CHAPTER 175

BEDFORMS, SEDIMENT CONCENTRATIONS AND SEDIMENT TRANSPORT IN SIMULATED WAVE CONDITIONS

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Abstract

Two series of experiments were conducted in a new Large Oscillating Water Tunnel of Delft Hydraulics with the main objectives to study the behaviour of bedforms and the transport of sand in controlled wave conditions simulated at full scale (1:1). The main results are:

i) Bedform dimensions are strongly influenced by the type of oscillatory flow. The transition from rippled bed to plane bed conditions - as predicted by Nielsen's (1979) empirical relations - was not observed for sinusoidal waves but did occur for (ir)regular asymmetric waves.

ii) The net sediment transports as measured during (ir)regular asymmetric wave experiments in plane or almost plane bed (sheet flow) conditions show a consistent linear relation with the third-order moment of the velocity $<U^3>$ and show a good agreement (within a factor 2) with the energetics total load sediment transport model of Bailard (1981). A calibrated formula of the form $q_s = A \cdot <U^3>$ shows a reasonable agreement (within a factor 1.5-3) with available existing datasets over a wide range of measured values (factor 1000).

Introduction

For the transport of sediment in the marine coastal environment the complex interactions between the wave and sea bed itself (bedforms, sediment stirring) play a key role. After several years of experimental research in a small oscillating water tunnel, recently a new large oscillating water tunnel was constructed at DELFT HYDRAULICS with the aim to extend the research to full scale (1:1) conditions.

Sediment transport under the influence of waves and current is generally divided into transport as carried by the current and transport as carried by waves. By splitting up of the horizontal velocity U

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and the sediment concentration C at a certain level in a time-averaged component and a fluctuating component due to the waves, the horizontal sediment flux at that level ϕ_{cw} can be split up in a current-related part ϕ_c and a wave-related part ϕ_w as follows. For a colinear situation (i.e. current and wave propagation have the same or opposite direction):

$$U = U_o + \tilde{U}$$

$$C = C_o + \tilde{C}$$

$$\phi_{cw} = \langle UC \rangle = \phi_c + \phi_w$$

$$= \langle U_o C_o \rangle + \langle \tilde{U}\tilde{C} \rangle$$

Much of the research on sediment transport in the past has been concentrated on the transport component as carried by the current (often dominant in longshore direction). The waves are treated as an additional stirring mechanism for the sand. The sediment transport component as carried by the waves (e.g. due to wave asymmetry outside the surfzone) is much less understood, which is probably caused by the complex character of this type of sediment transport which is governed by the intra-wave processes taking place in a relatively thin layer (millimeters to centimeters) near the sea bed. Nevertheless, the wave-carried transport is of great importance for especially the transport in cross-shore direction. For example, wave asymmetry (leading to relatively high orbital velocities in the direction of the wave propagation and relatively low orbital velocities in the opposite direction) is generally held responsible for the onshore motion of sand on the upper shoreface and for example for the onshore motion of offshore bars.

The experimental research programme around the new tunnel was therefore started with the objectives: i) to obtain a better understanding of the wave-carried sediment transport and ii) to verify and improve existing concepts for the description of this type of sediment transport.

Large Oscillating Water Tunnel

A general outline of the new tunnel is given in Figure 1. The horizontal test section has an appproximate length of 15 m, an inner width of 0.3 m and an inner height of 1.1 meter. The complete test section can be provided with a sand bed with a layer thickness of 0.3 meter, leaving 0.8 m height for the oscillatory flow above the bed. A desired oscillatory water motion (regular or irregular) can be imposed by a computer controlled hard driving system, which consists of a hydraulic servo-cylinder moving a steel piston in one of the cylindrical risers. The other cylindrical riser is open to the atmosphere. The maximum amplitude of the piston is 0.75 m which coincides with a maximum semi-excursion length of water particles in the test section of app. 1.75 meter.

Figure 2 shows the working regime of the new tunnel in terms of period and maximum velocity amplitude of the oscillatory flow, in comparison with the small tunnel of DELFT HYDRAULICS and the existing large tunnels at SCRIPPS (USA) and ISVA (TU Copenhagen). The main feature of the new tunnel is that it has the possibility of controlled simulation in the relevant velocity/period regime (scale 1:1). A desired regular and irregular oscillatory flow can be produced in the test section with a limited deformation. Figure 2 shows that the tunnel covers the bedform regimes from initiation of motion to sheet flow (D_{50} = 0.2 mm).

