by the average and the amplitude of the variation. Now the averages and the amplitudes can be compared.

In Fig. 7 the average sand transport $\bar{S}$ has been plotted against $\hat{u}_1^2 \cdot \hat{u}_{2\text{-stokes}}$ From this figure it is clear that the average sand transport under these test conditions is in all cases opposite to the direction of wave propagation and that there exists a rather consistent relationship with $\hat{u}_1^2 \cdot \hat{u}_{2\text{-stokes}}$. From this it may be assumed that a wave which can be described by second order Stokes theory causes a sand transport opposite to the direction of wave propagation and that the size of the transport can be described by an equation of the type

$$S = c_1 \hat{u}_1^2 \cdot \hat{u}_{2\text{-stokes}} + c_2$$

In Fig. 8 the variation of the sand transport has been plotted against $\hat{u}_1^2 \cdot \hat{u}_{2\text{-fontanet}}$. From this figure it is clear that a straight line with an equation of the type

$$\hat{S} = q_1 \hat{u}_1^2 \cdot \hat{u}_{2\text{-fontanet}} + q_2$$

may be fitted reasonably well through the plotted points.

Although in these comparisons the wave period has not been included it is shown that the measured results follow a trend which support the validity of the suggested relations.

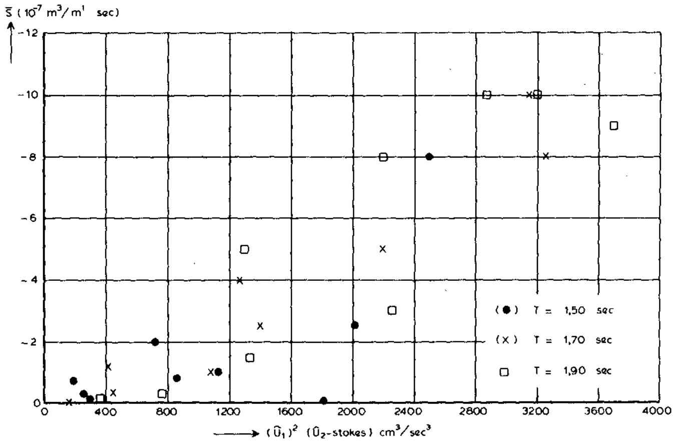


Fig. 7 Average sand transport as a function of wave parameters (negative $\tilde{S}$ corresponds with sand transport opposite to the direction of wave propagation)

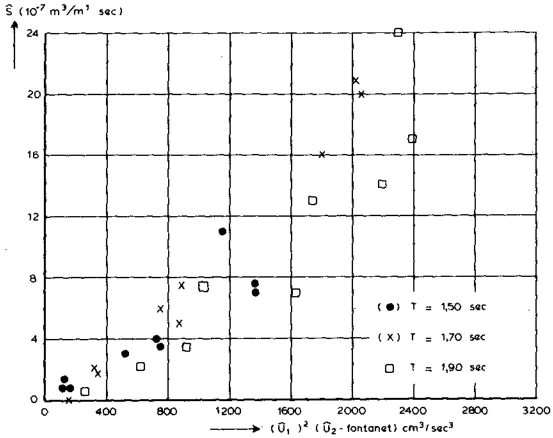
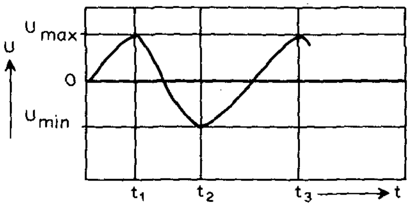


Fig. 8 Variation of sand transport as a function of the variation of wave parameters

A better way of analysing the results, however, is to compare the actual form of the velocity profile with the resulting sand transport. The velocity profile of the two interacting waves is only adequately described by the value of $\hat{u}_1$, $\hat{u}_2$ and the difference in phase between the two. Since this amounts to three variables it makes the physical understanding of the problem more difficult. That is why a small simplification of the velocity profile has been introduced, such that the profile is described by $\hat{u}_1$ and the difference between the acceleration and the deceleration of the fluid particles as defined in Fig. 9.



