CHAPTER 372

Grain-size influence on sand transport in oscillatory sheet flow

C. Marjolein Janssen[1], Jan S. Ribberink[2]

Abstract

Experimental investigations (Ribberink & Chen, 1993; Ribberink & Al-Salem, 1994; Katopodi et al., 1994) indicated that the grain diameter is an important parameter for the prediction of the *net* (time-averaged) transport rates in oscillatory sheet flow. As only little is known about the influence of the grain diameter on the net transport rates and the transport mechanisms, new experiments with fine sand (D_{50} = 0.13 mm) were carried out in the Large Oscillating Water Tunnel (LOWT) of Delft Hydraulics. Since 1992 the LOWT is equipped with a recirculation system, such that experiments with combined wave-current flow can be performed at full scale (1:1).

Several existing transport models are based on the assumption that the transport can be described in a quasi-steady way (see Janssen, 1995). In order to investigate whether or not this assumption is valid, both a 'quasi-steady' (Bailard, 1981) and a 'semi-unsteady' (Dibajnia & Watanabe, 1992) transport model are verified with existing and new experimental data.

Description of two existing sand transport models

a) Bailard (1981)

The first model described here, is the one developed by Bailard (1981), which is one of the 'quasi-steady' models. These models are based on the assumption that the transport rates under oscillatory flow can be described in a quasi-steady

1) PhD-student, Delft University of Technology, Dep. of Civil Engineering, p/a Delft Hydraulics, PO Box 152, 8300 AD Emmeloord, The Netherlands. e-mail: marjolein.janssen@wldelft.nl

2) Formerly Delft Hydraulics; University of Twente, Section Civil Engineering and Management, PO Box 217, 7500 AE Enschede, The Netherlands. e-mail: j.s.ribberink@sms.utwente.nl

way, which means that it is assumed that the sand transport reacts immediately to changes in flow condition. Therefore a direct relation exists between the instantaneous near-bed free stream velocity or instantaneous bed shear stress and the instantaneous transport rate. The assumption of quasi-steadiness is often applied in sheet flow conditions, where the majority of the sand transport takes place in a thin layer close to the bed and a quick sediment response to the oscillatory flow can be expected (see Ribberink et al., 1994).

The model of Bailard consists of a bed-load and a suspended-load part. Both parts contain a term which depends on the bed slope. Because the model is compared with measurements of sand transport above a horizontal bed, these terms become zero. In order to calculate the *net* sand transport rate, the equation is averaged over the wave-period, resulting in:

$$\langle q_s \rangle = \frac{\rho_w \, c_f}{(\rho_s - \rho_w)\, g} \, \frac{\varepsilon_b}{\tan\varphi} \, \langle u^3 \rangle \quad + \quad \frac{\rho_w \, c_f}{(\rho_s - \rho_w)\, g} \, \frac{\varepsilon_s}{w_s} \, \langle |u|^3 u \rangle \tag{1}$$

Where $\langle .. \rangle$ means time-averaging over the wave period, q_s is the sand transport rate per unit width (m^2/s), ρ_w and ρ_s are the density of the water and the sediment (kg/m^3), c_f is a friction coefficient (-), g is the gravity acceleration (m/s^2), ε_b and ε_s are efficiency factors for the bed-load and the suspended-load transport (-), $\tan\varphi$ is the tangent of the dynamic friction angle (-), w_s is the settling velocity of the sediment (m/s) and u is the horizontal near-bed velocity, directly above the wave boundary layer (m/s).

Because of the assumption of quasi-steadiness *and* the fact that q_s is related to the third- and fourth-power velocity moment, the *net* sand transport rate, predicted by this model, will always be in the direction of the largest velocity, i.e. under real asymmetric waves, generally this will be in the onshore direction.

b) Dibajnia & Watanabe (1992)

Dibajnia & Watanabe developed a 'semi-unsteady' model, which is able to take into account unsteady effects, like the time-lag between velocity and concentration, although it does not contain fully unsteady equations. Considering the amount of sand which is entrained during a positive half wave cycle, the model determines the part which will be transported directly by the positive half cycle and the part that will still be in suspension as the flow reverses and will therefore be transported by the negative velocity, during the successive half cycle. The relative magnitude of these parameters depends on the ratio of the fall time of the particles (determined by their settling velocity and the height to which the particles are suspended) and the period of the positive half wave cycle. Of course the same is valid for the negative half cycle. The net sediment transport rate is the difference between the two contributions in positive and the two contributions in negative direction. For the exact formulations, the reader is referred to the original paper.

