Bed-levelling experiments with suspended load

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ABSTRACT

Bed-leveling experiments are conducted in a straight laboratory channel. The experiments involve a significant fraction of suspended sediment transport. The purpose of the experiments is to provide data for modelling of the direction of sediment transport on a transverse sloping alluvial river bed, specifically in presence of suspended sediment transport. The transverse slope parameter for these experiments is determined.
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<td>a'</td>
<td>root mean square value of bed level variations</td>
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<td>exponent Engelund &amp; Hansen formula, bed-load part</td>
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<td>B</td>
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<td>median sand diameter</td>
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<td>g</td>
<td>gravitational acceleration</td>
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<td>i</td>
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<td>total sediment transport</td>
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<td>$\bar{u}$</td>
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<td>$u_*$</td>
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<td>$z_s$</td>
<td>water surface level</td>
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<td>$z_{sb}$</td>
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<tr>
<td>$\rho$</td>
<td>density water</td>
<td>[kg/m^3]</td>
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<td>$r$</td>
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<td>[N/m^2]</td>
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<td>$r_{bs}$</td>
<td>bed shear-stress in s-direction</td>
<td>[N/m^2]</td>
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<tr>
<td>$\psi$</td>
<td>direction bed-load transport</td>
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1 INTRODUCTION

Modelling of sediment transport on transverse inclined bed slopes is essential to mathematical models for the bed topography of alluvial rivers. For bed-load transport a limited number of empirical data is available. In the presence of suspended sediment no data are available.

The analysis of two fully developed river bend laboratory experiments (variables are constant in main flow direction) with suspended sediment transport, raised some questions concerning the magnitude of bed-slope induced sediment transport in presence of suspended load, Talmon (1991). One experiment could well be simulated. The other, with nearly the same flow conditions, but with a different median grain diameter, could not be simulated properly.

To investigate this, bed-levelling experiments in a straight flume were conducted. At the start of these, the bed is initially tilted in transverse direction. With time the transverse bed slope decreases due to transverse sediment transport. A horizontal bed finally results.

The hydraulic conditions of the experiments are chosen as close as possible to previous curved flume experiments, Talmon (1989) and Talmon & de Graaff (1990,1991). The bed-levelling experiments are conducted in a straight section of the same flume. The results of the bed-levelling experiments will be used for mathematical simulation of these curved flume experiments. The choice of the same hydraulic conditions has the additional advantage that the fraction of suspended sediment transport, determined for the curved flume experiments, also applies for the bed-levelling experiments. No concentration measurements are necessary.

Before the start of the experiments (= before an artificial transverse bed slope is prepared) the bed is horizontal. This stage is defined as the base state. At the end of the experiments the bed is again horizontal.
To simulate bed-levelling in a straight channel a simplified mathematical model may be used because of the simple geometry. The longitudinal water level slope is assumed to be parallel to the longitudinal river bed slope. In transverse direction no momentum exchange is assumed to take place. Consequently the water surface slope is constant in main and transverse direction. The physics are reduced to a time-dependent two-dimensional problem in a vertical plane perpendicular to the main flow direction. Given the same flow rate \( Q \), the water surface level associated with a transverse sloping bed is different than in case of a horizontal bed (the base state). A definition sketch is given in fig. 2.1. Except for the initial phase of the bed levelling experiments the water level variations \( \Delta z_s \) are small. In the analytical model for bed levelling, the water level variations are neglected.

Suspended sediment concentrations are assumed to be in equilibrium with local conditions. Theoretically, convective terms in main and transverse direction are zero, transverse diffusion and transverse shear-stresses are non-zero, but small. If the latter are neglected the sediment concentrations may be modelled by equilibrium concentrations profiles. At equilibrium conditions no exchange with the bed-load region takes place. Consequently suspended sediment concentrations do not have to be included in the model.
The local bed shear-stress is given by:

\[ r_{bs} = \rho gai \]  \hspace{1cm} (2.1)

By modelling the flow with a depth-averaged model the problem reduces to a time-dependent one-dimensional problem. The bed shear-stress is related to the depth-averaged velocity by:

\[ r_{bs} = \rho \frac{u^2}{g/C^2} \]  \hspace{1cm} (2.2)

The flow has to satisfy continuity. During the bed-levelling process the flow rate is constant. For a given bed topography the water surface level is determined by eq.(2.1), eq.(2.2) and the continuity equation, eq.(2.3):

\[ Q = \int_{h_w}^{h_b} u_w \, dn \]  \hspace{1cm} (2.3)

Bed-level changes are determined by the sediment continuity equation:

\[ (1-\Gamma) \frac{\partial z_b}{\partial t} = - \frac{\partial S_{\text{bed}}}{\partial n} \]  \hspace{1cm} (2.4)

Transverse sediment transport, which is due to a downslope gravity component, is modelled by a bed-load direction coefficient \( G \), which is a function of the Shields parameter \( \theta \):

\[ \tan \psi = G \frac{\partial z_b}{\partial n}, \quad G = A \theta^{-m/2} \]  \hspace{1cm} (2.5)

\[ S_{\text{bed}} n = \tan \psi \cdot S_{\text{bed}} s \]  \hspace{1cm} (2.6)

in which: \( m = \text{constant} \)

Bed-load sediment transport in main flow direction is modelled by using a formula for the total sediment transport, which is multiplied by the fraction of bed-load transport:

\[ S_{\text{tot}} = k \cdot \theta^{b/2} \]  \hspace{1cm} (2.7)
\[ S_{\text{bed}} = (1-X) S_{\text{tot}} \quad (2.8) \]

in which: \( k, b \) = constants.

The fraction of suspended sediment transport is a function of the ratio of bed shear velocity \( u_{*} = \sqrt{(\tau/\rho)} \) and the fall velocity \( w_{s} \). A graphical representation is given by van Rijn (1984, fig.18). An approximation, for \( 0.2 < X < 0.7 \), is (subscript \( b \) = base state):

\[ X = X_{b} + B \ln \left( \frac{u_{*}}{u_{*b}} \right), \quad B=0.5 \quad (2.9) \]

This way a variable fraction of suspended load is modelled explicitly.

An analytical model, developed by Struiksma, is reported by van Mierlo (1986). The model is developed for bed-load transport, and is theoretically valid for small bed amplitudes, water level changes are excluded. Using eq.(2.1) to eq.(2.9) the model is extended with suspended sediment transport, which in fact yields only a minor modification to the solution. The derivation is given in appendix A. The analytical solution as a function of time is:

\[
\begin{align*}
\Delta a_{b} &= 1 + \frac{\Delta a}{a_{b}} \sin(\pi \frac{1-X}{X_{b}}) e^{-t/T} + \left(\frac{b-m}{4} - \frac{B}{1-X_{b}}\right) \left(\frac{\Delta a}{a_{b}}\right)^2 \cos(2\pi \frac{1-X}{X_{b}}) e^{-2t/T} \\
&= 1 + \frac{\Delta a}{a_{b}} \sin(\pi \frac{1-X}{X_{b}}) e^{-t/T} + \left(\frac{b-m}{4} - \frac{B}{1-X_{b}}\right) \left(\frac{\Delta a}{a_{b}}\right)^2 \cos(2\pi \frac{1-X}{X_{b}}) e^{-2t/T} \\
\end{align*}
\[
\quad (2.10a) 
\]

in which: \( T = \left( \frac{\pi}{2} \right)^2 \frac{1}{G_{b}} \frac{1-X}{X_{b}} \frac{1}{S_{\text{tot}}} \) = characteristic time scale \quad (2.10b)

\( a \) = water depth

\( \Delta a \) = amplitude

\( G_{b} \) = \( G \) at base state
The solution consists of two goniometric functions: \( \sin(y/W) \) and \( \cos(2y/W) \), fig.2.2. The first term on the right hand side of eq.(2.10a) is the zeroth order (base state) solution. The summation of the first and second term is the first order solution. The sum of all three terms is the second order solution. The second order solution has an asymmetric bed shape. The second order contribution to the solution, the last term of eq.(2.10a), decays faster than the first order contribution, consequently with time the solution becomes more symmetric.

