Bedload Under Asymmetric and Irregular Waves: Theory Versus Laboratory Data

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Abstract

The results of laboratory bedload measurements are presented. The study comprises a wide range of regular-asymmetric and irregular wave conditions in the ripple regime. A new theoretical model of the moveable bed boundary layer is used for computation of sedimentation volume in the sand trap. The theoretical results are tested against experimental data.

1. Introduction

The model is based on the concept proposed by Kaczmarek & O’Connor (1993) who used the procedure for matching the solutions of equation of motion in the turbulent flow above the theoretical bed level and in the collision-dominated granular-fluid region. This concept, first used for regular linear waves, has recently been developed for random waves by Kaczmarek et al. (1994) and for non-linear waves by Kaczmarek (1995).

Then, on the above basis, the first attempt was made by Kaczmarek et al. (1995) to formulate bedload theory and verify it using available laboratory data and IBW PAN radio-tracer field results. The summary of theoretical findings obtained by use of the unbiased bedload model for both regular and irregular waves was presented by Kaczmarek et al. (1996).

This paper mainly concerns the results of experiments carried out at IBW PAN laboratory. The verification of the theory for regular and irregular waves using own experimental data was the major goal of the study. There are few experimental data sets for the ripple regime, especially in the range \( \theta_{2.5} = 0.1 \div 0.4 \). Therefore the laboratory survey covered this range, particularly taking into account the identification of non-linear effects. This range of small \( \theta_{2.5} \) is extremely important as one can expect the equivalence of bedload and total sediment transport in this regime (small suspended load rate). Thus, only in this regime can the
bedload theory be precisely verified while in more severe hydrodynamic conditions
bedload is a minor part of the total sediment transport.

A concise description of the theoretical model (with some reference to earlier
studies) is given in Section 2 of the paper. The details of laboratory survey, com-
parison of experimental and theoretical data and discussion are presented in Sec-
tion 3.

2. Theoretical Bedload Model

2.1. Basic Equations

The nearbed dynamics is modelled for the flow regions above and beneath the
original static bed line, see Figure 1. The collision-dominated granular-fluid region
I stretches below the nominal static bed while the wall-bounded turbulent fluid
region II extends above it. Since both water and sand grains are assumed to move
in both regions, there must be a certain transition zone between I and II, in which
the velocity and stress profiles of I and II would merge and preserve continuity
of shape. The intersection of the two velocity profiles is marked as point A in
Figure 1.

The flow in the turbulent upper region for regular waves is described by the
integral momentum model based on the solution proposed by Fredsøe (1984), de-
volved and adapted – inter alia – for non-linear waves by Kaczmarek & Ostrowski

The approach for irregular waves incorporates a time-invariant, two-layer eddy
viscosity model including the representative parameters: friction velocity and bot-
tom boundary layer thickness. Bed roughness is calculated using the method pro-
posed by Kaczmarek (1995), taking into account the reduction of this parameter
due to irregularity of wave motion. More detailed discussion on modelling of bed
roughness is given in section 2.2

The problem for irregular waves is closed by the iterative scheme for finding
the wave period representing the random wave field (T_r) – see Scheme 1. The
scheme allows to solve the task associated with the appropriate choice of the
equivalent wave period and to include the coupling effects between the harmonic
components, incorporated in the eddy viscosity. The detailed description of the
above can be found in Kaczmarek & Ostrowski (1995).

In the sub-bed flow region, the sediment concentration is high and chaotic
collisions of grains are the predominant mechanism. Particle interactions are as-
sumed to produce two distinct types of behaviour. The Coulomb friction between
particles give rise to rate-independent stresses (of the plastic type) and the particle
collisions bring about stresses that are rate-dependent (of the viscous type). The
use of the mathematical description by Sayed & Savage (1983) for determination
of the stress tensor was made and the balance of linear momentum according to
Kaczmarek & O’Connor (1993) leads to the following equations:
\[ \alpha^0 \left[ \frac{c - c_0}{c_m - c} \right] \sin \phi \sin 2\psi + \mu_1 \left[ \frac{\partial u}{\partial z^l} \right]^2 = \rho u_f^2 \] (1)

\[ \alpha^0 \left[ \frac{c - c_0}{c_m - c} \right] (1 - \sin \phi \cos 2\psi) + (\mu_0 + \mu_2) \left[ \frac{\partial u}{\partial z^l} \right]^2 = \left[ \frac{\mu_0 + \mu_2}{\mu_1} \right] \rho u_f^2 + (\rho_s - \rho) g \int_0^{z'} c \, dz \] (2)

in which:

- \( \rho_s \) and \( \rho \) are the densities of the solid and fluid, respectively,
- \( \alpha^0 \) is a constant,
- \( c_0 \) and \( c_m \) are the solid concentrations corresponding to fluidity and the closest packing, respectively,
- \( \mu_0, \mu_1 \) and \( \mu_2 \) are functions of the solid concentration \( c \):

\[ \frac{\mu_1}{\rho_s d^2} = \frac{0.03}{(c_m - c)^{1.5}} \] (3)
Scheme 1. Computation of bedload under irregular waves

<table>
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<tr>
<th>Step</th>
<th>Description</th>
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<tr>
<td>1</td>
<td>Fourier decomposition of the free stream velocity input $U(t)$</td>
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<td>$U(t) = \sum_{n} U_n \sin(n \omega t + \phi_n) + \frac{1}{2} U_0$</td>
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<td>1a</td>
<td>Alternatively Fourier decomposition of the water surface elevation input $\eta(t)$</td>
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<td></td>
<td>$U(t) = \sum_{n} \eta_n \frac{n \omega}{\sinh(kh)} \sin(n \omega t + \phi_n) + \frac{1}{2} U_0$</td>
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<td>2</td>
<td>Calculation of the input root mean square value:</td>
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<td>$U_{rms} = \sqrt{\sum_{n} U_n^2}$</td>
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<td>3</td>
<td>Computation of bed roughness for irregular waves</td>
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<tr>
<td>4</td>
<td>Assumption of representative period $T_r$</td>
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<tr>
<td>5</td>
<td>Determination of parameters of representative eddy viscosity distribution: $u_{fr}$ &amp; $\delta_r$ (running Fredsøe's (1984) model with $U_{rms}$ &amp; $T_r$ as an input)</td>
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<td>6</td>
<td>Computation of representative shear stress amplitude $\rho u_f^2 B$ (using Brevik's (1981) approach with $U_{rms}$, $T_r$ &amp; eddy viscosity distribution from step &lt; 5 &gt; as an input)</td>
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<td>7</td>
<td>Computation of bed shear stress components $\tau_n$ &amp; $\phi_{rn}$ using Brevik's approach with $U_n$, $n \omega$ (from step &lt; 1 &gt; or &lt; 1a &gt;) and representative eddy viscosity (determined in step &lt; 5 &gt;) as an input</td>
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<td>Calculation of bed shear stress root mean square value:</td>
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<td>$\tau_{rms} = \sqrt{\sum_{n} \tau_n^2}$</td>
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<td>9</td>
<td>Checking whether $\rho u_f^2 B$ (step &lt; 6 &gt;) = $\tau_{rms}$ (step &lt; 7 &gt;)</td>
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<td>if NO --- correction of $T_r$ and going to step &lt; 5 &gt;</td>
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<td></td>
<td>if YES --- going to step &lt; 10 &gt;</td>
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<td>10</td>
<td>Calculation of output time series (bed shear stress):</td>
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<td>$\rho u_f^2(t) = \tau(t) = \sum_{n} \tau_n \sin(n \omega t + \phi_n + \phi_{rn})$</td>
</tr>
<tr>
<td>11</td>
<td>Calculation of bedload time series with the boundary conditions $u_f</td>
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</table>

\[
\frac{\mu_0 + \mu_2}{\rho_s d^2} = \frac{0.02}{(c_m - c)^{1.75}}. \tag{4}
\]

The value $\phi$ in Equations (1) i (2) is the quasi-static angle of internal friction, while the quantity $\psi$ is equal to:

\[
\psi = \frac{\pi}{4} - \frac{\phi}{2}. \tag{5}
\]