$$\overline{acc} = \frac{U_{max} + |U_{min}|}{t_3 - t_2}$$

$$\overline{dec} = \frac{U_{max} + |U_{min}|}{t_2 - t_1}$$

Fig. 9 Definition sketch of acceleration ($\overline{acc}$) and deceleration ($\overline{dec}$)

This simplification has been carried out for all the measured velocity profiles, and the difference between the acceleration and the deceleration of the fluid particles has been plotted for all tests as a function of the distance from the wave generator (see Fig. 10). In the tests it is apparent that the variation of the value of the $\overline{acc} - \overline{dec}$ is in phase with the variation of the sand transport along the flume (compare Fig. 4 with Fig. 10).

Now another relationship for the amplitude of sand transport can be tried. Like before $\hat{u}_1^2$ is proportional to the quantities moving back and forth but in this case the resulting transport is caused by the difference between $\overline{acc}$ and $\overline{dec}$. In Fig. 11 the amplitude of the variation in sand transport has been plotted against the amplitude of the variation in $\hat{u}_1^2 \cdot (\overline{acc} - \overline{dec})$. For each wave period the proportionality constant is different. This is understandable from the fact that the simplification does not really hold for the longer periods. The relation for the shorter period: T = 1.50 sec holds very well since the coefficient of linear regression equals 0.995.

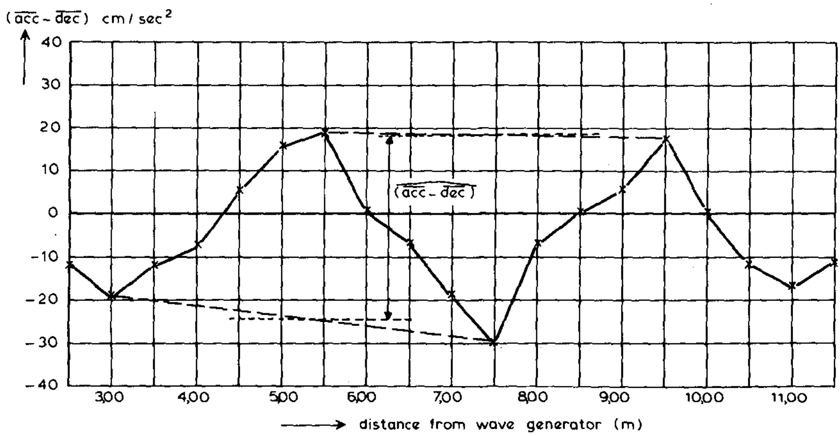


Fig. 10 Variation of the difference between acceleration and deceleration of the fluid particles with the distance from the wave generator ($T = 1.70$ sec, $d = 0.30$, $Hd^{-1} = 0.3$)

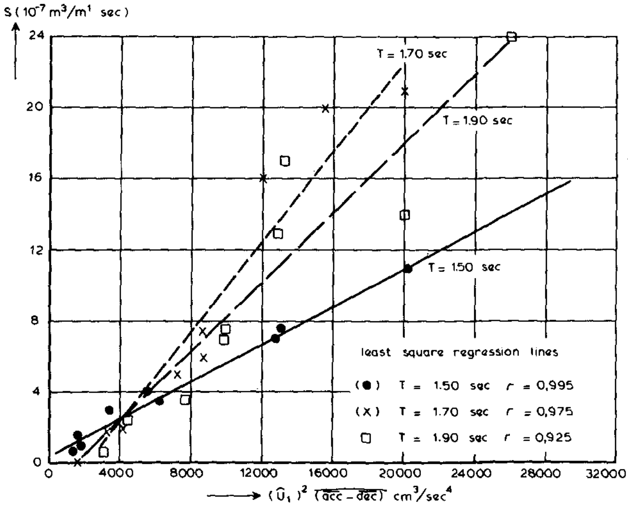


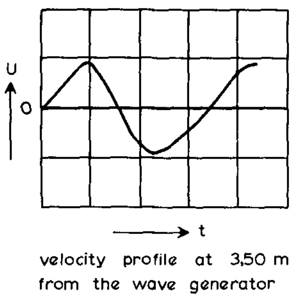
Fig. 11 Amplitude of variation in sand transport against $\hat{u}_1^{\,2}$ times the amplitude of $\overline{acc} - \overline{dec}$

No attempt has been made to develop a relationship between the pertinent dimensionless parameters as the testing range is limited and the process may be different on another scale.