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\begin{align*}
W & \\
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3 THE EXPERIMENTS

The bed-levelling experiments are conducted in the straight section of a curved flume, fig. 3.1. Preceding these, five experiments at comparable hydraulic conditions were conducted in the curved section of the same flume, they are designated by: run 1...5. The channel width is \( W = 0.5 \) m. The length of the straight section used for the bed levelling experiments is about 10 m. The measuring section is located near the bend entrance, its length is 4 m. Two sand sizes are involved, median grain diameters are: \( d_{50} = 90 \) and 160 \( \mu \)m.

The bed topography is prepared manually. First the desired longitudinal bed slope is prepared. Then sand is moved in transverse direction. The bed is screened to yield a linear transverse slope. The resulting tilted bed is smooth. The first experiments, run 5 exp.1, 2 & 3, were started with such a smooth bed. It turned out that during the initial phase of these experiments the water level was quite low, because the bed roughness was not yet established. It was decided to roughen the bed artificially. This was done with a small spade (judged on the water level measurements during the initial phase of the experiments, this method turned out to reproduce fairly well).

![figure 3.1. Flume layout, bed topography of run 2](image-url)
The sand supply is effectuated by a sand feeder located near the entrance of the flume. In the bottom of the sand feeder an array of small holes is available to supply the sand. In the experiments the sand is supplied uniformly in transverse direction. In the shallow part of the flow, just beneath the sandfeeder, this sometimes lead to an accumulation of sand. If so it was removed by shoving it manually to the deeper part.

The bed topography is measured by means of cross flume traverses with a bed profile indicator (mini PROVO) at longitudinal intervals of 0.5 m. The measuring section is made up of 9 measuring cross-sections. The output of the PROVO is digitized by an A/D converter operating at 10 Hz. x,y,z and t values are recorded. At the end of a measuring session, when the bed has tilted to the horizontal, a reference measurement is made. The upper surface of a small immersed plank, which was held at known elevations at each of the 9 measuring cross-sections, is measured by the PROVO.

Water levels are read from staff gauges (read with 0.5 mm accuracy, s-interval: 2 m) attached to the glass side walls of the flume. Due to the effect of local bed forms on the water levels some scatter is noticed in the water level data.

Three parameter sets corresponding to the bend measurements run 2, run 4 and run 5, Talmon (1989), Talmon & de Graaff (1990), Talmon & de Graaff (1991), are selected for the bed-levelling experiments. For each parameter set more than one bed-levelling experiment has been conducted.

The investigation started with experiments in which the parameter values corresponded with those of the run 5 curved flume experiment. For these conditions, six experiments are conducted. This way boundary conditions or measuring techniques could be altered and the reproductivity of results could be investigated. Run 5 turned out to be the most difficult because of its tendency to develop "free bars" and because of its shallow depth in combination with relatively large ripple dimensions. In run5 exp.5 free bar development was observed after about 1.5 hour. Their wavelength was about 2-2.5 m and were most clearly observed in the deeper part of the flow. Their amplitude increased during the experiment. In run 5 exp.6 free bars were noticed after about 1 hour. Their amplitude remained small and nearly constant.
For the conditions of run 4, five experiments are conducted. The results reproduce fairly well. The effect of the length of the bed-levelling section is also investigated, no significant effects are found.

For the conditions of run 2, two experiments are conducted. The bed-levelling experiments ended with run 2.

Typical measurement durations are: run 2: 40 hours, run 4: 8 hours, run 5: 3 hours. Each run 2 experiment lasted 5 working days. For run 2 reference measurements were conducted at the end of each day. The parameters of the experiments are given in table 3.1 (not in chronological order). The water temperature during the experiments was about 18°C.

The sand supply rate is determined by weighing the sandfeeder plus contents with a spring-balance. This is done when the sand feeder is nearly empty and needs to be refilled. In these experiments this takes place circa once per week. The sand output is measured by weighing, under water, the sand gathered in a settling tank at the flume exit. The same spring-balance is used. This usually takes place when the sandfeeder is being refilled.

Equilibrium of sand transport takes time to establish. For run 2 exp.1 the bed topography in the bend was not fully developed at the start of the measurements. This explains the difference between sand in and output. The bed-level measurements indicate that the bed is eroded 2...3 mm during the experiment, fig.2.1.4. The water level during the mid- and end-phase of the experiment is circa 3...4 mm lower than the water levels measured just before the transverse bed was prepared. Run 2 exp.2 is eroded 1 mm during the experiment, fig.2.2.4. Visually run 4 seemed to be fully developed, average bed-levels remained constant during the course of the experiments. Still there is a difference between sand in and output (5%). The run 5 bed-levelling experiments were conducted following several months of experiments at these conditions (bend measurements) consequently sand in and output balance. The porosity of the 160 μm sand has been determined to be Γ=0.41-0.42.

Visual inspection of bed-levels at the side walls during the experiments revealed that the bed tilted uniformly (except for some experiments of run 5). In the beginning, the experiments have been conducted with a bed topography prepared with a constant 6 m long transverse tilted bed section. Between the horizontal bed at the sand
feeder and the tilted bed, a section of 2 m length was prepared in which
the bed slope adapted gradually. Some doubt arose during the mid and end
phase of bed-levelling. It could be possibly that the bed also levelled
due to upstream effects. From run 4 exp.4 on it was decided to enlarge
the tilted bed section in upstream direction to 10 m. Consequently the
bed at the sand feeder is also tilted. The bed-levelling data in the
measuring section shows no differences (run 4).

table 3.1 Parameter values of the experiments.

<table>
<thead>
<tr>
<th></th>
<th>d_50 [μm]</th>
<th>Q [m³/s]</th>
<th>Q_s [g/s]</th>
<th>a [m]</th>
<th>i [10⁻³]</th>
<th>Δz_b [m]</th>
<th>bed</th>
<th>tilt</th>
<th>sect.</th>
<th>comments</th>
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<tr>
<td>all</td>
<td>90</td>
<td>0.0077</td>
<td>1.17</td>
<td>1.67</td>
<td>0.069</td>
<td>1.9</td>
<td>0.05</td>
<td>rough 10</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>E.1</td>
<td>160</td>
<td>0.0098</td>
<td>4.01</td>
<td>4.29</td>
<td>0.07</td>
<td>3.06</td>
<td>0.05</td>
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<tr>
<td>E.2</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td>0.0037</td>
<td>4.24</td>
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<td>smooth 6</td>
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<td></td>
</tr>
<tr>
<td>run5</td>
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<td>smooth 6</td>
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</tr>
<tr>
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<td></td>
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<td></td>
<td>no data</td>
<td>smooth 6</td>
<td>smooth 6</td>
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<td>E.3</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>E.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>smooth 6</td>
<td>smooth 6</td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

The run 5 experiments were conducted with a PROVO that slipped
mechanically. It has been tried to eliminate associated errors during
data processing. For the bed-levelling experiments of run 2 & 4 another
mini PROVO is used.