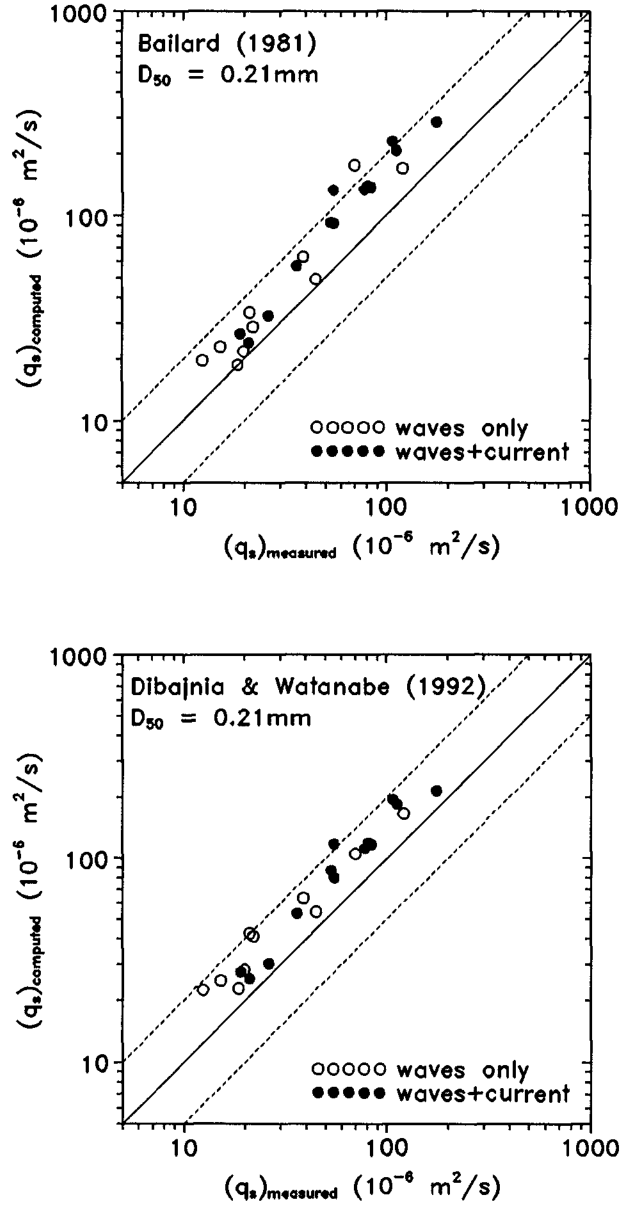

Figure 1: Comparison between measured and calculated net transport rates for sand with D_{50} = 0.21 mm. Model results of Bailard (1981) and Dibajnia & Watanabe (1992).

Comparison between two models and existing data

In order to verify the two transport models and to check whether the assumption of quasi-steadiness is always valid in sheet flow conditions, predicted net transport rates were compared with measurements, performed in the Large Oscillating Water Tunnel (LOWT) of Delft Hydraulics. This facility enables experiments to be performed at full scale and is able to generate oscillatory flows with net currents superimposed. Net transport rates are derived from a mass-conservation technique by measuring the bed level before and after a test and determining the weight of sand collected during the test in the sand traps. (For a more detailed description see the following pages).

Fig.1 shows the measured and calculated transport rates on log-log scale for the models of Bailard and Dibajnia & Watanabe, respectively. All data are for sand with a mean diameter D_{50} = 0.21 mm (settling velocity w_s = 0.026 m/s) and both experiments with purely oscillatory flow (Ribberink & Al-Salem, 1994) and combined wave-current flow (Ribberink et al., 1994) are included. All conditions were in the sheet-flow regime. For the model of Bailard the following values of the input parameters are used: $\varepsilon_b = 0.1$, $\varepsilon_s = 0.02$, $\tan\varphi = 0.625$. For the case of purely oscillatory flow c_f is calculated as the friction factor of Jonsson, slightly modified by Swart (1974) with $k_s = D_{50}$. For the case of combined wave-current flow, c_f is calculated as a combined wave-current flow friction factor, developed by Ribberink & Van Rijn and described by Koelewijn (1994). The model of Dibajnia & Watanabe does not require any further input parameters. The solid lines represent perfect agreement between the predicted and the measured transport rates, while the dashed lines represent a factor two difference. It is clear that both models perform similarly, with almost all predictions within a factor two of the measurements. Apparently, the assumption of quasi-steadiness is reasonable in this case of sheet flow conditions and relatively coarse sand.