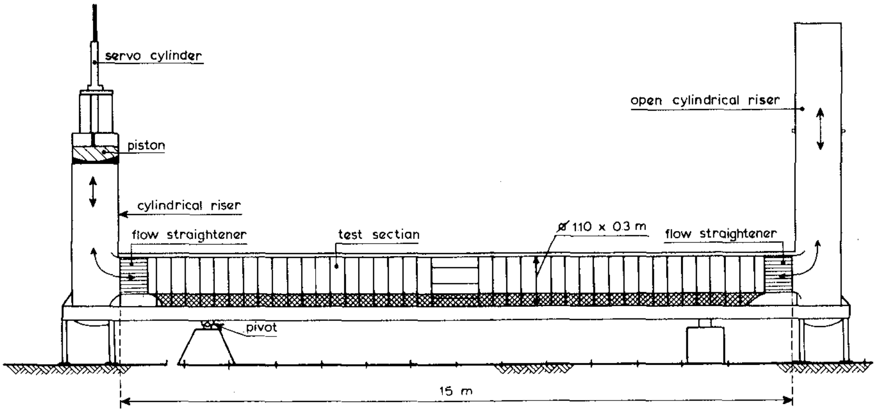


Figure 1 Large Oscillating Water Tunnel

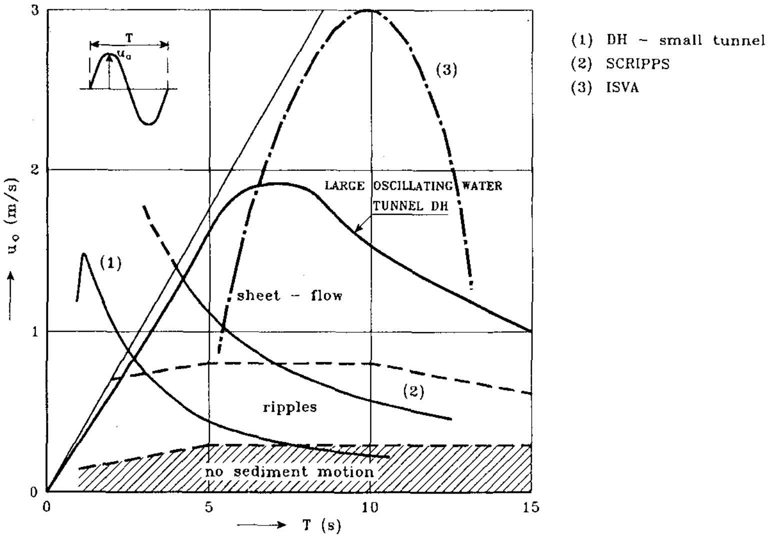


Figure 2 Velocity-amplitude and period regime

Set-up of experiments

Because bedforms are essential features for the sediment transport process, a first set (series A) of experiments was focussed on bedform behaviour under the influence of regular sinusoidal oscillations, covering the major part of the tunnel´s working regime. Twenty-nine tests were conducted with periods 4-10 s and velocity amplitudes 0.3-1.5 m/s using quartz sand with D_{50} = 0.21 mm. The main objectives of this first series were: i) to compare the observed bedforms (dimensions, transition to sheet flow) with existing datasets and empirical formulations (tunnel validation) and, ii) to study the bedform behaviour in the still very unknown high velocity (U > 1 m/s) and large period (T > 5 s) regimes.