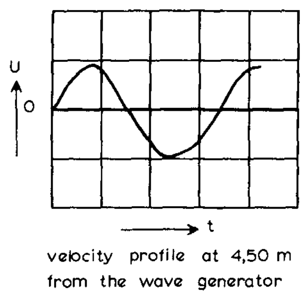
By the simplification of the velocity profile and comparing the result with the sand transport it has been found that there exists a qualitative relationship which holds for all the tests carried out with sand with a mean particle diameter size of 250 μm:

- Sand transport by waves is in the direction of wave propagation when the $\overline{acc}$ is greater than the $\overline{dec}$, and opposite to the direction of wave propagation when the $\overline{dec}$ is greater than the $\overline{acc}$.
- When the $\overline{acc}$ equals the $\overline{dec}$ and there is a second harmonic component present, the sand transport is opposite to the direction of wave propagation.

This phenomenon can be explained as follows: from visual observations it has become clear that the extent of vortex formation is closely related to the acceleration and the deceleration of the fluid particles, so that a small acceleration creates a large vortex whereas by the folowing large deceleration this sand laden vortex is brought up high in suspension and the sand is carried quite far backwards by the orbital velocity so transport opposite to wave propagation will result (see Fig. 12a). In the same way a small deceleration creates a large vortex on the upwave side of the ripple and the following large acceleration lifts the sand laden vortex high in suspension and the sand is carried quite far forwards by the orbital velocity, so transport in the direction of wave propagation will result (see Fig. 12c).



a



b

Fig. 12 a,b Velocity profile along the length of the flume (T = 1.70 sec, d = 0.30 m, Hd^{-1} = 0.3)

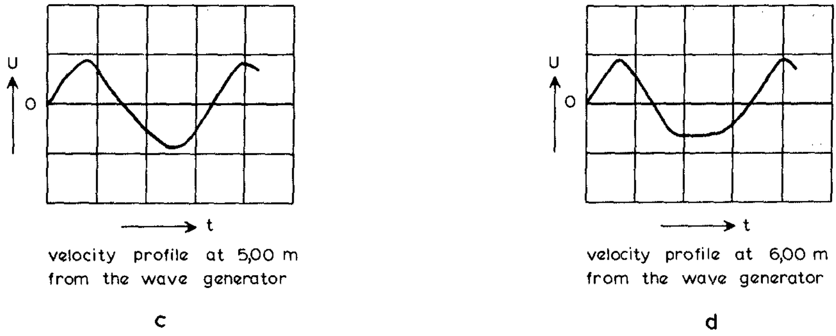


Fig. 12 c,d Velocity profile along the length of the flume (T = 1.70 sec, d = 0.30 m, Hd^{-1} = 0.3)

During tests with standing waves, conducted in the past, it has been possible to observe the vortex formation in photographs. Through this it has been possible to find a certain relationship between the phase of orbital velocity and the development of the vortex (see Fig. 13 and the corresponding photographs). It appears that due to inertial effects vortex formation starts at about $\frac{1}{4}$ T after the zero crossing of the orbital velocity. This means that with a small acceleration the developed vortex reaches its maximum during a high orbital velocity.