However, the situation is completely different for transport rates of sand with a mean grain diameter D_{50} of 0.13 mm. Fig.2 shows a comparison between the experimental data (Ribberink & Chen, 1993) and the predictions by the two models. The test conditions of these experiments concerned purely oscillatory, asymmetric (2^{nd}-order Stokes) flow. It must be emphasized that again all test conditions were in the sheet-flow regime. The experiments show the surprising behaviour of a negative net transport rate for increasing root-mean-square velocity (U_{rms}), corresponding to increasing oscillatory velocities. This means that for large oscillatory velocities the *net* sand transport rate is opposite to the direction of the largest velocity (i.e. in 'offshore' direction). Because of the assumption of quasi-steadiness, the model of Bailard is not capable to predict this behaviour and apparently, the assumption of quasi-steadiness is not valid for this fine sand.

In contrast to the model of Bailard, the model of Dibajnia & Watanabe predicts decreasing and even negative net transport rates for increasing oscillatory velocities. This is caused by the part of the entrained sand which remains in suspension and is transported in opposite direction. Due to the asymmetry of the flow this results in negative net transport rates. Although the trend shown in the data is followed much better by the model of Dibajnia & Watanabe, the magnitudes are still different.

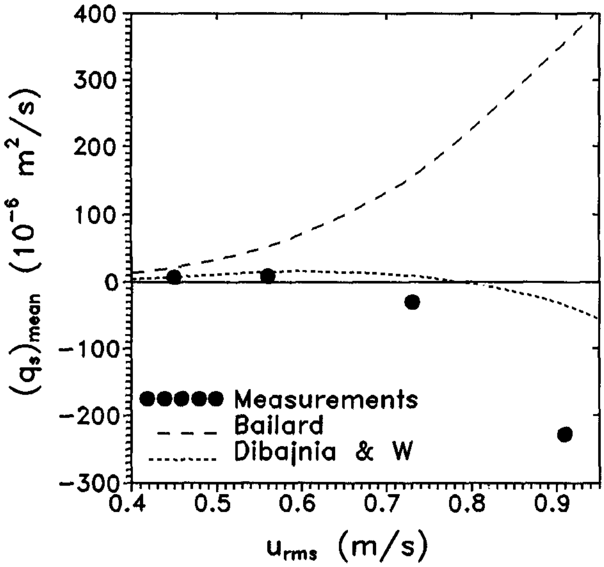

Figure 2: Net transport rates as a function of the root-mean-square velocity (U_{rms}). Measurements by Ribberink & Chen (1993), model results of Bailard (1981) and Dibajnia & Watanabe (1992)

New experiments

From the previous section it is clear that the grain diameter is an important parameter in the prediction of the net transport rate. Apparently, the assumption of quasi-steadiness is not valid in the case of sand transport of very fine sand in purely oscillatory sheet flow conditions. In order to investigate the influence of the grain diameter on the net transport rates and the transport mechanisms in *combined wave-current flow*, a new set of experiments with fine sand (D_{50} = 0.13 mm) was performed in the LOWT of Delft Hydraulics. The experimental research was carried out between October 1995 and January 1996 and consisted of two parts. In the first part, net sand transport rates were measured and in the second part, detailed time-dependent measurements of velocity and concentration were performed. This paper focuses on the first part of the experiments, i.e. the net transport measurements.

i) The Large Oscillating Water Tunnel

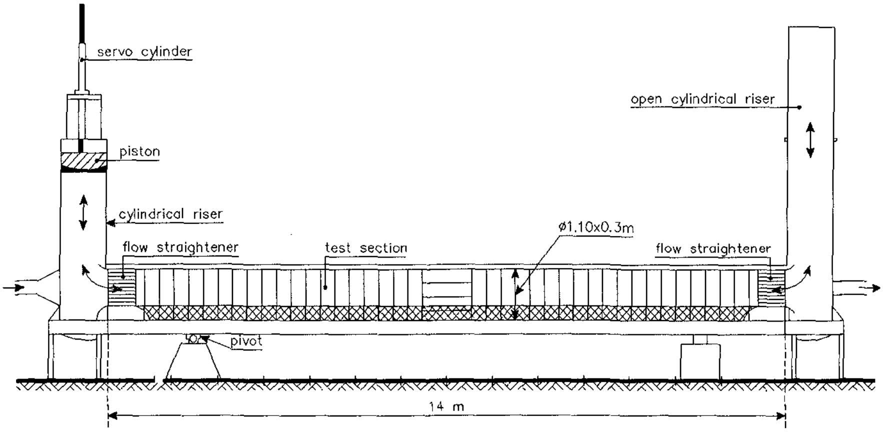

Figure 3: General outline of the Large Oscillating Water Tunnel of Delft Hydraulics.