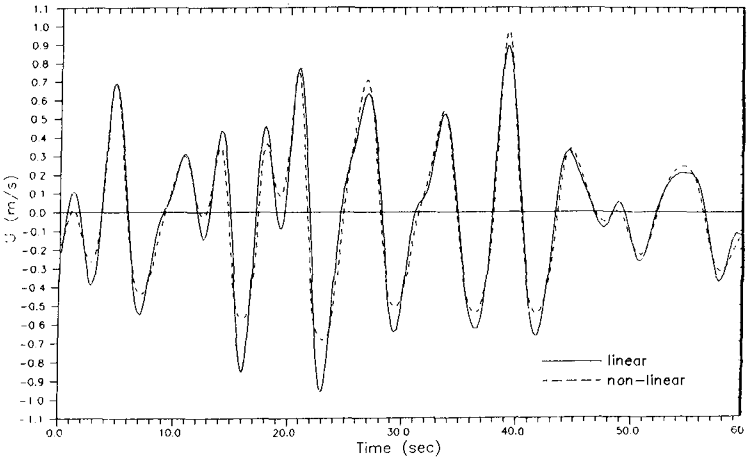
A second set of experiments (series B) was focussed on the net sediment transport as induced by wave asymmetry. Only a limited set of data is available on this type of transport especially in the high velocity regime (Horikawa et al, 1982 and Sawamoto & Yamashita, 1986). A series of 12 experiments were carried out in the large tunnel with irregular (exps. 1-6) and regular (exps. 7-12) asymmetric oscillatory flow in which the net sediment transport, bed form dimensions and time-averaged suspended concentration profiles were measured. The experimental conditions are summarized in Table 1 (U_{rms} = root mean square value of the measured velocity in the tunnel, $T_{(peak)}$ = (peak) period of the oscillatory flow).

exp. -	U_{rms} m/s	$T_{(peak)}$ s	(ir)regular -
1	0.48	6.5	irregular JONSWAP 2nd order Stokes
2	0.32		
3	0.43		
4	0.48	9.1	
5	0.33		
6	0.44		
7	0.50	6.5	regular 2nd order Stokes
8	0.70		
9	0.92		
10	0.54	9.1	
11	0.70		
12	0.97		

Table 1 Experimental conditions series B (wave-asymmetry)

The irregular wave experiments are based on a JONSWAP spectrum for the water surface elevation in combination with a second-order Stokes wave theory (Liu and Dingemans, 1989). The 2nd-order theory is also applied for the regular wave experiments. Figure 3 shows an example of a time series of the applied non-linear (asymmetric) velocity signal in comparison with the linear (symmetric) signal. The degree of asymmetry, expressed in (significant) crest velocity U_c divided by the sum of (sinificant) crest and trough velocity ($U_c + U_t$), was kept constant (0.62-0.65).

Two different oscillation (spectral peak) periods were used (6.5 and 9.1 s) for similar velocity time series in order to study the validity of a quasi-steady approach for the description of the sediment transport.
A laser-doppler system is used for the measurement of the horizontal velocity variation outside the boundary layer (20 cm above the sand bed). The net sediment transport rate in the middle of the test section (not disturbed by boundary effects at the two ends of the test section) is determined with a mass-conservation technique. The measured bed-level change along the test section and the collected sand volume in two sand traps at both ends of the test section during a certain time interval (5 - 50 min) are used for the integration of the sediment continuity equation, yielding the distribution of the net transport rate along the test section. By repeating each experiment 5-8 times the net transport rate could be determined with an error of approximately 10-15%. Totally 93 tests were carried out in the above mentioned 12 different conditions.



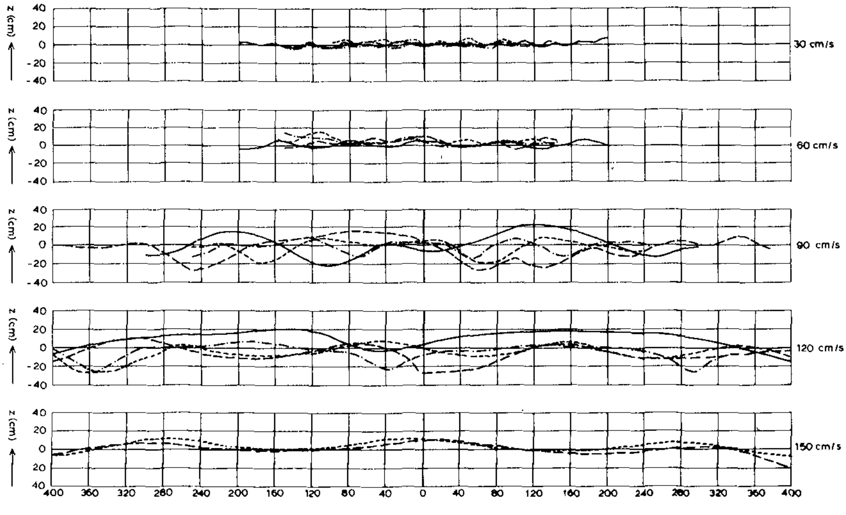
H_{sig} = 1.5 m
T_p = 6.5 s
h = 4.5 m
JONSWAP

Figure 3 Irregular asymmetric velocity signal

The data analysis was concentrated on the bedform behaviour and the sediment transport rate. For information about the measured suspended concentration profiles (time-averaged), reference is made to Ribberink and Al-Salem (1989, 1990).