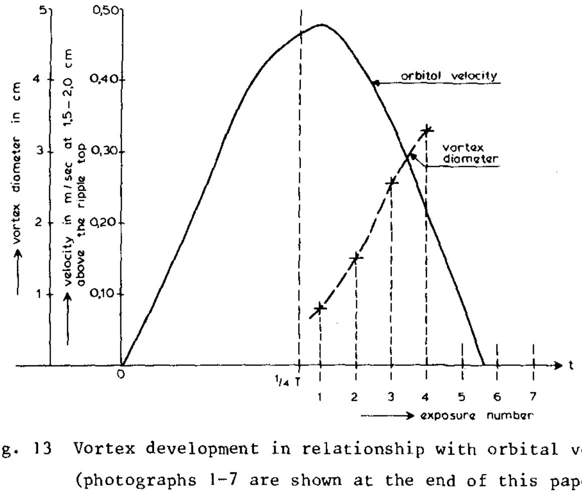


Fig. 13 Vortex development in relationship with orbital velocity (photographs 1-7 are shown at the end of this paper)

7 Sand transport when a small uniform current is superimposed in the direction of wave propagation

Under these circumstances sand transport in the direction of net water transport can be expected. From tests however, it appears that this is not always the case (see Fig. 14). When the uniform flow velocity is zero, the direction of sand transport can be in the direction of wave propagation, as well as opposite to it, depending on the wave form. Under the combined action of waves and current the sand transport can still be opposite to the direction of net water transport.

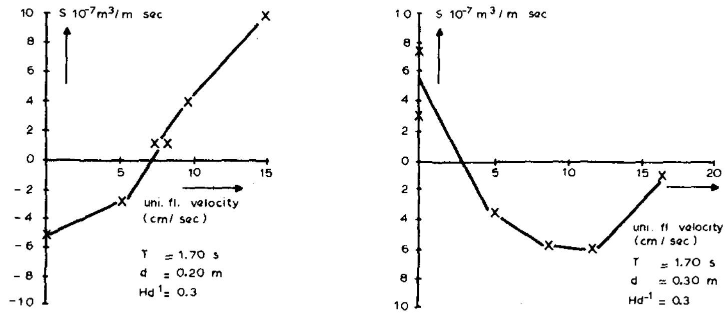


Fig. 14 Sand transport as a function of the velocity of uniform flow superimposed on waves

The explanation for the initial increase of the sediment movement in the direction opposite to wave propagation is the growth of the vortex at the forefront of the ripple, so that more sand is brought into suspension and is carried backwards by the orbital motion. Only with large uniform flow velocities this effect is overruled. Because of this it can be concluded that insight into the vortex formation as a function of wave and flow parameters is essential for the understanding of sand transport caused by waves and currents.

8 Sand transport under standing waves

Under standing waves also it has been found that the direction of sand transport with sand having a mean particle diameter of 250 μm is in the direction corresponding with the largest temporal gradient of orbital velocity [3]. At first the difference in inertial forces on the grains was considered to be the cause of this. However, further tests showed that the difference in vortex formation was more likely to be the cause.
In the test series with standing waves, finer sand (D_m = 150 μm) was also used as bottom material. It was apparent that in this case the direction of sand transport did not agree with the results of the coarser sand. With the finer sand the transport direction was according to the net water transport close to the bottom as described by Longuet Higgins. These results show that two mechanisms of sand transport are present: a first mechanism where sand transport is caused by a small asymmetry in orbital motion and a second mechanism where sand transport is caused by a net water transport. With coarse sands the first mechanism will prevail whereas with finer sands the second mechanism will prevail. When the net water transport is large compared to the orbital velocity, then of course the second mechanism will dominate. The existance of these two mechanisms make it necessary to be very careful in extrapolating data since the domination of a certain mechanism will depend on the scale.

9 Conclusions

- A specially designed procedure for measuring sand transport by waves has given good results. This measuring procedure does not disturb the transport process and very small transports can also be measured.
- Secondary waves which together with the primary wave always originate from a sinusoïdally moving wave board cause a spatially varying sand transport resulting in the formation of bars and troughs. The distance between the generated bars is equal to the distance which is required for the primary wave to overtake the secondary wave.
- In all tests with sand of a mean particle diameter of 250 μm, the average of the sand transport along the flume is opposite to the direction of wave propagation and is proportional to $\hat{u}_1^2 \cdot \hat{u}_{2-stokes}$, whereas the amplitude of the variation in sand transport is proportional to $\hat{u}_1^2 \cdot \hat{u}_{2-fontanet}$, where $\hat{u}_1$ is the first harmonic component of the velocity profile, $\hat{u}_{2-stokes}$ is the spatial average of the second harmonic component and $\hat{u}_{2-fontanet}$ is the amplitude of the variation of the second harmonic component.