Fig.3 shows a general outline of the LOWT. The tunnel has the shape of a vertical U-tube with a rectangular horizontal test section and two cylindrical risers on either end. The desired oscillatory water motion inside the test section is imposed by a steel piston in one of the risers. The other riser is open to the atmosphere. The test section is 14 m long, 1.1 m high and 0.3 m wide and is provided with flow straighteners on either end. A 0.3 m thick sand bed can be brought into the test section, leaving 0.8 m height for the flow above the bed. Two sand traps are located underneath the cylindrical risers.

The maximum piston amplitude is 0.75 m, which means a maximum semi-excursion length of the water particles in the test section of 2.45 m. The range of velocity amplitudes is 0.2 - 1.8 m/s and the range of oscillation periods is 4 - 15 seconds. It is possible to generate purely sinusoidal, regular asymmetric and irregular oscillatory motions with the piston.

In 1992 the tunnel was extended with a recirculating flow system connected to the cylindrical risers, so that a steady current can be superimposed onto the oscillatory motion. The maximum superimposed current velocity in the test section of the tunnel is 0.5 m/s. The recirculating flow system is also provided with a sand trap, consisting of a 12 m long pipe with a diameter of 1.2 m. The trap was designed for trapping 90% of the suspended sediments (minimum grain size 100 microns) at maximum flow discharge.

ii) Measurement procedure

During these experiments net transport rates as well as near-bed velocities were measured. The velocities were measured at 10 cm above the bed, using a 2D forward scatter Laser-Doppler system, developed by Delft Hydraulics.

Net transport rates were derived from a mass-conservation technique. Therefore the bed level along the test section is measured before and after the test and the weight of sand, collected in the traps during the test, is determined.

The bed levels in earlier experiments were measured by hand. However, for the present experiments a bed level profiling system (BLPS) was built. The BLPS consists of three bed profilers, mounted on a measurement carriage, which can be moved along the test section. The bed level measurement technique is based on a conductivity measurement. The profilers measure the bed level every cm along the test section, accurate to about 0.4 mm in the vertical. From the difference between the bed level before and after a test, the total volume of sand, eroded from the test section (including pores), can be determined. This sand is collected in the three sandtraps and weighed under water, giving the total volume (without pores).

The transport rate in the middle undisturbed part of the test section can now be calculated by solving the continuity equation for the sediment over the test section, starting either from the left- or from the right-hand side, resulting in two estimates of the net transport rates.

iii) Test conditions

Table 1 Test conditions present experiments

Condition	T (s)	U_m (m/s)	U_a (m/s)
H2	7.2	0.23	0.70
H3	7.2	0.23	0.95
H4	7.2	0.23	1.10
H5	7.2	0.23	1.30
H6	*7.2*	*0.23*	*1.47*
H7	7.2	0.44	0.50
H8	7.2	0.44	0.70
H9	*7.2*	*0.44*	*0.95*
H24	4.0	0.23	0.70
H4S	4.0	0.23	1.10
H12	12.0	0.23	0.70
H12S	12.0	0.23	1.10

The test conditions of the present experiments consisted of combinations of sinusoidal oscillatory flow, with varying amplitudes of the velocity (U_a) and varying oscillation periods (T), superimposed onto varying net current velocities (U_m). Again all test conditions are in the sheet-flow regime. The test conditions are summarized in Table 1, where the italic typed conditions represent the two test conditions which are equal to the test conditions of earlier experiments with coarser sand (Katopodi et al., 1994).

Results of new experiments in comparison with model predictions

Fig.4 shows the measured net transport rates of the new experiments (D_{50} = 0.13 mm) in comparison with the predictions of the two models. The results for a constant net current velocity (U_m) of 0.23 m/s and a constant wave period (T) of 7.2 s are shown as a function of the amplitude of the oscillatory velocity (U_a).

Because of the assumption of quasi-steadiness in the model of Bailard, this model predicts strongly increasing net transport rates for increasing oscillatory velocities. The measured net transport rates have much smaller values and show a weaker increase for increasing oscillatory velocities. The predictions of the model of Dibajnia & Watanabe are much closer to the measured values. However, a more detailed comparison (Fig.4b) shows that this model predicts *decreasing* transport rates for amplitudes of the oscillatory velocity larger than about 1.1 m/s. This is again caused by the unsteady effects. Although the increase in the measured net transport rates is much smaller than predicted by the quasi-steady model, the measurements do not yet show a decrease in transport rate. Thus apparently the unsteady effects are smaller than predicted by the model of Dibajnia & Watanabe. This is opposite to the situation for purely oscillatory flow, where the measurements showed a larger unsteady effect, than predicted by the model of Dibajnia & Watanabe (see Fig.2).