Bedforms

Figure 4 gives an impression of the bedform behaviour in the test section (central 8 m) for different velocity amplitudes and periods (series A: regular sinusoidal oscillations). The bedform length and height increase for increasing velocity amplitude and period. Very large bedforms developed in the high velocity/period regime (U > 0.9 m/s) which, although considerably larger than generally observed in small wave flumes, show a clear consistency with results from other wave tunnels and flumes in the world (see Fig. 5, $X_2 = D_{50}/\Delta g T^2$).



T (s)	symbol
4	— · —
6	- - - -
8	— —
10	———

Figure 4 Bed geometry, regular sinusoidal flow (series A)

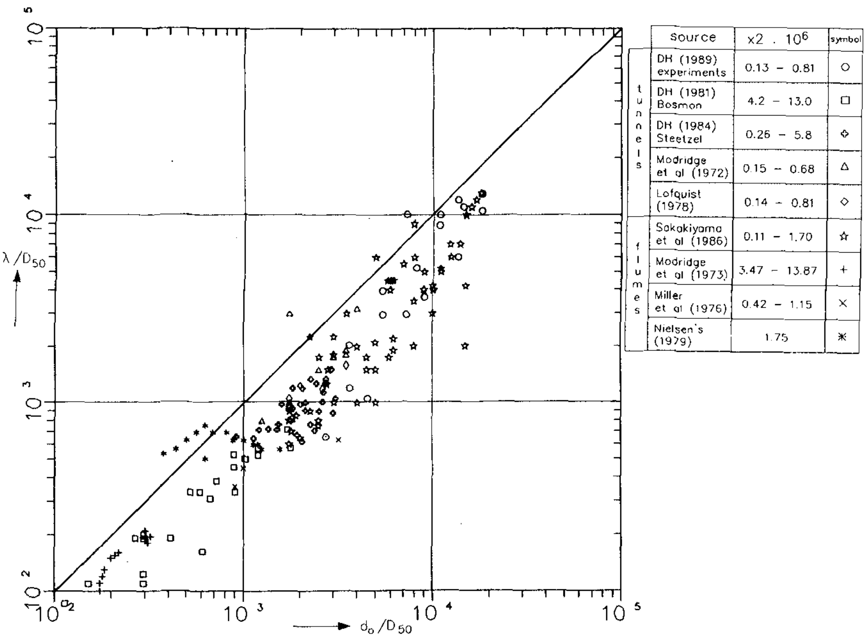
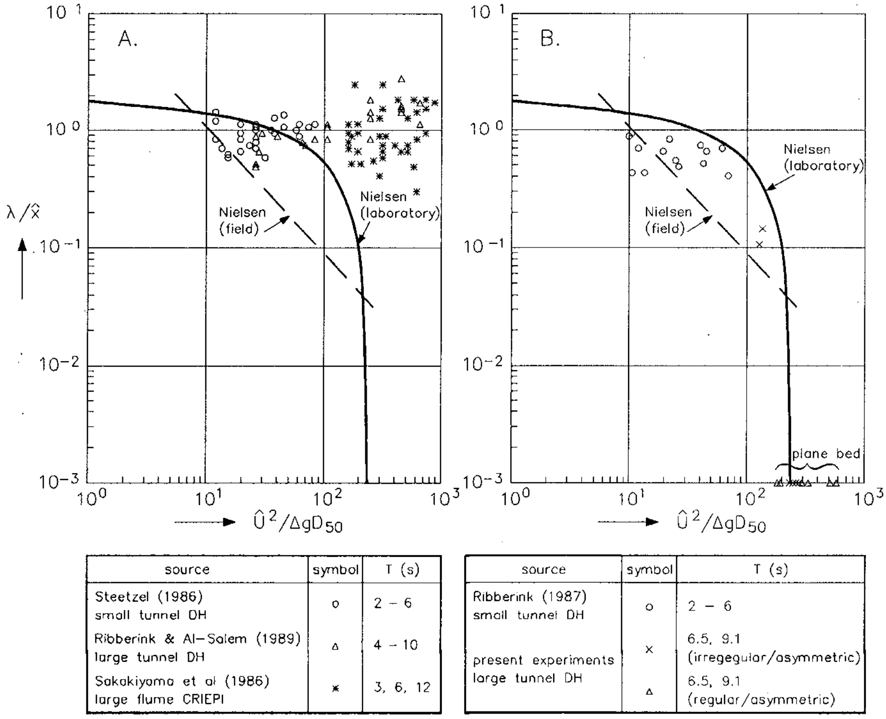


Figure 5 Ripple length as a function of orbital excursion length

It is shown that the measured dimensionless bedform lenght λ is roughly a linear function of the dimensionless total orbital excursion length d_o of water particles near the bed ($\lambda \approx 0.5 \cdot d_o$).