Bed levels, as a function of time, are given in the appendices,
fig. 2.1.1, 2.2.1, 4.1.1, 4.2.1, 4.3.1, 4.4.1, 4.5.1, 5.3.1, 5.6.1. The
water surface as a function of time is also given in the appendices,
fig. 2.1.6, 2.2.6, 4.1.6, 4.2.6, 4.3.6, 4.4.6, 4.5.6, 5.3.6, 5.5.6,
5.6.6. The bed-levels are given with respect to the base state water
levels (z_sb). These were measured just before the tilted bed was
prepared or at the end of the bed-levelling experiments. To reduce
ripple associated scatter, average values of longitudinal traverses are
given (average of 9 measuring locations in s-direction).

Root mean square values of the bed-level fluctuations, with respect
to the temporal average bed topography, are a measure of the ripple
height (these are calculated on basis of 9 measurements in s-direction), appendices fig. 2.1.5, 2.2.5, 4.1.5, 4.2.5, 4.3.5, 4.4.5, 4.5.5, 5.3.5, 5.6.5. The root mean square values are listed in table 3.2. The data collected during the end-phase of the bed-leveling process is, again, associated with the base state conditions. Although it was tried to uniformly roughen the prepared bed, the ripples seemed to develop skew with respect to the main flow direction (about 10...20 degrees, the most advanced being in the deep part of the flow).

Comparison of water level data for initial smooth and rough bed preparation, indicated that within 10...20 min (run 5), roughness effects due to the initial bed preparation are absent. Run 5 exp.1, 2 & 3 are conducted with an initial smooth bed. It was observed that starting from the smooth bed, the ripples developed within 5...10 min. Run 5 exp.5 & 6 are conducted with an initial rough bed. The evolution of the water surface levels is different, fig. 5.3.6, 5.5.6 and 5.6.6, but the adaptation of the water level surface after 10...20 min is nearly the same (run 5 exp.5 seems to be prepared with a rougher initial bed than run 5 exp.6).

<table>
<thead>
<tr>
<th>Table 3.2</th>
<th>Root mean square bed level values associated with ripples</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>initial phase</td>
</tr>
<tr>
<td>run 2</td>
<td>n=-0.3W: a'=4 mm, n=-0.3W: a'=8 mm</td>
</tr>
<tr>
<td>run 4</td>
<td>n=-0.3W: a'=6 mm, n=-0.3W: a'=8 mm</td>
</tr>
<tr>
<td>run 5</td>
<td>n=-0.3W: a'=6 mm, n=-0.3W: a'=9 mm</td>
</tr>
</tbody>
</table>

The water levels increased during continuation of the experiments. If the bed roughness is assumed to be fully developed with respect to local flow conditions, this has to explained by the cross-sectional geometrical shape the channel.

The water levels as a function of the s-coordinate are given in the appendices, fig.2.1.7, 2.2.7, 4.1.7, 4.2.7, 4.3.7, 4.4.7, 4.5.7, 5.3.7, 5.5.7, 5.6.7. A definition sketch is given in fig.3.2. A backwater curve is present in run 2 and run 4. At the end of the straight channel measuring section the water level is different than at the base state. Consequently, backwater effects will also occur in the first part of the bend. Further downstream, in the second part of the curved section and the straight outflow channel, the water level is unchanged because it is determined by the local bed topography, which is hardly affected by the
bed-leveling process (except for run 2 exp.1 in which the bend topography was not developed to full extend at the beginning of the experiment).

In the first part of the straight channel the water levels may be assumed to be near the equilibrium value (longitudinal slopes of the water level and the bed are equal). The deviations in the initial phase are $\Delta z_s = 5...8$ mm.

![Figure 3.2. Definition sketch of the water surface level.](image-url)
4 TIME SCALE AND TRANSVERSE SLOPE PARAMETER

4.1 Introduction

The objective of the bed-leveling experiments is to determine G-values for suspended sediment transport.

By identifying the time scale of the process, the G-value can be determined. The relation with the time scale is given by eq.(6.10b) of the linearized analytical model. Two methods are applied.

1 Because of the exponential decay of the transverse bed slope with time, the time scale of the process can easily be determined by plotting the bed elevation difference of the measurements near the sidewalls on a logarithmic scale.

2 By applying curve-fit techniques the time scale can also be determined. This yields the possibility to estimate the confidence interval of the calculated G parameters.

The experiments are conducted in a region where backwater effects are present, consequently the problem is theoretically not s-independent. The one-dimensional bed-leveling model is valid when longitudinal slopes of the water level and the bed are the same. In the measuring section the water levels are larger than the equilibrium level due to backwater effects. For run 2 and run 4 the deviation of the water level surface $\Delta a_e$ in the measuring section at the start of the simulation from the equilibrium level is only 2 mm. A definition sketch of the water surface was given in fig.3.2.

The estimate of the time-scale yielded by the curve fit procedure is affected by the following:

- In the initial phase the alluvial roughness is not fully developed.
- The theory is valid for small bed deformation amplitudes, but it is unknown to which amplitude the model is still applicable.
- As a consequence of the tilted bed, the water surface level is lower than at the base state. This is not accounted for in the analytical model. Consequently the model may only be applied when the water level is near the base state level.
In the end phase, where the bed deformation is less than about 10% of the waterdepth, the noise due to the ripples is relatively strong.

As a consequence the whole measurement can not be used to determine the time-scale (T) of the process. The uncertainties in the time-scale are due to:

- The selected time-interval for the curve-fit procedure (start and end of time-interval).
- Given a selected time interval, the closeness of fit with the data also involves uncertainty.

The water levels do not vary much for: run 2: \( t > 500 \) min, run 4: \( t > 100 \) min, run 5: \( t > 30 \) min. These instances could be used as a lower bound of the data-intervals on which curve-fitting is performed.

### 4.2 Time-scale by curve-fitting with log-scale diagrams

The time scale of the process is determined by plotting the difference of bed elevation in the shallow and the deep part on a logarithmic scale (analogous to van Mierlo), fig.2.1.2, 2.2.2, 4.1.2, 4.2.2, 4.3.2, 4.4.2, 4.5.2, 5.3.2, 5.6.2.

The measurements during the end-phase are excluded from the analysis because of statistical fluctuations, due to the ripples, which yield negative values for the elevation difference. These can not be represented on a logarithmic scale.

The analytical model for bed-levelling eq.(2.10ab) is valid for small bed amplitudes and also assumes a certain bed shape. Consequently the initial phase is skipped. Time scales determined from the measurements (≈63% decrease of amplitude), are given in table 4.1.