Fig.5 shows a comparison between the measured and calculated net transport rates as a function of the wave period (T), for a constant amplitude of the oscillatory velocity (U_a) of 1.1 m/s and a constant net current velocity (U_m) of 0.23 m/s. In the quasi-steady model of Bailard the wave period only has an effect on the friction factor. Increasing wave periods lead to decreasing friction factors, resulting in decreasing sand transport rates, as shown in Fig.5. However, the measurements show decreasing net transport rates for *de*creasing oscillation periods. The same trend is predicted by the model of Dibajnia & Watanabe. It is caused by the fact that the unsteady effects become relatively more important for decreasing wave periods.

Grain-size influence on net sand transport rates in sheet flow conditions.

The influence of the grain size can be analyzed by just comparing the experimental data and by analyzing the performance of both models for all data of fine and coarser sand. In Fig.6 the net sand transport rates are plotted as a function of the third power velocity moment for all experiments in combined wave-current flow (Ribberink et al., 1994 and present tests). From this figure it is clear that the net transport rates of fine sand are smaller than those of coarser sand. This is completely opposite to the behaviour in uni-directional steady flow, where finer sediments would result in larger transport rates. The decrease in net transport rate

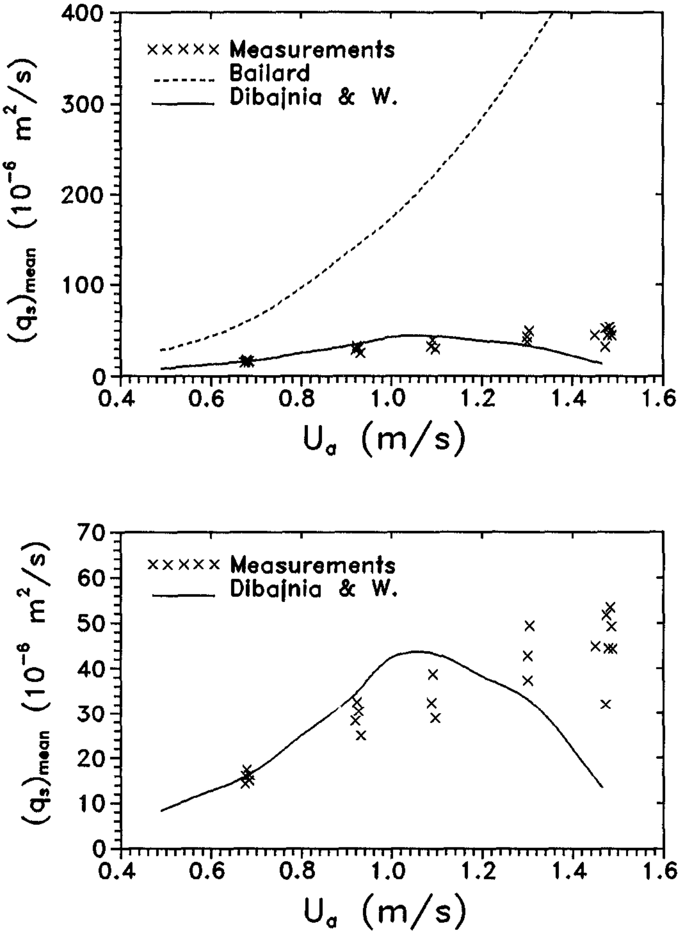

Figure 4: Net transport rates as a function of the amplitude of the oscillatory velocity U_a, for U_m = 0.23 m/s and T = 7.2 s. Present tests compared with model results of Bailard (1981) and Dibajnia & Watanabe (1992).

is caused by the unsteadiness, as the amount of sand in motion (or gross transport rate) will be larger for the finer sand. However, part of the sand remains suspended and is transported in opposite direction, resulting in smaller net transport rates.