The new tunnel observations (DH, 1989) show a good agreement with the measurements conducted by Sakakiyama et al (1986) in the large Japanese CRIEPI wave flume (field scale).
The transition to sheet flow conditions in the high-velocity regime did not coincide with the transition to plane bed conditions. For example, for $\hat{U}$ = 1.5 m/s large bedforms could be observed with a lenght $\lambda \approx 0.5 \cdot d_o$, with sheet flow taking place in a thin layer (appr. 0.5 cm) along the bedforms and without vortex generation in the bedform troughs (no flow separation on the bedform crests).

This behaviour is also shown in Figure 6A in which the measured bedform lenghts are compared with Nielsen's (1979) empirical formulations (laboratory and field conditions).
In Figure 6: $\hat{x} = 0.5 \cdot d_o$ and $\hat{U}^2/\Delta g D_{50}$ is the mobility number with $\Delta = (\rho_s - \rho)/\rho$, ρ_s = density of sediment, ρ = density of water and g = gravity acceleration.
Although the transition to sheet flow indeed took place for mobility numbers > 100-200, the (dimensionless) bedform lenght measured in the tunnel but also in the CRIEPI flume did not show the expected decrease.



source	symbol	T (s)
Steetzel (1986) small tunnel DH	o	2 - 6
Ribberink & Al–Salem (1989) large tunnel DH	Δ	4 - 10
Sakakiyama et al (1986) large flume CRIEPI	*	3, 6, 12

source	symbol	T (s)
Ribberink (1987) small tunnel DH	o	2 - 6
present experiments large tunnel DH	×	6.5, 9.1 (irregegular/asymmetric)
	Δ	6.5, 9.1 (regular/asymmetric)

Fig. 6 Dimensionless ripple length as a function of mobility number

However, the situation changed in case the oscillatory flow becomes asymmetric (experimental series B) as shown in Figure 6B. Only the experiments 2 and 5 showed the presence of small two-dimensional rolling grain ripples, during the other 10 experiments the bed was plane and sheet flow was present. Now the reduction in ripple length roughly coincides with Nielsen´s relations.
Similar results were obtained for the measured ripple height. For more details, see Ribberink and Al-Salem (1990).

Sediment transport induced by wave asymmetry

For the modelling of sediment transport as carried by waves several approaches exist varying from relatively simple to very sophisticated (research) formulations. In the most simple approach the instantaneous transport during the wave cycle is directly related to the instantaneous horizontal velocity above the wave boundary layer near the sea bed. It is assumed that (time) phase lags between transport rate, sediment concentration and bed-shear stress and between bed-shear stress and velocity above the boundary layer can be neglected (quasi-steadiness). A general notation for this kind of transportconcept is:

$$q_s(t) = A|U(t)^{(n-1)}|U(t) \qquad (1)$$

in which $q_s(t)$ = transport rate during the wave cycle expressed in volume per unit width and time, $U(t)$ = horizontal velocity during the wave-cycle above the wave boundary layer, n = power and A = factor depending on several parameters such as grain size and friction factor.
Madsen & Grant (1976) base their transport description on the transport formula for uni-directional steady flow of Einstein-Brown, yielding $n = 6$.
Bailard (1981) proposes formulations for bed-load and suspended transport based on energy considerations of Bagnold, yielding $n = 3$ for bed-load transport and $n = 4$ for suspended transport.
For plane bed conditions also more sophisticated model concepts exist in which the detailed behaviour of sediment concentration and water/grain velocities during the wave cycle (also vertical structure) is described. For example, a wave-boundary layer flow model is used in combination with a convection-diffusion model (see Fredsøe et al, 1985). The above-mentioned phase lag effects are taken into account and for example, the delayed response of suspended particles to the varying (unsteady) flow conditions is modelled. Although even more extensive modelling efforts are carried out (see e.g. Bakker and van Kesteren, 1987), a general problem is the lack of detailed measurements for the verification of the various concepts. Observations and measurements are often done in small laboratory flumes and tunnels in which the orbital velocities and wave periods are generally far below their natural values.