For the calculations the following numerical values are recommended:

\[
\frac{a_0}{\rho_s g d} = 1 \quad c_0 = 0.32 \quad c_m = 0.53 \quad \phi = 24.4^\circ.
\]

where $d$ denotes the diameter of grains.
2.2. Moveable Bed Roughness

The apparent bed roughness parameter $k_a$ is a central quantity in the model. Both the turbulent and sub-bed velocity profiles depend on $k_a$, which is not known a priori. Therefore an iteration procedure is proposed for finding the matching point $A$ between these profiles. The matching is assumed to take place at the phase of maximum shear stress, although at any other phase of oscillatory motion there must be some transition between the two profiles. The new theoretical approach for the evaluation of moveable bed roughness under regular and irregular waves, sinusoidal/asymmetric waves with/versus currents has been proposed by Kaczmarek (1995). Here, the advantage is taken of solutions obtained for the cases of regular and irregular waves without currents.

For engineering purposes it is useful to approximate the theoretical results by a curve expressed in terms of skin friction. To determine the skin friction one can follow Nielsen’s (1992) description:

$$
\theta_{2.5} = \frac{0.5 f_{2.5} (a_{1m} \omega)^2}{(s - 1) g d},
$$

$$
f_{2.5} = \exp \left[ 5.213 \left( \frac{2.5d}{a_{1m}} \right)^{0.194} - 5.977 \right]
$$

in which $s = \rho_s/\rho$.

The parameter $\theta_{2.5}$ is introduced for the sake of approximation of theoretical bed roughness and bedload results as well as presentation of experimental data.

The ability of the new theoretical approach to predict the moveable bed roughness height has been demonstrated and confirmed in various contexts by Kaczmarek (1995), Kaczmarek et al. (1995) and Kaczmarek et al. (1996) using a wide range of available laboratory and field data. The results of theoretical modelling have shown quite the opposite trend of behaviour of the roughness parameter to those suggested by many authors, where the roughness parameter increases drastically with increasing transport intensity. It has been shown that the roughness parameter decreases with increasing dimensionless maximum shear stress (Shields parameter). This finding, however, can be verified directly only by a few experimental data sets presented by Nielsen (1992) while it is consistent indirectly – via bedload quantities, friction factors etc. – with the bulk of other laboratory and field results.

The model was run for a wide range of small and large scale conditions and for a few diameters of sandy bed. Then the results were approximated yielding the following formulae for regular and irregular waves, respectively:

$$
\frac{k_a}{d} = 47.03 \theta_{2.5}^{0.66}
$$
\[ \frac{k_a}{d} = 26.64 \theta_{2.5}^{-0.71} \]  

(9)

For irregular waves \( k_a \) is calculated using Equation (9) taking root-mean-square wave height (or free stream velocity) and peak period for determination of \( \theta_{2.5} \). Then bedload rate series is modelled following steps \(< 4 >-< 11 >\) of the computational procedure shown in Scheme 1.

2.3. Bedload Transport

Once \( k_a \) is determined the velocity distributions can be computed for regions I and II, as well as the concentration of grains in the bedload layer.

Basing on Bagnold’s definition, according to which the bedload is a part of sediment transport subject to inter-granular forces, the bedload layer can be represented as region II. Knowing the instantaneous shear stress one can calculate the instantaneous bedload rate from velocity and concentration profiles in this layer:

\[ Q_B = \int_0^{\delta_s} u(z’, t)c(z’, t)dz \]  

(10)

The dimensionless bedload rate \( \Phi_B \) is defined as:

\[ \Phi_B = \frac{Q_B}{d\sqrt{(s-1)gd}} \]  

(11)

It has been found that for regular waves the present theoretical results are close to that of Meyer-Peter and their approximation yields the same exponent of 1.5, i.e.:

\[ \Phi_{B_{max}} = 3.4\theta_{2.5}^{1.5} \]  

(12)

while the approximation of the theoretical results averaged over half wave period \( T/2 \) reads:

\[ \Phi_{T/2} = 1.3\theta_{2.5}^{1.5} \]  

(13)

3. Laboratory Survey

3.1. Experimental Setup and Procedure

The measurements were carried out in the IBW PAN wave flume, 0.5 m wide and 22.5 m long, this is equipped with a programmable wave maker and can be filled with water up to 0.7 m. Reinforced concrete slabs 8 cm thick were placed on the
bottom and the sandy measuring section (also 8 cm thick) 7 m long was situated about the middle of the flume. Natural sand was used in the experiments, with the grain diameter $d_{s0} = 0.22$ mm.