Fig.7 is similar to Fig.1, but now also includes the data for fine sand. The two tests with negative transport rates in purely oscillatory flow (see Fig.2) are left out, because they cannot be plotted on a log scale. As observed before, both

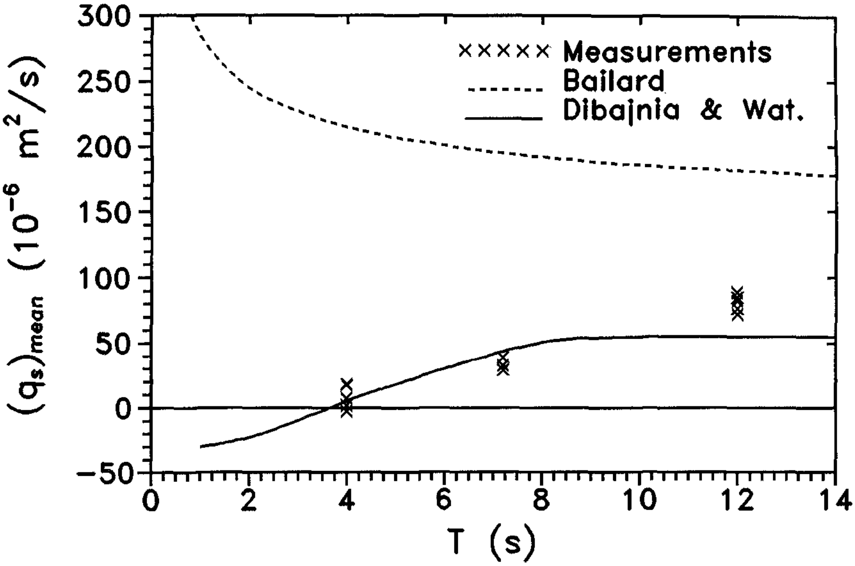

Figure 5: Net transport rates as a function of the oscillation period T, for U_m = 0.23 m/s and U_a = 1.08 m/s. Present tests compared with model results of Bailard (1981) and Dibajnia & Watanabe (1992).

models show a similar kind of agreement with the experimental data for sand with a mean grain diameter of 0.21 mm. However, the 'quasi-steady' model of Bailard largely overpredicts the measured transport rates of fine sand. Due to the inclusion of unsteady effects in the model of Dibajnia & Watanabe, predictions by the latter model for fine sand are much better. This confirms the fact, already observed for the purely oscillatory flow data, that even in sheet flow conditions the assumption of quasi-steadiness of the transport rates is not always valid for fine sand.

Analysis of unsteady behaviour of net transport rate of fine sand

In order to analyze the unsteady behaviour of the transport rate of fine sand, use is made of the results from the second part of the experiments (time-dependent measurements of velocity and concentration). The net sand transport rate can be calculated from:

$$\langle q_s \rangle = \int_0^h \langle u(z,t) * c(z,t) \rangle dz = \int_0^h \langle \varphi(z,t) \rangle dz \tag{2}$$

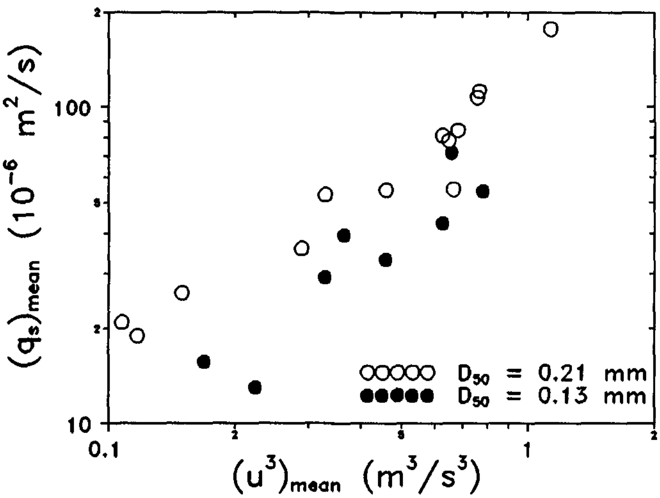

Figure 6: Measured net transport rates for fine (D_{50} = 0.13 mm) and coarse (D_{50} = 0.21 mm) sand as a function of the third-power velocity moment.

Where c is the sediment concentration (m^3/m^3), φ is the sediment flux (m/s), z is the height above the bed (m), t is time (s) and h is the water depth (m).