During all tunnel experiments in series B: i) the bed was plane or almost plane (rolling grain ripples in exps. 2 and 5), ii) a uniform (net) transport distribution could be realized in the central 8 meters of the test section, and iii) a net ´onshore´ transport was measured. The latter agrees qualitatively with the power-law formulation eq. (1) (power $n > 1$) in combination with a velocity signal $U(t)$ based on 2nd-order Stokes wave theory.

The validity of the power law approach was verified by testing the relation between the measured net transport rates $<q_s>$ and the velocity moments $<|U^{n-1}|U>$ with n = 3, 4 and 6 (see Fig. 7). Hereto, the horizontal velocity signal, as measured (lda) during the complete experimental duration, was substituted into the power-law formulation and averaged over this duration. It is shown in Figure 7 that a clear correlation exists between the velocity moments and the net transport rate and that the power n = 3 yields the best results (i.e. dashed and solid line almost coincide).

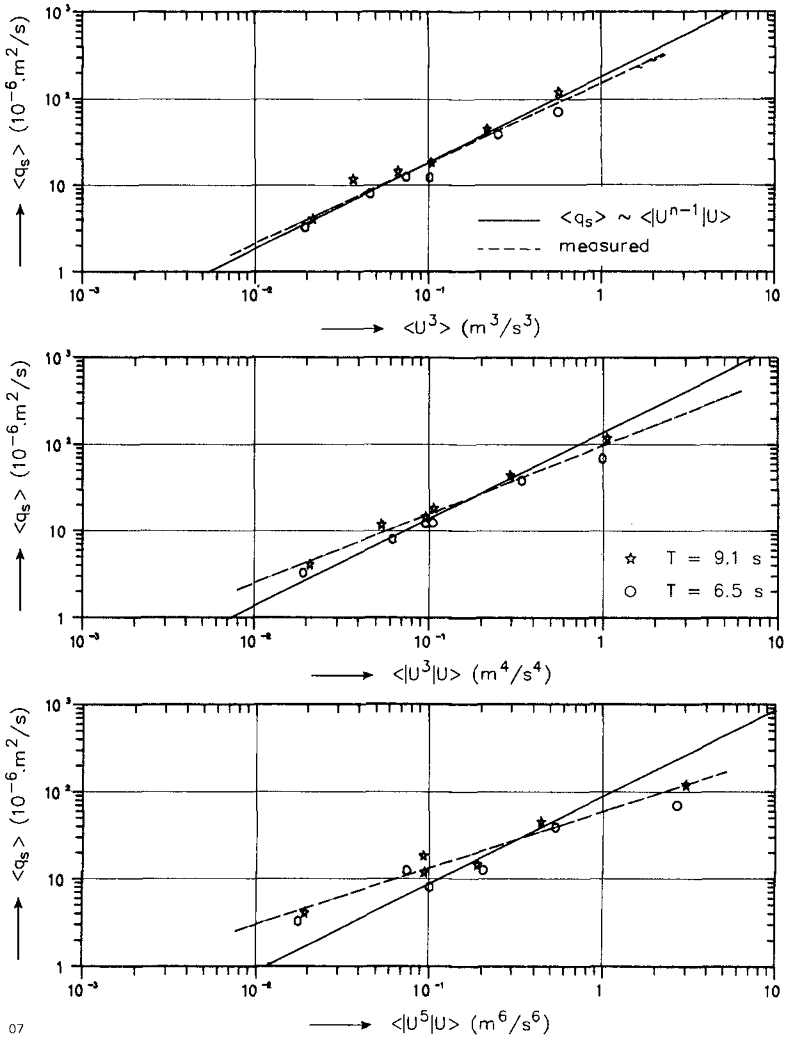


Figure 7 Net transport rate as a function of velocity moments

The experiments with regular and irregular oscillatory flow seem to follow the same line, which confirms the quasi-steady approach of the power-law description.

Nevertheless, a wave period influence is present (see Fig. 8) as for the experiments with T = 9.1 s the measured net transport rates are systematically higher (20-60%) than for the experiments with T = 6.5 s. This indicates that phase-lag effects (or acceleration/inertia effects) are present and should be taken into account for more accurate transport modelling.