- Throughout these tests it has been found that:
  1 sand transport is in the direction of wave propagation when the front of the wave is steeper than the rear face
  2 sand transport is opposite to the direction of wave propagation when the rear face of the wave is steeper then the front.
- With sand transport by waves two mechanisms are present; a first mechanism where sand transport is caused by a small asymmetry in orbital motion and a second mechanism where sand transport is caused by a net water transport.
- One should be aware of the different sand transport mechanisms when extrapolating results from movable bed wave-models since the dominating transport mechanism can be different under different scales. Recent tests with finer sands and propagating waves have already shown that the dominating mechanism with sand with a mean particle diameter (D_m) of 150 μm is different from the dominating mechanism with sand with a D_m of 250 μm.
- The test results can be of significant interest in the explanation of the origination of bars in model as well as in nature.

REFERENCES

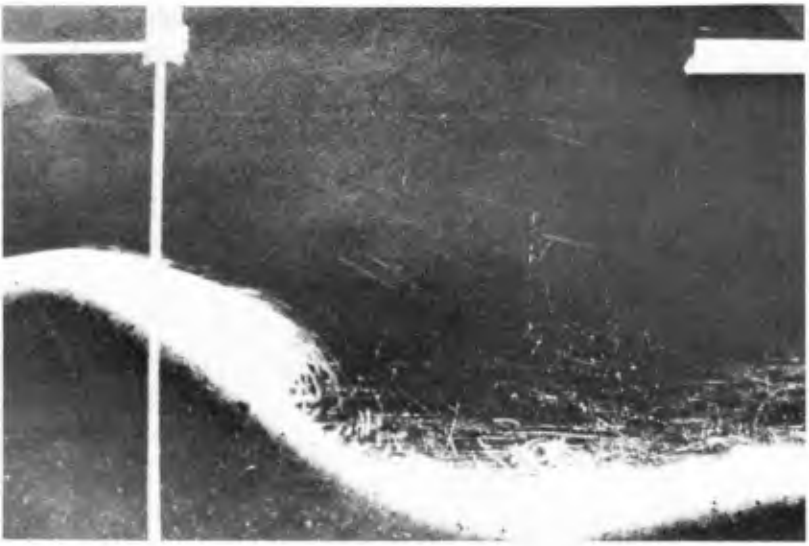
1 HULSBERGEN, C.H.,
14th C.E.C., chapter 22, Origin, effect and suppression of secondary waves, 1974

2 BUHR HANSEN, J. and SVENDSEN, Ib.A.,
14th C.E.C., chapter 17, Laboratory generation of waves of constant form, 1974

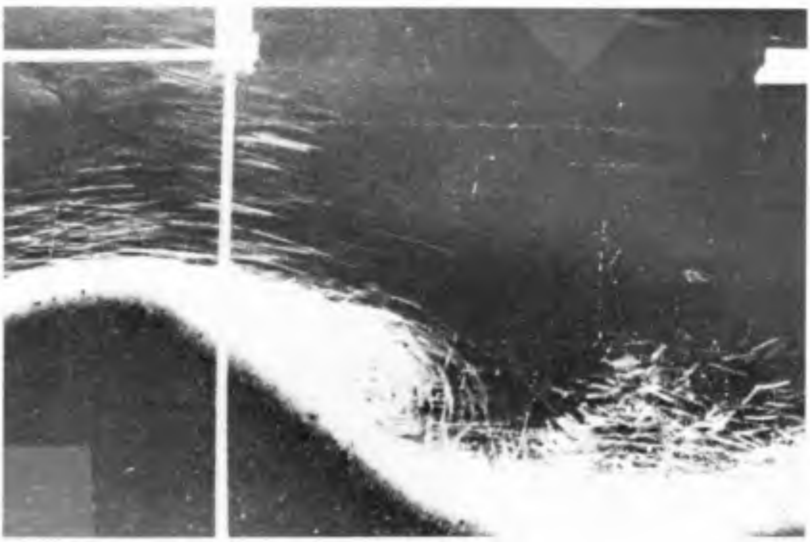
3 BIJKER, E.W. de BEST, A. and WICHERS, J.E.W.,
Proc. 1st Conf. on Port and Ocean Engineering under arctic conditions, vol. 2, pp. 1077-1086, Trondheim, 1971