Because both the velocity and concentration consist of a time-averaged ($\langle .. \rangle$) and an oscillatory ($\sim$) component, the time-averaged sediment flux $\langle \varphi(z) \rangle$ can be split up into a current-related $\langle \varphi_c(z) \rangle$ and a wave-related $\langle \varphi_w(z) \rangle$ contribution, as follows:

$$\langle u(z,t) * c(z,t) \rangle = \langle u(z) \rangle * \langle c(z) \rangle + \langle \tilde{u}(z,t) * \tilde{c}(z,t) \rangle = \langle \varphi_c \rangle + \langle \varphi_w \rangle \qquad (3)$$

The vertical distributions of these two contributions, as well as the total (time-averaged) flux profile, are shown in Fig.8 (for more detail about the time-dependent measurements, see Janssen et al., 1996). The results are for test condition H6 (see Table 1). It is clear that the total net transport rate (derived by integrating the total flux profile over the height), will be positive (i.e. in the direction of the net current). Of course the current-related contribution is positive everywhere, because it is just the product of the time-averaged velocity (which is positive by definition, because it is the velocity of the net current) and the time-averaged concentration. However, the wave-related contribution has a value which is of the same order of magnitude, but in opposite direction (against the net current). This must be caused by a time-lag effect between the oscillatory component of the concentration and the oscillatory velocity. Because of this negative wave-related transport rate, the total net transport rate will be much smaller than

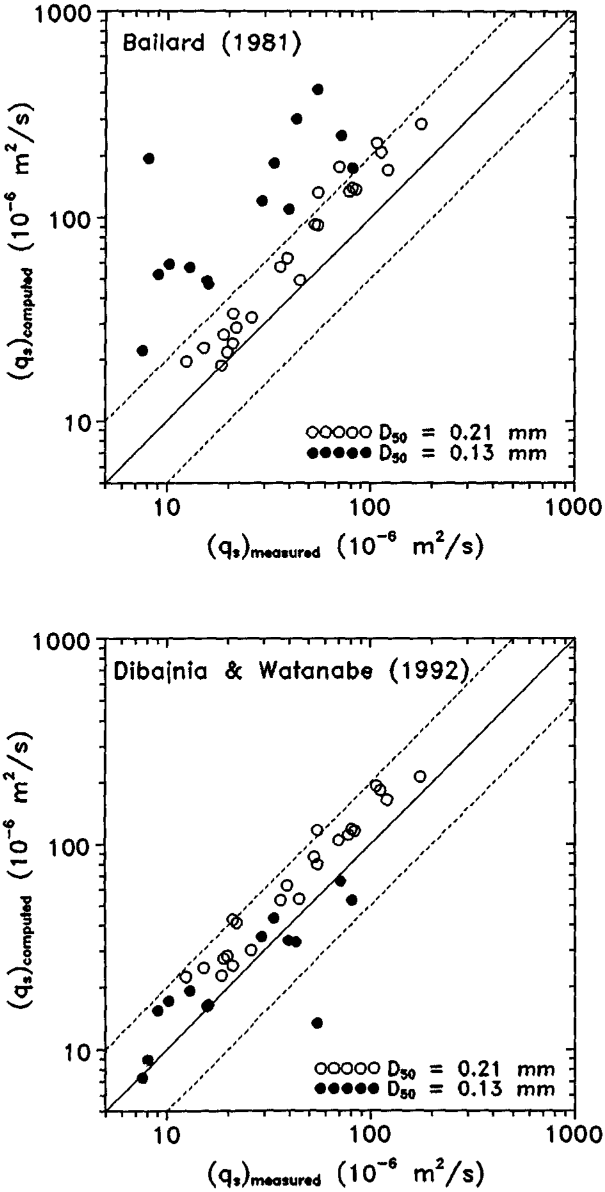

Figure 7: Comparison between measured and calculated net transport rates for fine sand (D_{50} = 0.13 mm) and coarse sand (D_{50} = 0.21 mm). Model results of Bailard (1981) and Dibajnia & Watanabe (1992).

predicted by the 'quasi-steady' model, which does not include this effect. Additionally, the total net transport rate will be smaller than in the case of coarser sand, where the larger particles result in a smaller time-lag between concentration and velocity and therefore less negative wave-related transport rates. So apparently, the behaviour, as present in the concept of the model of Dibajnia & Watanabe is not only occurring in rippled bed conditions, but also occurs in sheet flow conditions with fine sand.