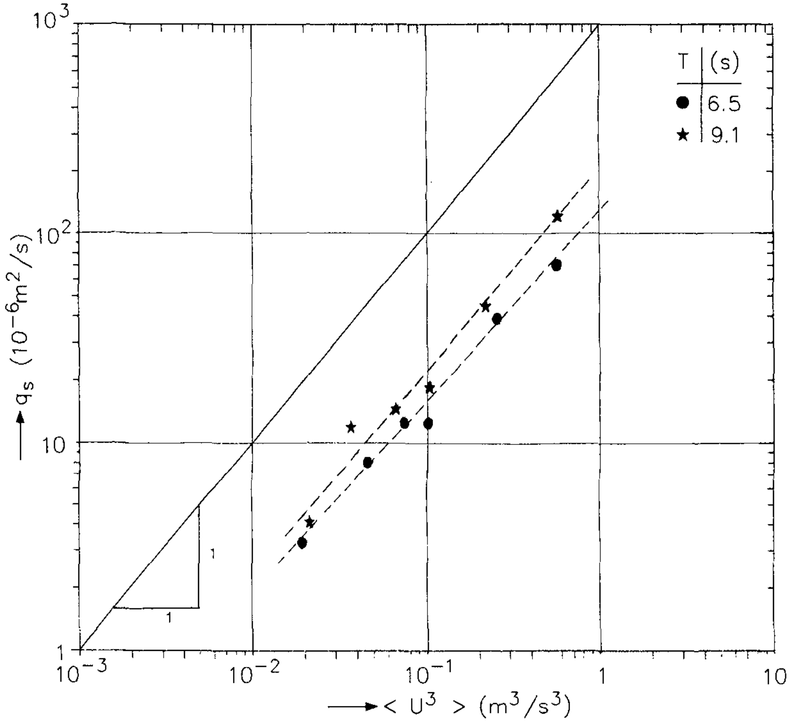
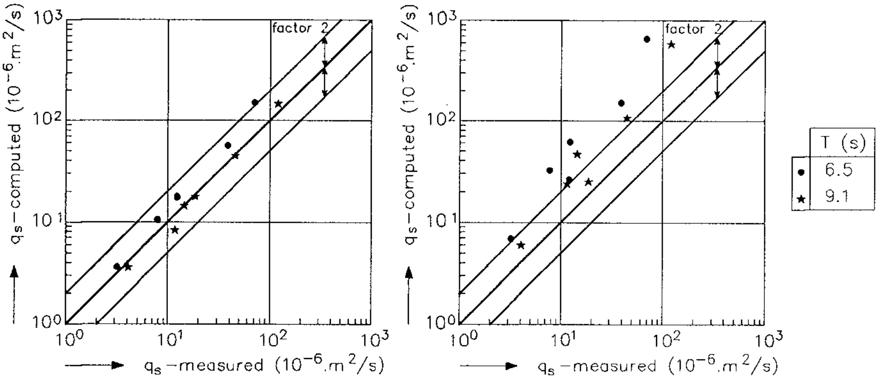


Figure 8 Period influence

In Figure 9 the formulas of Bailard (1981) and Madsen & Grant (1976) are verified in an absolute way by comparing computed net transport rates with the measurements. It is shown that the formula of Bailard (1981) can produce the measured transport rates within inaccuracy limits of a factor 2. The Madsen & Grant formula not only has the wrong power n (≈ 6) but also clearly overpredicts the transport rate in the high-velocity regime.

Remark: In both formulae the friction factor formulation of Jonsson (1980) was used with roughness height $k_s = D_{50}$ and the significant water particle semi-excursion lengh (x_{sig} for the tests with irregular waves). The Bailard formula was applied with bed-load efficiency factor $\varepsilon_b = 0.1$ and suspended-load efficiency factor $\varepsilon_s = 0.02$ as suggested by Bailard.