4 HIJUM, E. van,
Master thesis, Dept. of Civ. Eng., Delft Univ. of Techn., in Dutch, 1972

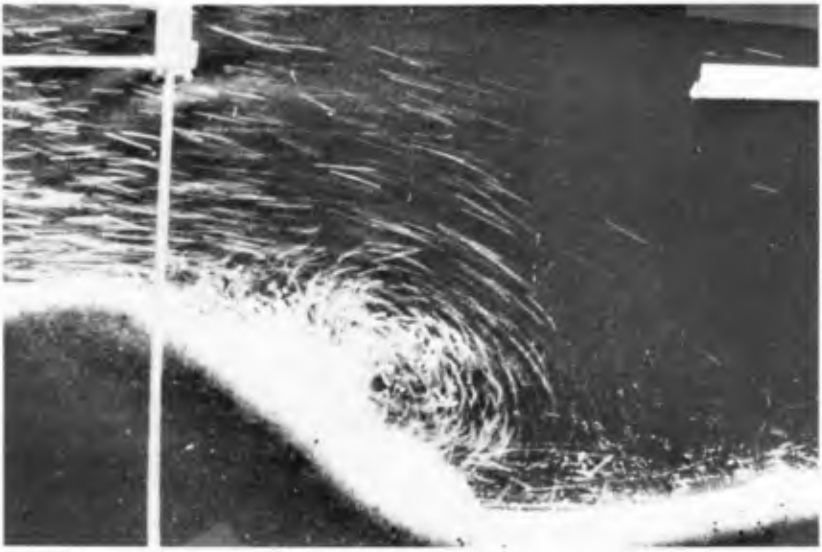
5 VELLINGA, P.,
Master thesis, Dept. of Civ. Eng., Delft Univ. of Techn., in Dutch, 1975