For each test, free surface elevation was registered at three points along the flume. The horizontal component of free stream velocity was measured at one point of the measuring section, using a micro-propeller. The micro-propeller and one of the wave gauges were located above the sand trap. The other two wave gauges were spaced $1/4 * L$ from each other ($L$ being a wave length) to estimate the reflection effects in the flume. Experimental setup, together with sand trap, is shown in Figure 2.

The sand trap was covered by a lid and buried in the sandy section before each test. Then the waves were generated until bed ripples were fully formed, which took 25–60 minutes. The lid, suspended on four strings, was removed thereafter, together with a thin layer of sand on it. Then the wave series was continued for 1.2–15 minutes and sediment grains were being accumulated in the sand trap. Finally, the grains were siphoned from the trap and weighed with water in a measuring cylinder. Thus, the amount of sediment could be determined using the formula:

$$V = \frac{\Delta m}{\rho_s - \rho}$$

(14)

in which $\Delta m$ is the difference between mass of the cylinder with water + soil and mass of the cylinder with water only.

The sand trap had two cells to ensure the determination of onshore and offshore bedload components. The sum of these components has been assumed to represent the dimensionless bedload rate $\Phi_{T/2}$, cumulated during the time of the test.

Together with the sedimentation, bed form geometry was measured and shape assessed after each test.

3.2. Experimental Parameters and Results

During each test a constant water depth of $h = 0.5$ m was maintained above the measuring section. The measurements were carried out for six sets of parameters for regular waves (Tests 1, 2, 3, 4, 11 and 12) and six irregular wave series (Tests 5, 7, 8 for JONSWAP and Tests 6, 9, 10 for Pierson-Moskowitz spectrum generated by the wave maker). The experiments comprised a few tests for each set of wave parameters. In all, 141 series were run, among which 103 were regular.

The results for regular-asymmetric waves in comparison with theoretical bedload data, together with wave parameters, are shown in Figure 3. The conformity of theoretical evaluations and experimental data can be seen, especially while using the non-linear approach (except for Test 2). It should be pointed out that for long
Fig. 2. Experimental setup
and highly asymmetric waves, represented by Test 11 (Ursell parameter amounts to 40), the experimental data fit the present non-linear theory while they differ significantly from the linear approach. The most severe shear stress conditions without wave breaking, attaining $\theta_{2.5} = 0.4$, were achieved in Test 12, however, the Ursell parameter (equalled to 31) was less than in Test 11. In test 12 a very distinct concentration of suspended sediment was observed which could result in increased accumulation in the sand trap, bigger than theoretically modelled, using both linear and non-linear theory.

![Diagram](image)

**Fig. 3.** Bedload laboratory data vs. present linear and non-linear theory for regular waves

The detailed results for regular waves, i.e. wave parameters at the wave maker, ripple geometry, reflection coefficients and sedimentation rates, are given in Appendix – Tables 1, 2 and 3. It should be mentioned that for regular waves a few experimental sedimentation values – registered in disturbed conditions, e.g. during
occurrence of distinct scours at sand trap edges – have not been included in the plots while they are all given in Tables of Appendix, with appropriate comments.

The laboratory bedload data for irregular waves in comparison with theoretical results are depicted in Figure 4. Computed values have been modelled using the present theory, i.e. Equations (1–7), (9–11), and Scheme 1, on the basis of full-time (15 minutes) water surface elevation series registered at the measuring section. Conformity between theoretical and experimental results appears to be very good.

![Graph showing comparison between JONSWAP and Pierson-Moscowitz models](image)

**Fig. 4.** Bedload laboratory data vs. present theory for irregular waves

The irregular wave parameters at the wave maker, ripple geometry, reflection coefficients and sedimentation rates are given in the Appendix – Table 4, while the parameters computed and registered at the measuring section are presented in Table 5 of the Appendix.