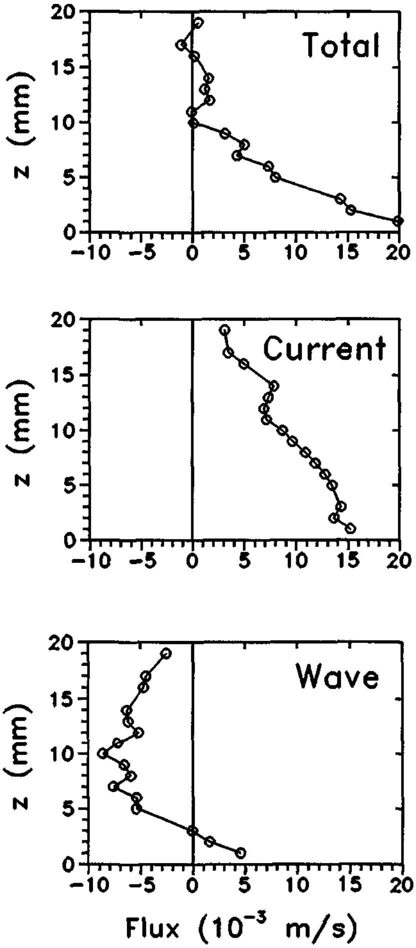

Figure 8: Vertical distribution of time-averaged total, current- and wave-related sediment flux, determined from time-dependent velocity and concentration measurements (experiment H6).

Conclusions

Modelling the sand transport in a quasi-steady way leads to the following predictions for net sand transport rates: i) increasing net transport rates for decreasing grain diameter, ii) largely increasing net transport rates for increasing oscillatory velocities and iii) increasing net transport rates for decreasing wave periods. However, experimental data of net transport rates in oscillatory sheet flow show the following results:

- *Smaller* net transport rates for 0.13 mm sand than for 0.21 mm sand.
- A much *weaker increase* in net transport rates for 0.13 mm sand than for 0.21 mm sand, with increasing oscillatory velocities.
- *Decreasing* net transport rates with decreasing wave periods for sand with D_{50} = 0.13 mm and conditions with sufficiently large oscillatory velocities.

All these 'unsteady effects' are caused by a time-lag between velocity and concentration, resulting in negative wave-related transport rates and therefore smaller total net transport rates than without these effects. Apparently, even in sheet flow conditions, the net sand transport rate cannot always be described in a quasi-steady way. Obviously, the quasi-steady model of Bailard (1981) is not able to predict these phenomena. The 'semi-unsteady' model of Dibajnia & Watanabe (1992) is at least able to predict the behaviour qualitatively. However, this model underpredicts the unsteady effects in purely oscillatory asymmetric flow and overpredicts the unsteady effects in the case of combined wave-current flow (compare Fig.2 and Fig.4b).

Acknowledgements

The authors want to thank the Dutch Ministry of Transport and Public Works (RIKZ), for the financial support to perform the experiments. The help of Mr. W.N. Hassan and Mr. R.J. v.d. Wal during the experiments and the data-processing is greatly appreciated. The first author also wants to thank the Technology Foundation (STW) for their financial support during the complete research project.

References

Bailard, J.A. (1981). An energetics total load sediment transport model for a plane sloping beach. J. Geoph. Res., Vol. 86, No. C11, pp. 10938-10954.

Dibajnia, M. & A. Watanabe (1992). Sheet flow under nonlinear waves and currents. Proc. 23rd ICCE, Venice, pp. 2015-2028.

Janssen, C.M. (1995). Sand transport in oscillatory sheet-flow; a literature review. Delft University of Technology, Communications on Hydraulic and Geotechnical Engineering, Rep. No. 95-6, ISSN 0169-6548.

Janssen, C.M., W.N. Hassan, R. v.d. Wal, J.S. Ribberink (1996). Net sand transport rates and transport mechanisms of fine sand in combined wave-current sheet flow conditions. Delft Hydraulics, Data report H2462, Part IV.

Katopodi, I., J.S. Ribberink, P. Ruol & C. Lodahl (1994). Sediment transport measurements in combined wave-current flows. Proc. Coast. Dyn.'94, Spain.

Ribberink, J.S. & Z. Chen (1993). Sediment transport of fine sand under asymmetric oscillatory flow. Rep. H840, Part VII, Jan 1993, Delft Hydraulics.

Ribberink, J.S. & A.A. Al-Salem (1994). Sediment transport in oscillatory boundary layers in cases of rippled bed and sheet-flow. J.Geoph.Res., Vol.99, C6.

Ribberink, J.S., I. Katopodi, K.A.H. Ramadan, R. Koelewijn & S. Longo (1994) Sediment transport under (non)linear waves and currents. Proc.24th ICCE.

Jonsson, I.G. (1966): Wave boundary layers and friction factors. Proc.10th ICCE.

Koelewijn, H. (1994): Sediment transport under sheet-flow conditions. M.Sc. Thesis, Delft University of Technology, October 1994, 98 pp.

Swart, D.H. (1974): Offshore sediment transport and equilibrium beach profiles. Delft Hydr. Lab. Publ., No. 131, Delft Hydraulics, The Netherlands.