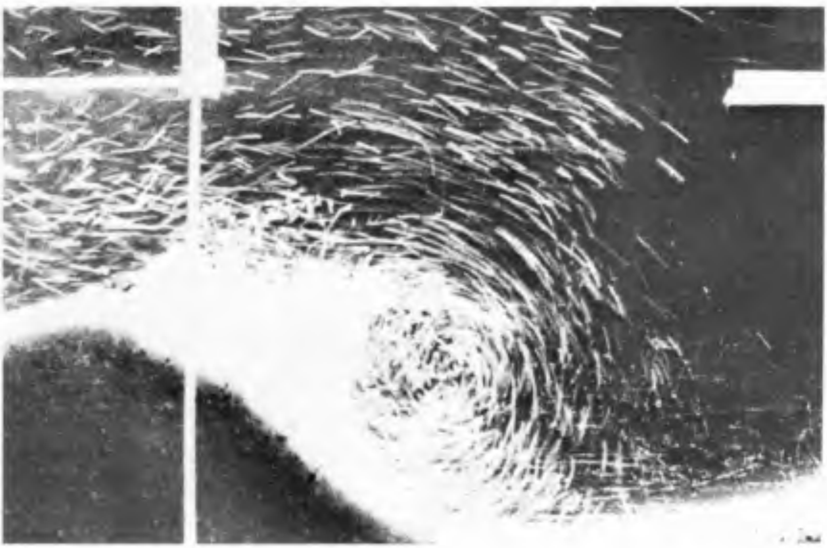
exposure 1



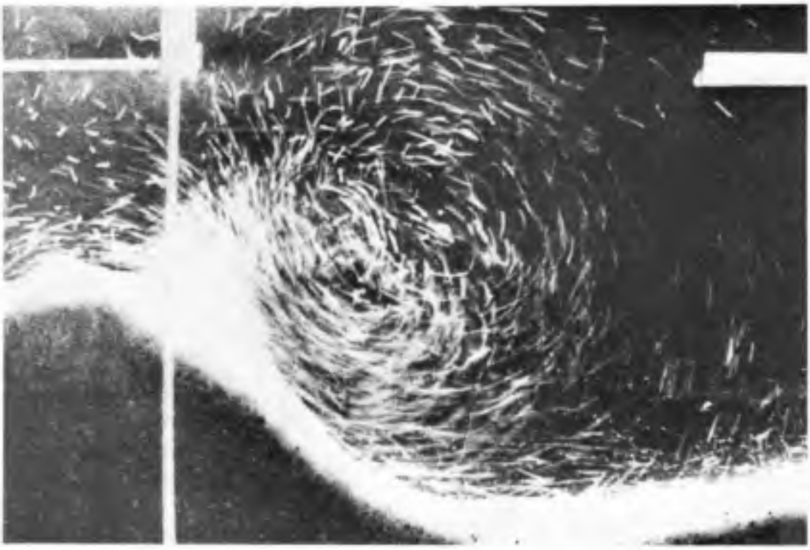
exposure 2



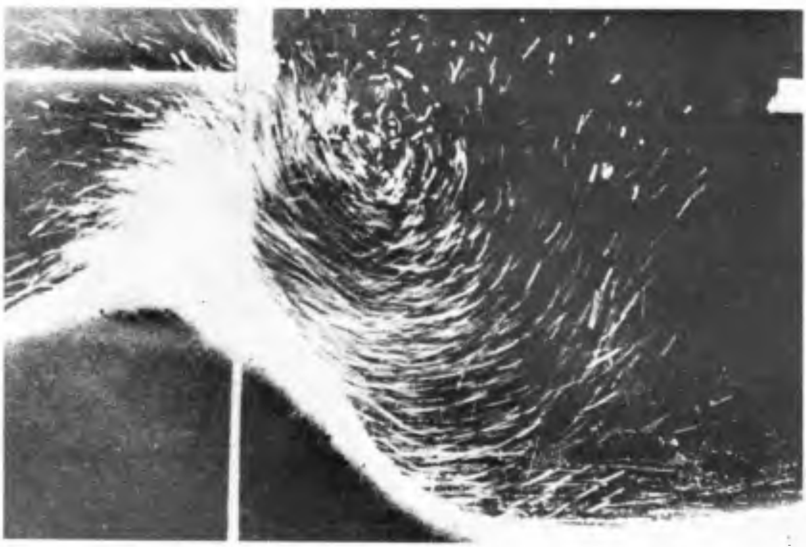
exposure 3



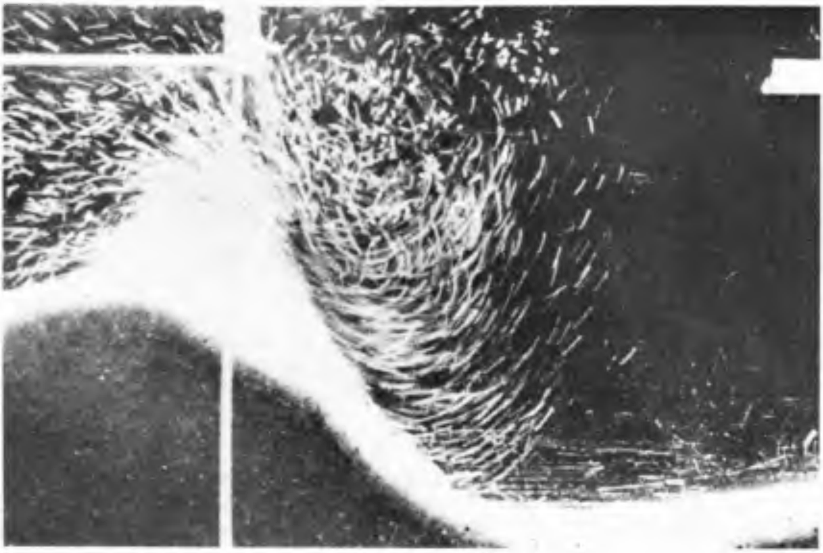
exposure 4



exposure 5



exposure 6



exposure 7