Although net transport effects are not discussed in the present paper, offshore and onshore sediment transport components are distinguished in Tables 1–4 of the Appendix to provide more extensive information on the experimental results.

For the sake of full comparison the laboratory bedload data for regular and irregular waves are plotted together against the linear theory in Figure 5. The
results for irregular waves are presented as a function of dimensionless stress $\theta_{2.5}$, calculated using root-mean-square wave height and representative wave period, see Table 5 in the Appendix.

![Graph](image)

**Fig. 5.** Bedload laboratory regular and irregular data vs. present linear theory

Figure 5 implies that the bedload rate for irregular cases can be successfully modelled with the use of present linear theory taking root-mean-square wave height $H_{rms}$ and representative wave period $T_r$ as an input. It should be pointed out that computed values of $T_r$ are close to those of $T_p$, which is depicted in Table 5 of the Appendix. However, further studies are necessary to find out whether this conclusion is valid for other (wider) spectra as well.

It can also be seen from Figure 5 that for weak and moderate shear stress conditions the regular laboratory bedload data lie slightly above the results obtained using the linear theory, thus for precise determination of bedload rate under regular-asymmetric waves a non-linear approach should be used. Finally, it can be concluded that for high shear stresses the present linear theory underestimates bedload rate, most probably due to significant concentration of suspended sediment.
4. Summary and Conclusions

The paper presents the results of comparison between the original bedload theory and experimental data collected by IBW PAN laboratory. The theoretical bedload approach is based on the moveable bed boundary layer concept taking grain-grain interactions into account. The laboratory survey covers the range of ripple regime for relatively small dimensionless Shields parameter. This range is very important as there are few experimental data sets for this regime. Secondly, in this regime one can expect the equivalence of bedload and total sediment transport because the contribution of suspended load is very small.

The compliance between theoretical and experimental results appears to be very good for both regular and irregular waves. It can be concluded that for weak and moderate shear stresses the present linear theory slightly underestimates bedload rate. Hence, for precise determination of bedload rate under regular-asymmetric waves the non-linear approach should be used. For high shear stresses the present linear theory also underestimates bedload rate, however, in this regime, most probably — due to significant contribution of suspended load.

Very good results of comparison between theoretical and experimental data for irregular waves imply the usefulness of the proposed routine of bedload modelling, starting from full-time wave series, calculating reduced roughness, shear stress time series and yielding bedload transport rate series.

It is shown that the bedload rate for irregular waves can be successfully modelled with the use of present linear theory taking root-mean-square wave height and peak period as an input. This conclusion can be important in practical engineering applications.

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References


Record of bedload measurements 1996

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<th>Test No.</th>
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<th>H [m]</th>
<th>T [s]</th>
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<th>Ripple length [mm]</th>
<th>Ripple height [mm]</th>
<th>Ripple shape</th>
<th>Refl. coeff.</th>
<th>Data files</th>
<th>Accum. time [min]</th>
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Table 1a continued.

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<th>Bedload sand trap (at) side</th>
<th>Incident wave height</th>
<th>Wave crest elevation</th>
<th>Wave direction</th>
<th>Wave period</th>
<th>Wave length</th>
<th>Wave speed</th>
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**Notes:**
- Incident wave height, wave crest elevation, wave direction, wave period, wave length, wave speed, and wave energy are all measured in the trap, respectively.
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<thead>
<tr>
<th>Test No</th>
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<th>T [s]</th>
<th>Time after which the ripples were measured [min]</th>
<th>Ripple length [mm]</th>
<th>Ripple height [mm]</th>
<th>Ripple shape</th>
<th>Refl. coeff</th>
<th>Data files</th>
<th>Accum. time [min]</th>
<th>Offshore directed accum. [+] [kg]</th>
<th>Onshore directed accum. [+] [kg]</th>
<th>Remarks</th>
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<td>140</td>
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<tr>
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<td>140</td>
<td>26</td>
<td></td>
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<td>21</td>
<td>8-10 min.</td>
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<td>0.131</td>
<td>4</td>
<td>0.110</td>
<td>0.101</td>
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<td>4</td>
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<td>shore (1 cyc.)</td>
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<td>0.480</td>
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<td>0.182</td>
<td>0.282</td>
<td>Distinct crest effects at (-) &amp; (+)</td>
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<td>0.253</td>
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Table 2