<table>
<thead>
<tr>
<th>run</th>
<th>( T ) [min]</th>
<th>data interval [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>550</td>
<td>400...1400</td>
</tr>
<tr>
<td>4</td>
<td>75</td>
<td>50...200</td>
</tr>
<tr>
<td>5</td>
<td>85</td>
<td>10...110</td>
</tr>
</tbody>
</table>

The initial phases of the experiments reproduce well, fig.2.1.2, 2.2.2, 4.1.2, 4.2.2, 4.3.2, 4.4.2, 4.5.2, 5.3.2, 5.6.2. At later stages the
logarithmic representation displays more scatter and it is only possible to determine the time scale by considering more experiments.

The analysis of run 5 by this method is very difficult because of the large statistical fluctuations. Further free bars developed in some of these experiments. Fluctuations associated with ripples are filtered out, free bar effects remain in some of the data. During run 5 exp.5 & 6 more attention has been paid to the visual observation of free bars. Free bar observations are confirmed by the bed level data. In these experiments it has also been tried to suppress the development of free bars by smoothing out non-horizontal bed-levels beneath the sand feeder. The result for run 5 is still an inaccurate estimate.

4.3 Time-scale by a curve-fitting program

By using a curve-fitting program a more objective estimate of the time-scale of the process will be obtained.

From a physical point of view the data interval for the curve-fit has to be chosen carefully, otherwise the model assumptions and experimental conditions do not correspond, section 4.1. The choice of data interval affects the estimated time-scale. The start- and end-time of the data-interval are varied to investigate its effect on the estimated time scale and to determine a confidence interval for the time scale. Data at a distance of 10 cm from the flume sidewalls are used.

First the time-scale of the process is calculated for a varying end-time, the start-time is kept fixed, fig.4.1. If chosen large enough the end-time does not affect the results significantly. Consequently the choice of end-time of the data-interval is not very critical.

The next step is to investigate the effect of the choice of start-time of the data-interval on the calculated time-scale of the bed levelling process. To do so, the end-time is kept fixed. The resulting time-scale as a function of the start-time is given in fig.4.2. The results show that the initial phase of the bed-levelling experiments is not suited for the determination of the time-scale by the mathematical model. The computations show that if time-scales are determined on basis of data
Figure 4.1 Time-scale of bed-levelling as a function of the stop-time of the data-interval
figure 4.2 Time-scale of bed-levelling as a function of the start-time of the data-interval
from the initial phase, the time-scales decrease with increasing start-time. Consequently this phase has to be skipped. To determine the time-scale, however, a time-interval of sufficient length has to remain. Consequently the start- and end-time of the data-interval have to be chosen with care. The results, fig.4.2, show that if the start-time is chosen too high the results deteriorate. This is due to insufficient data being available for the curve-fit if the start-time is chosen too large. Also statistical scatter due to the relatively large ripples is affecting the results. The calculated time-scales for each experiment are given in table 4.2. Judged on the water level variations in run 5 the start-time should be chosen in the interval 20...50 min. For run 5 exp.3 the time-scale varies more than a factor 2 if the start-time is chosen in this interval. This is probably caused by the small number of data points available (it is the earliest measurement) and the small bed amplitude with respect to ripple dimensions. For this experiment the start-times are consequently chosen smaller, in the interval 10...20 min. For run 5 exp.6 again a decrease of the time-scale with the start-time is found. The number of data-points of both experiments is very small, consequently only the average value of the time scale is of any significance.

<table>
<thead>
<tr>
<th>T [min]</th>
<th>T [min]</th>
<th>T [min]</th>
<th>data interval [min]</th>
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<tbody>
<tr>
<td>run 2el</td>
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<td>e4</td>
<td>e5</td>
</tr>
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<td>526</td>
<td>97</td>
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<td>485</td>
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<td>e3</td>
<td>e4</td>
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</table>

On basis of these individual calculations, the time-scale of each series of experiments has to be determined. Fig.4.1 shows that the time-scale is still a week function of the start-time of the data interval. The choice of start-time is merely a compromise between using the model at
large bed amplitude (where the model is theoretically invalid) or using the model at a stage where the bed amplitude has already become small, but ripple associated noise could be important. The calculated time-scale for each experiment consequently involves some spread which is inherent to the choice of start-time. In all of the experiments of run 2 and run 4 the functional dependency on the start-time is the same, fig.4.1. In run 4 exp.1 & 4 the same dependency is found, but the absolute values of the calculated time-scales are different. For run 4 exp.1 this cannot be explained. The data does not differ significantly with the other experiments, fig.4.1.1. In the data of run 4 exp.4 a more rapid convergence to the horizontal is noticed, fig.4.4.1. The original data does not show a typical exponential decay. The magnitude of the time-scales of run 4 exp.1 and exp.4 seem to cancel each other out, fig.4.1.

The average time scale of each series of experiments is calculated by averaging all calculated time-scales within the chosen data-interval. The spread of this value is determined on basis of the spread which is found in each individual experiment. This spread is fundamental, because it is related to the validity of the exponential decay model. The results are given in table 4.3. Because the results are nearly independent of the choice of end-time, the stop-time in table 4.3 is indicated to be equal or greater than the stop-time used in the calculations. For run 5 only the average time-scale is given because it is unrealistic to estimate the spread for a limited number of data points and because of the experimental difficulties involved.

<table>
<thead>
<tr>
<th>run 2</th>
<th>523 + 12%</th>
<th>300...600</th>
<th>&gt;1250</th>
</tr>
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<tbody>
<tr>
<td>run 4</td>
<td>73 + 8%</td>
<td>40...80</td>
<td>&gt;200</td>
</tr>
<tr>
<td>run 5</td>
<td>77</td>
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</table>

Another source of uncertainty is the goodness of fit of the model with the data. This is related to scatter in the data and the number of data points. Estimates of the 95% confidence interval for the calculated time scale, for a fixed data-interval, are given in appendix B. The resulting 95% confidence intervals are: run 2: + 5%, run 4: + 8% and
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run 5: +/- 32% (for simplicity, it is assumed that these are independent on the choice of start- and end-times). In case of run 2 and run 4 sufficient data are available. For run 2 the data series are lengthy, for run 4 five experiments were conducted. The wide confidence interval for run 5 indicates that the time-scale for run 5 is highly inaccurate, and should only be used as an indication.

The uncertainty in the time-scale calculated by the curve-fit program and the uncertainty associated with the choice of data interval do not simply add-up. Although the latter is of fundamental nature, it will also be affected by ripple associated scatter in the data-series and the number of data-points. At this point a subjective estimate of the time-scale of each series of experiments has to be made. It seems that the time-scales of run 2 and run 4 are determined within a range of +/- 10...15%. The time-scale of run 5 is determined within: +/- 30...40%.