Bailard (1981)

Madsen & Grant (1976)

Figure 9 Verification of transportformulae of Bailard (1981) and Madsen & Grant (1976)

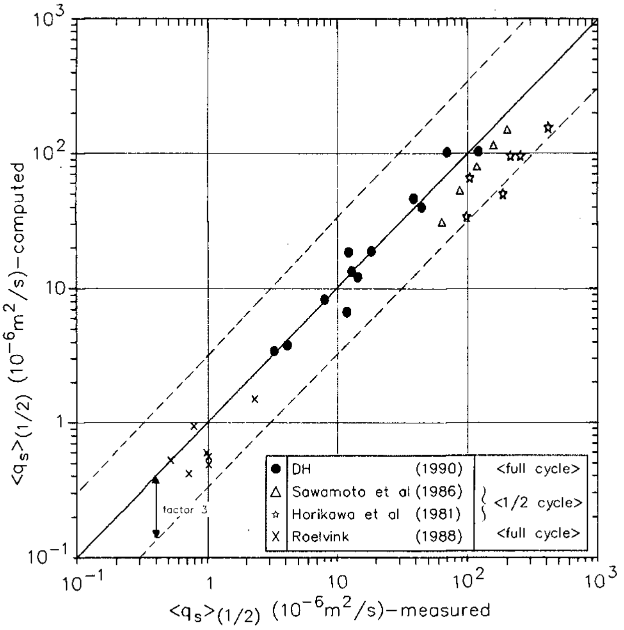


Figure 10 Comparison with other measurements (D_{50} ≈ 0.2 mm)

In Fig. 10 a comparison is made between the present measurements and other available datasets. The measurements of Horikawa et al (1982) and Sawamoto & Yamashita (1986) were carried out in tunnels in the sheet flow regime using almost the same sand as during the present experiments (D_{50} = 0.2 mm). However, sinusoidal oscillations were applied (Horikawa: T = 2-6 s and Sawamoto: 3.1 s) and the transport per half wave cycle ($<q_s>_{½}$) was measured. The measurements of Roelvink and Stive (1988) were carried out in the large wave flume of DELFT HYDRAULICS (DELTA flume) using the same sand as used for the present tests. A net (onshore directed) transport $<q_s>$ (due to wave asymmetry) was measured in case of irregular waves (T_{peak} = 5.1, 6.1 s, U_{rms} ≈ 0.3 m/s). The inter-comparison of the different data sets is made through the power-law formulation (1), as calibrated with the new tunnel data (factor $A = 0.18 \cdot 10^{-3}$ s²/m and n = 3) and applied to the other datasets. A reasonable agreement is obtained (within a factor 1.5-3) over a wide range (factor 1000) of measured values. Although the data of Horikawa and Sawamoto are systematically underpredicted by the calibrated formula (effect of wave period, 1/2 cycle transport?), the validity of the power n = 3 is clearly confirmed (see slope of the data points in Fig. 10).

Conclusions

Two series of experiments were conducted in a new Large Oscillating Water Tunnel of Delft Hydraulics with the objectives to verify and develop (existing) relationships for sediment transport carried by waves, for suspended sediment concentrations and for bedform dimensions in controlled full-scale (1:1) conditions. Series A was conducted with regular sinusoidal waves, series B with regular and irregular asymmetric waves.

Bedforms

For regular sinusoidal waves the observed ripples:

i) were considerably larger in the high velocity regime (sheet flow) than as predicted by the empirical relations of Nielsen (1979) and did not show the expected transition to plane bed,

ii) had dimensions (height/lenght) which were linearly correlated with the orbital excursion lenght and showed a clear consistency and agreement with existing datasets including the large wave flume measurements of Sakakiyama et al (1986).

For (ir)regular/asymmetric waves the expected transition to plane bed conditions (sheet flow) did occur and agreed well with the relations of Nielsen (1979).

Sediment transport

The net sediment transports as measured during the regular and irregular asymmetric wave experiments in plane or almost plane bed (sheet flow) conditions showed:

i) a consistent linear relation with the third-order moment of the velocity $<U^3>$,

ii) a systematic (20-60%) wave-period influence (phase-lag effects),

iii) a much better agreement with the energetics total load sediment transport formula of Bailard (1981) (within a factor 2) than with the bed-load formula of Madsen & Grant (1976).

A formula of the form $q_s = A \cdot <U^3>$, calibrated with the new experimental data ($A = 0.18 \cdot 10^{-3}$ s²/m), showed a reasonable agreement (within a factor 1.5-3) with the small number of existing datasets (Horikawa et al, 1982, Sawamoto & Yamashita, 1986 and Roelvink, 1988, all: $D_{50} \approx 0.2$ mm) over a wide range of measured values (factor 1000).

Acknowledgements

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