L. M. Kaczmarek, R. Ostrowski
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<tr>
<th>Record of bedload measurements 1996</th>
<th>Regular waves</th>
<th>Additional tests (new conditions)</th>
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<td>A two-cell sand trap; (+) and (-) denote the onshore and offshore directed sediment accumulated in the trap, respectively.</td>
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<td>Immediate scours</td>
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<tr>
<td>126 17 asymmetric 0290.001</td>
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<td></td>
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<tr>
<td>128 19 locality 3-D 029010EF</td>
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<td>120 17</td>
<td>11.07 0.25 2.00 thicker layer of sand at the trap</td>
<td>2 0.259 0.299</td>
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<td>2 0.252 0.222</td>
<td>2 0.205 0.165</td>
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<td>1.2 0.120 0.127</td>
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<td>1.2 0.100 0.087</td>
<td>1.2 0.114 0.099</td>
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**Table 2a continued.**
### Record of bedload measurements 1996

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<th>Time after which the ripples were measured [min]</th>
<th>Ripple length [mm]</th>
<th>Ripple height [mm]</th>
<th>Ripple shape</th>
<th>Refl. coeff.</th>
<th>Data files</th>
<th>Accum. time [min]</th>
<th>Offshore directed accum. [kg]</th>
<th>Onshore directed accum. [kg]</th>
<th>Remarks</th>
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<td>0.106REF</td>
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<td>Small scour at (+)</td>
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<td>110</td>
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*Water depth h=0.5 m*

A two-cell sand trap; (+) and (-) denote the onshore and offshore directed sediment accumulated in the trap, respectively.

Table shows wave parameters at the wave maker.

Table 3.
<table>
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<tr>
<th>Test No.</th>
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<th>T [s]</th>
<th>Time after which the ripples were measured [min]</th>
<th>Ripple length [mm]</th>
<th>Ripple height [mm]</th>
<th>Ripple shape</th>
<th>Refl. coeff.</th>
<th>Data files</th>
<th>Accum. time [min]</th>
<th>Offshore directed accum. (+) [kg]</th>
<th>Onshore directed accum. (+) [kg]</th>
<th>Remarks</th>
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Water depth h=0.5 m

A two-cell sand trap; (+) and (-) denote the onshore and offshore directed sediment accumulated in the trap, respectively.

Table shows wave parameters at the wave maker.
<table>
<thead>
<tr>
<th>Test No</th>
<th>Date</th>
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<th>T (s)</th>
<th>Water depth (m)</th>
<th>Wave type (m/s)</th>
<th>Wave height (m)</th>
<th>Wave period (s)</th>
<th>Water depth (m)</th>
<th>Wave type (m/s)</th>
<th>Wave height (m)</th>
<th>Wave period (s)</th>
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<td>0.16</td>
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<td>0.19</td>
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<td>0.19</td>
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<td>0.16</td>
<td>0.19</td>
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</table>

### Table 4

A two-cell sand trap, (1) and (2) denote the onshore and offshore directed sediment accumulated in the trap, respectively.

Recorded field measurements 1998.

Irregular waves: JONSWAP (J.) & Pierson-Moskowitz (P.-M) spectra.
<table>
<thead>
<tr>
<th>Test No</th>
<th>Date</th>
<th>H [m]</th>
<th>T [s]</th>
<th>Time after which the ripples were measured [min]</th>
<th>Ripple length [mm]</th>
<th>Ripple height [mm]</th>
<th>Ripple shape</th>
<th>Refl. coeff.</th>
<th>Data files</th>
<th>Accu. time [min]</th>
<th>Offshore direct ed accum. [-] [kg]</th>
<th>Onshore direct ed accum. [-] [kg]</th>
<th>Remarks</th>
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<td>0.140</td>
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<td>PhibT2 comp.</td>
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