4.4 Values of the transverse slope parameter

The transverse bed-slope parameter (G) can be determined with eq.(2.10b). In this equation the fraction of suspended sediment transport (X) is a variable which is difficult to determine. It is preferred to calculate G(1-X) instead of G because this is more accurate. According to the mathematical model only the fraction (1-X) of the total sediment transport rate is subject to the transverse slope effect. By calculating (1-X)G, the bed-slope effect is determined irrespective of the fraction of suspended load. The variables in eq.(2.10b), which are measured in the experiments, also involve some uncertainty. The total sediment transport rate ($S_{tot}$) is the most difficult to determine accurately. The measured sand in- and output did not always balance during these experiments. The total sediment transport rate (without pores, per unit width) for run 2 is estimated to be $S_{tot} = 8.9 \times 10^{-7} \text{m}^2/\text{s} +\text{-}4\%$ (in- and output of exp.2 are used). For run 4: $S_{tot} = 3.1 \times 10^{-7} \text{m}^2/\text{s} +\text{-}3\%$. For run 5 the sediment transport rate is known very well, because it was a continuation of an experiment in the curved section of the flume. The sand transport rate was stabilized over the preceding months. It was measured frequently. The sand transport rate for run 5 is: $S_{tot} = 3.2 \times 10^{-7} \text{m}^2/\text{s} +\text{-}0.5\%$. The resulting (1-X)G product for the three experiments is given in table 4.4. The confidence
intervals are an estimate based on start-time associated uncertainty, the accuracy of the curve-fit itself and the uncertainty in the other variables. The results, together with van Mierlo's (1986) results (in these only bed-load transport occurred: X=0) and Struiksma's (1988) model for the transverse slope parameter are given in fig.4.3. Struiksma's model reads:

\[ G = \frac{E}{0.85 / \theta} \]

\( E=1 \) prototype
\( E=0.5 \) laboratory flumes

| Table 4.4 The value of the transverse slope parameter |
|---------------------------------|-----------------|-----------------|
| (1-X)G                          | \( \Theta \)    |
| run 2                           | 0.53 +15%       | 0.90            |
| run 4                           | 1.1 +15%        | 0.82            |
| run 5                           | 1.0 +40%        | 0.75            |

Figure 4.3 (1-X)G-values of the present study and of the bed-leveling experiments by van Mierlo.

If the fraction of suspended load (X=0.5) is substituted the G-values for run 4 and run 5 are more than 2 times larger than the values reported for bed-load only (van Mierlo near \( \theta=0.8 \)). The product (1-X)G, given in fig.4.3, is somewhat larger than according to van Mierlo's
data. The product \((1-X)G\) of run 2 is a factor 2 smaller than in run 4 and 5. The sand diameter in run 2 is different than in run 4 and 5.

The results of the present bed-levelling measurements do not agree with the results of bed-levelling experiments with 100% bed-load. The large difference between \(G\)-values found for suspended-load experiments with 90 & 160 \(\mu\)m sand is not understood. The following question arises: Does suspended sediment also contribute to the bed slope effect, or are \(G\)-values simply larger than in 100% bed-load situations (at the same \(\theta\) values)?

The results show that in morphological models for conditions with suspended sediment transport, the transverse slope parameter \((G)\) can not be simply taken the same as in 100% bed-load conditions.
5 CONCLUSIONS

Parameter values for the effect of a transverse bed slope on the direction of sediment transport has been determined from bed-levelling experiments. In these experiments about 50% of the bed material is transported as suspended-load. The bed-levelling experiments are conducted for three different experimental conditions. For each condition more than one experiment is conducted.

The results are analysed by a linearized analytical model. The experiments are prepared with a relatively large bed-amplitude. The results show that the linearized model is not applicable in the initial phase of bed levelling when the bed amplitude is still relatively large.

If the product of the fraction of bed-load transport times the transverse slope parameter is considered \((1-X)G\), the transverse slope effect irrespective of the fraction of suspended-load is yielded. This product is determined by curve-fitting methods. The accuracy of the results is estimated.

It is remarkable that the transverse slope effect differs about a factor 2 for situations, with suspended-load, in which the hydraulic conditions are the same but median sand diameters are different. Shields parameter values do not differ much.

Whichever way the results are compared with those of bed-levelling experiments with 100% bed-load, the results do not agree.

The results show that in morphological models for conditions with suspended sediment transport, the value of the transverse slope parameter \((G)\) can not be simply taken identical as in 100% bed-load conditions.
REFERENCES

Mierlo, M.C.L.M. van, 1986, Rivers, Influence of a sloping bed on the sediment transport direction, Delft Hydraulics, R 657-XXIX, Q 186.

Struiksma, N., 1988, RIVCOM: A summary of results of some test computations, Delft Hydraulics, Q 794.


APPENDIX A  ANALYTICAL MODEL FOR TIME-DEPENDENT BED-LEVELLING

The sediment continuity equation in a uniform straight channel is given by:

\[ \frac{\partial}{\partial t} \left( G \frac{\partial z_b}{\partial n} S_{\text{bed}} s \right) - (1-\Gamma) \frac{\partial z_b}{\partial t} = 0 \]  \hspace{1cm} (A.1)

This is equal to (G and \( S_{\text{bed}} s \) are a function of \( \theta \)):

\[ \frac{G S_{\text{bed}} s}{1-\Gamma} \left[ \frac{1}{S_{\text{bed}} s} \frac{\partial S_{\text{bed}} s}{\partial n} - G \frac{\partial l/G}{\partial n} \left( \frac{\partial z_b}{\partial n} \right)^2 + \frac{\partial^2 z_b}{\partial n^2} \right] - \frac{\partial z_b}{\partial t} = 0 \]  \hspace{1cm} (A.2)

The local water depth is approximated by an asymptotic expansion:

\[ a = a_0 + \epsilon a_1 + \epsilon^2 a_2 + \ldots \]  \hspace{1cm} (A.3)

in which: \( \epsilon \) - a small parameter

\[ a_i = i^{th} \text{ order contribution, } O(1) \]

The zeroth order solution is the base state (= when the bed is levelled horizontally). Through eq.(6.1) the Shields parameter is linearly related to the water depth. The asymptotic approximations of bed load sediment transport and the direction of transverse bed slope induced sediment transport are given by:

\[ S_{\text{bed}} s = S_{\text{bed}} s_0 + \epsilon S_{\text{bed}} s_1 + \epsilon^2 S_{\text{bed}} s_2 + \ldots \]  \hspace{1cm} (A.4)

\[ G = G_0 + \epsilon G_1 + \epsilon^2 G_2 + \ldots \]  \hspace{1cm} (A.5)

Substitution of eq.(6.5), eq.(6.7), eq.(6.8) and eq.(6.9) yields:

\[ S_{\text{bed}} s = S_{\text{tot}} \left( (1-X_b) + \epsilon \left( \frac{\partial}{\frac{1}{2} (1-X_b) - \frac{B}{2} \frac{a_1}{a_0} \right) + \ldots \right) \]  \hspace{1cm} (A.6)
The water level is assumed not to vary during bed levelling. Substitution of eq. (A.6) and eq. (A.7) in eq. (A.2) and collecting terms with respect to the small parameter $\epsilon$ yields:

\[ \epsilon \left[ \frac{1-X_b}{1-\Gamma} G_b S_{tot} \frac{\partial^2 a_1}{\partial n^2} - \frac{\partial a_1}{\partial t} \right] + \]

\[ + \epsilon^2 \left[ \frac{1-X_b}{1-\Gamma} G_b S_{tot} \left( \frac{b}{2} (\frac{B}{2} - b) \left( \frac{1}{a_0} \frac{\partial a_1}{\partial n} \right)^2 + \frac{a_1}{a_0} \frac{\partial^2 a_1}{\partial n^2} \right) - \frac{\partial a_2}{\partial t} \right] + \]

\[ + \ldots = 0 \quad (A.8) \]

The first order solution is (the solution of the $\epsilon$ terms):

\[ \frac{a_1}{a_0} = -t/T \quad \frac{n}{n_W} \quad \sin(n_W) \quad (A.9) \]

in which: \[ T = \left( \frac{\pi^2}{\pi^2} \frac{1}{G_b} \frac{1-\Gamma}{1-X_b} \frac{1}{S_{tot}} \right) \quad (A.10) \]

The second order solution (the solution of the $\epsilon^2$ terms) is obtained by separation of variables. The second order contribution to the water depth is split into:

\[ a_2 = c a_2_n a_2_t \quad (A.11) \]

in which: \[ c = \text{constant} \]

\[ a_2_n = a_2(n) \]

\[ a_2_t = a_2(t) \]
Substitution of the first order solution eq.(A.9) and eq.(A.11) in the second order part of eq.(A.8) yields:

\[
\frac{1-X_b}{1-\Gamma} G_s \text{tot} \left( \frac{b B/2}{1-X_b} \right) \left( \frac{\pi}{W} \right)^2 a_0 \frac{-2t/T}{2a_t} e^{-\frac{a_0}{2a_t}} \cos(2\pi \frac{n}{W}) + \frac{1}{a_2y} \frac{\partial^2 a_2y}{\partial n^2} = \frac{-1}{a_2t} \frac{\partial a_2t}{\partial t} \tag{A.11}
\]

The solution of the right hand side is no function of \(n\). The left hand side is supposed not to be a function of \(t\). Consequently:

\[
a_{2t} = e^{-2t/T} \tag{A.12}
\]

Both sides are constant and independent of \(n\) and \(t\). The right hand side is equal to:

\[
\frac{1}{a_{2t}} \frac{\partial a_{2t}}{\partial t} = -2 \left( \frac{\pi}{W} \right)^2 \frac{1-X_b}{1-\Gamma} G_s \text{tot} \tag{A.13}
\]

The \(y\) dependent part of \(a_{2n}\) is obtained by solving eq.(A.11) with eq.(A.13) is substituted. The resulting equation reads:

\[
\left( \frac{b B/2}{2 \cdot 1-X_b} \right) \left( \frac{\pi}{W} \right)^2 \frac{a_0}{ca_{2n}} \cos(2\pi \frac{n}{W}) + 2 \left( \frac{\pi}{W} \right)^2 + \frac{1}{a_2n} \frac{\partial^2 a_2n}{\partial n^2} = 0
\]

The solution is:

\[
\frac{ca_{2y}}{a_0} = \frac{1}{2} \left( \frac{b B/2}{2 \cdot 1-X_b} \right) \cos(2\pi \frac{n}{W}) \tag{A.14}
\]

The second order approximation of the bed level is consequently given by:
\[
\frac{a}{a_0} = 1 + \epsilon e^{-t/T} \sin\left(\frac{\pi n}{W}\right) + \epsilon^2 \frac{1}{2} \left( \frac{b}{2} \frac{B/2 - W}{1 - X_b} \right) e^{-2t/T} \cos\left(2\frac{\pi n}{W}\right)
\]  
(A.15)

The small parameter \( \epsilon \) is determined by the initial condition at \( t=0 \). The initial amplitude at the side walls is of the order \( \epsilon \). For the analysis to be theoretically valid only small initial bed amplitudes are allowed, because otherwise the asymptotic expansion of the sediment transport formula is inappropriate, eq.(A.6) (more terms should be incorporated).

The solution shows that higher order modes disappear faster. At the side walls the solution yields \( \delta a/\delta n=0 \), consequently sediment continuity is satisfied. The analysis, however, does not satisfy the flow continuity equation because water level variations are not included. For small amplitude bed deformations these are very small and can be neglected.
APPENDIX B: CONFIDENCE INTERVAL ON CALCULATED TIME-SCALE FOR FIXED START- AND END-TIME OF THE DATA-INTERVAL

The calculated time-scale by the curve-fitting programme also involves some uncertainty. This is associated with the goodness of fit of the curve (function) with the data. Confidence intervals for the calculated parameters are given by the program.

If the same time intervals are used as for the graphical determination of the time scale, section 4.2, the resulting estimated time scale and its 95% confidence interval are given in table B.1. The data 10 cm remote from the side walls is used. The curve-fit programme has yielded for each experiment an estimate of the variance of T. The 95% confidence interval is given by \( \pm 2\sigma \), with \( \sigma = \sqrt{\text{var} T} \). The average of these for a particular run divided by the square root of the number of experiments yields the variance of the estimated time scale of the process. The results are given in table B.2.

\[
T = \frac{(T_1 + \ldots + T_n)}{n}
\]
\[
\text{var} T = \frac{(\text{var} T_1 + \ldots + \text{var} T_n)}{\sqrt{n}}
\]

**Table B.1. Time scales and confidence interval by curve-fit**

<table>
<thead>
<tr>
<th>run</th>
<th>T [min]</th>
<th>95% confidence</th>
<th>data interval [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2e1</td>
<td>543</td>
<td>( \pm 6% )</td>
<td>400...1400</td>
</tr>
<tr>
<td>e2</td>
<td>513</td>
<td>( \pm 9% )</td>
<td>400...1400</td>
</tr>
<tr>
<td>4e1</td>
<td>96</td>
<td>( \pm 27% )</td>
<td>50...200</td>
</tr>
<tr>
<td>e2</td>
<td>74</td>
<td>( \pm 14% )</td>
<td>50...200</td>
</tr>
<tr>
<td>e3</td>
<td>72</td>
<td>( \pm 16% )</td>
<td>50...200</td>
</tr>
<tr>
<td>e4</td>
<td>50</td>
<td>( \pm 14% )</td>
<td>50...200</td>
</tr>
<tr>
<td>e5</td>
<td>75</td>
<td>( \pm 18% )</td>
<td>50...200</td>
</tr>
<tr>
<td>5e3</td>
<td>68</td>
<td>( \pm 49% )</td>
<td>10...110</td>
</tr>
<tr>
<td>e6</td>
<td>78</td>
<td>( \pm 41% )</td>
<td>10...110</td>
</tr>
</tbody>
</table>

**Table B.2. Time scales and confidence interval by curve-fit**

<table>
<thead>
<tr>
<th>run</th>
<th>T [min]</th>
<th>95% confidence</th>
<th>data interval [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>529</td>
<td>( \pm 5% )</td>
<td>400...1400</td>
</tr>
<tr>
<td>4</td>
<td>73</td>
<td>( \pm 8% )</td>
<td>50...200</td>
</tr>
<tr>
<td>5</td>
<td>73</td>
<td>( \pm 32% )</td>
<td>10...110</td>
</tr>
</tbody>
</table>
APPENDIX 2.1 RUN 2 EXPERIMENT 1

DATA: RUN 2 EXPERIMENT 1

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{50}$ median diameter</td>
<td>90 $[\mu m]$</td>
<td></td>
</tr>
<tr>
<td>Q flow rate</td>
<td>0.0077 $[m^3/s]$</td>
<td></td>
</tr>
<tr>
<td>$Q_{s_{in}}$ transport rate</td>
<td>1.17 $[g/s]$</td>
<td></td>
</tr>
<tr>
<td>$Q_{s_{out}}$ transport rate</td>
<td>1.67 $[g/s]$</td>
<td></td>
</tr>
<tr>
<td>a average water depth</td>
<td>0.069 $[m]$</td>
<td></td>
</tr>
<tr>
<td>$\Delta z_b$ deformation ampl.</td>
<td>0.05 $[m]$</td>
<td></td>
</tr>
<tr>
<td>i base state ch. slope</td>
<td>$1.9*10^{-3}$ [-]</td>
<td>from run2 bend exp.</td>
</tr>
<tr>
<td>$T_{meas}$ measuring period</td>
<td>2000 $[min]$</td>
<td></td>
</tr>
<tr>
<td>X fraction susp. load</td>
<td>0.55 [-]</td>
<td></td>
</tr>
<tr>
<td>C Chézy</td>
<td>19 $[^{1/3}]$ $[m^3/s]$</td>
<td></td>
</tr>
<tr>
<td>U average velocity</td>
<td>0.22 $[m/s]$</td>
<td></td>
</tr>
<tr>
<td>$\theta$ average Shields val.</td>
<td>0.88 [-]</td>
<td></td>
</tr>
</tbody>
</table>

base state water level slope determined for:
- in flowing state before the transverse bed is prepared
- for $t>1500$ min
BED LEVELLING RUN2, EXP.1

FIG. 2.1.1 BED LEVEL AS A FUNCTION OF TIME
FIG. 2.1.2 BED ELEVATION DIFFERENCES

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FIG. 2.1.3 TRANSVERSE BED PROFILES
FIG. 2.1.4 WIDTH-AVERAGED BED LEVEL

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BED LEVELLING RUN2 EXP.1
Root Mean Square Values of Bed Level

FIG. 2.1.5
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BED LEVELLING RUN2, EXP.1

WATER LEVELS AT GAUGES

FIG. 2.1.6

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BED LEVELLING RUN2, EXP. 1

WATER SURFACE LEVEL AS A FUNCTION OF TIME

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FIG. 2.1.7
APPENDIX 2.2 RUN 2 EXPERIMENT 2

DATA: RUN 2 EXPERIMENT 2

<table>
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<tr>
<th>parameter</th>
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<tbody>
<tr>
<td>$d_{50}$ median diameter</td>
<td>90 [µm]</td>
<td></td>
</tr>
<tr>
<td>Q flow rate</td>
<td>0.0077 [m$^3$/s]</td>
<td></td>
</tr>
<tr>
<td>$Q_s$ in transport rate</td>
<td>1.14 [g/s]</td>
<td></td>
</tr>
<tr>
<td>$Q_s$ out transport rate</td>
<td>1.23 [g/s]</td>
<td></td>
</tr>
<tr>
<td>a average water depth</td>
<td>0.069 [m]</td>
<td></td>
</tr>
<tr>
<td>$\Delta z_b$ deformation ampl.</td>
<td>0.05 [m]</td>
<td></td>
</tr>
<tr>
<td>i base state ch. slope</td>
<td>1.9*10^{-3} [-]</td>
<td></td>
</tr>
<tr>
<td>$T_{meas}$ measuring period</td>
<td>2000 [min]</td>
<td></td>
</tr>
<tr>
<td>X fraction susp. load</td>
<td>0.55 [-]</td>
<td>from run2 bend exp.</td>
</tr>
<tr>
<td>C Chézy</td>
<td>19 [m$^4$/s]</td>
<td></td>
</tr>
<tr>
<td>U average velocity</td>
<td>0.22 [m/s]</td>
<td></td>
</tr>
<tr>
<td>$\theta$ average Shields val.</td>
<td>0.88 [-]</td>
<td></td>
</tr>
</tbody>
</table>

base state water level slope determined for:
- in flowing state before the transverse bed is prepared
- for t>1500 min
BED LEVELLING RUN2, EXP.2

FIG. 2.2.1 BED LEVEL AS A FUNCTION OF TIME

FIG. 2.2.2. BED ELEVATION DIFFERENCES

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BED LEVELLING RUN 2 EXP.2

FIG. 2.2.3 TRANSVERSE BED PROFILES

FIG. 2.2.4 WIDTH-AVERAGED BED LEVEL

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BED LEVELLING RUN2, EXP.2

r.m.s values of bed level, at n=-0.4W

BED LEVELLING RUN2, EXP.2

r.m.s values of bed level, at n=0.4W

FIG. 2.2.5

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BED LEVELLING RUN2, EXP.2

WATER LEVELS AT GAUGES

FIG. 2.2.6

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BED LEVELLING RUN2, EXP.2

WATER SURFACE LEVEL AS A FUNCTION OF TIME

DELFT UNIVERSITY OF TECHNOLOGY
APPENDIX 4.1 RUN 4 EXPERIMENT 1

DATA: RUN 4 EXPERIMENT 1

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{50}$ median diameter</td>
<td>160 $\mu$m</td>
<td></td>
</tr>
<tr>
<td>$Q$ flow rate</td>
<td>0.0098 m$^3$/s</td>
<td></td>
</tr>
<tr>
<td>$Q_s$ in transport rate</td>
<td>4.01 g/s</td>
<td>average of 5 experiments</td>
</tr>
<tr>
<td>$Q_s$ out transport rate</td>
<td>4.29 g/s</td>
<td>average of 5 experiments</td>
</tr>
<tr>
<td>$a$ average water depth</td>
<td>0.07 m</td>
<td></td>
</tr>
<tr>
<td>$\Delta z_b$ deformation ampl.</td>
<td>0.05 m</td>
<td></td>
</tr>
<tr>
<td>$i$ base state ch. slope</td>
<td>$3.06 \times 10^{-3}$ [-]</td>
<td>for $t&gt;120$ min</td>
</tr>
<tr>
<td>$T_{meas}$ measuring period</td>
<td>360 min</td>
<td></td>
</tr>
<tr>
<td>$X$ fraction susp. load</td>
<td>0.50 [-]</td>
<td>from run4 bend exp. (corrected)</td>
</tr>
<tr>
<td>$C$ Chézy</td>
<td>19 $m^2$/s</td>
<td></td>
</tr>
<tr>
<td>$U$ average velocity</td>
<td>0.28 m/s</td>
<td></td>
</tr>
<tr>
<td>$\theta$ average Shields val.</td>
<td>0.81 [-]</td>
<td></td>
</tr>
</tbody>
</table>
BED LEVELLING RUN 4, EXP. 1

**FIG. 4.1.1** BED LEVEL AS A FUNCTION OF TIME

**FIG. 4.1.2** BED ELEVATION DIFFERENCES

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BED LEVELLING RUN4, EXP.1

FIG. 4.1.3 TRANSVERSE BED PROFILES

FIG. 4.1.4 WIDTH-AVERAGED BED LEVEL

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BED LEVELLING RUN4, EXP.1
r.m.s values of bed level, at n=−0.4W

$z'_b$ [cm]

BED LEVELLING RUN4, EXP.1
r.m.s values of bed level, at n=0.4W

$z'_b$ [cm]

FIG. 4.1.5
BED LEVELLING RUN4 EXP.1
ROOT MEAN SQUARE VALUES OF BED LEVEL
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BED LEVELLING RUN4, EXP.1
WATER SURFACE LEVEL AS A FUNCTION OF TIME

FIG. 4.1.7
### APPENDIX 4.2 RUN 4 EXPERIMENT 2

**DATA: RUN 4 EXPERIMENT 2**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
<th>Comment</th>
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<tr>
<td>$d_{50}$ median diameter</td>
<td>160</td>
<td>$\mu$m</td>
<td></td>
</tr>
<tr>
<td>Q flow rate</td>
<td>0.0098</td>
<td>$m^3/s$</td>
<td></td>
</tr>
<tr>
<td>$Q_s$ in transport rate</td>
<td>4.01</td>
<td>$g/s$</td>
<td>average of 5 experiments</td>
</tr>
<tr>
<td>$Q_s$ out transport rate</td>
<td>4.29</td>
<td>$g/s$</td>
<td>average of 5 experiments</td>
</tr>
<tr>
<td>a average water depth</td>
<td>0.07</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>$\Delta z_b$ deformation ampl.</td>
<td>0.05</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>i base state ch. slope</td>
<td>$3.15 \times 10^{-3}$</td>
<td>[-]</td>
<td>for $t&gt;120$ min</td>
</tr>
<tr>
<td>$T_{meas}$ measuring period</td>
<td>290</td>
<td>min</td>
<td></td>
</tr>
<tr>
<td>X fraction susp. load</td>
<td>0.50</td>
<td>[-]</td>
<td>from run4 bend exp. (corrected)</td>
</tr>
<tr>
<td>C Chézy</td>
<td>19</td>
<td>$m^4/s$</td>
<td></td>
</tr>
<tr>
<td>U average velocity</td>
<td>0.28</td>
<td>$m/s$</td>
<td></td>
</tr>
<tr>
<td>$\theta$ average Shields val.</td>
<td>0.84</td>
<td>[-]</td>
<td></td>
</tr>
</tbody>
</table>
BED LEVELLING RUN4, EXP.2

**FIG. 4.2.1** BED LEVEL AS A FUNCTION OF TIME

**FIG. 4.2.2** BED ELEVATION DIFFERENCES

DELTFT UNIVERSITY OF TECHNOLOGY
BED LEVELLING RUN4, EXP.2

**Transverse bed profiles**

\[ z_{sb} - z_b \] [cm]

- \( t = 2 \) min.
- \( t = 10 \) min.
- \( t = 30 \) min.
- \( t = 60 \) min.
- \( t = 90 \) min.
- \( t > 240 \) min.

**Width-averaged bed level**

\[ z_{sb} - z_b \] [cm]

0 100 200 300 400

0 5 10 15 20 25 30

FIG. 4.2.3 TRANSVERSE BED PROFILES
FIG. 4.2.4 WIDTH-AVERAGED BED LEVEL

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BED LEVELLING RUN4, EXP. 2
r.m.s values of bed level, at n=−0.4W

FIG. 4.2.5
DELFt UNIVERSITY OF TECHNOLOGY
BED LEVELLING RUN4, EXP.2

WATER LEVELS AT GAUGES

FIG. 4.2.6

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BED LEVELLING RUN4, EXP.2

WATER SURFACE LEVEL AS A FUNCTION OF TIME

FIG. 4.2.7

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APPENDIX 4.3 RUN 4 EXPERIMENT 3

DATA: RUN 4 EXPERIMENT 3

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{50}$ median diameter</td>
<td>160 [μm]</td>
<td></td>
</tr>
<tr>
<td>$Q$ flow rate</td>
<td>0.0098 $m^3/s$</td>
<td></td>
</tr>
<tr>
<td>$Q_s$ in transport rate</td>
<td>4.01 [g/s]</td>
<td>average of 5 experiments</td>
</tr>
<tr>
<td>$Q_s$ out transport rate</td>
<td>4.29 [g/s]</td>
<td>average of 5 experiments</td>
</tr>
<tr>
<td>$a$ average water depth</td>
<td>0.069 [m]</td>
<td></td>
</tr>
<tr>
<td>$\Delta z_b$ deformation ampl.</td>
<td>0.05 [m]</td>
<td></td>
</tr>
<tr>
<td>$i$ base state ch. slope</td>
<td>$3.01 \times 10^{-3}$ [-]</td>
<td>for $t&gt;120$ min</td>
</tr>
<tr>
<td>$T_{meas}$ measuring period</td>
<td>330 [min]</td>
<td></td>
</tr>
<tr>
<td>$X$ fraction susp. load</td>
<td>0.50 [-]</td>
<td>from run4 bend exp. (corrected)</td>
</tr>
<tr>
<td>$C$ Chézy</td>
<td>19 $m^4/s$</td>
<td></td>
</tr>
<tr>
<td>$U$ average velocity</td>
<td>0.28 [m/s]</td>
<td></td>
</tr>
<tr>
<td>$\theta$ average Shields val.</td>
<td>0.79 [-]</td>
<td></td>
</tr>
</tbody>
</table>
BED LEVELLING RUN4, EXP.3

Figure 4.3.1: Bed level as a function of time.

Figure 4.3.2: Bed elevation differences.

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BED LEVELLING RUN4, EXP.3

transverse bed profiles

\[ z_{sb} - z_{b} \text{ [cm]} \]

\[
\begin{align*}
&\square \ t = 2 \text{ min.} \\
&\bigstar \ t = 10 \text{ min.} \\
&\diamond \ t = 30 \text{ min.} \\
&\triangleleft \ t = 60 \text{ min.} \\
&\times \ t = 90 \text{ min.} \\
&\triangle \ t > 240 \text{ min.}
\end{align*}
\]

BED LEVELLING RUN4, EXP.3

width-averaged bed level

\[ z_{sb} - z_{b} \text{ [cm]} \]

\[
\begin{align*}
&0 \quad 100 \quad 200 \quad 300 \quad 400 \\
&0 \quad 0.5 \quad 1.0 \quad 1.5 \quad 2.0 \quad 2.5 \quad 3.0 \quad 3.5 \quad 4.0 \quad 4.5 \quad 5.0 \quad 5.5 \quad 6.0 \\
&6.0 \quad 6.5 \quad 7.0 \quad 7.5 \quad 8.0 \\
&0 \quad 100 \quad 200 \quad 300 \quad 400 \\
&\text{time [min]}
\end{align*}
\]

BED LEVELLING RUN4 EXP.3

FIG. 4.3.3 TRANSVERSE BED PROFILES
FIG. 4.3.4 WIDTH-AVERAGED BED LEVEL

DELFt UNIVERSITY OF TECHNOLOGY
BED LEVELLING RUN4, EXP. 3
r.m.s values of bed level, at $n=-0.4W$

$z'_b$ [cm]

0.0
0.5
1.0
1.5
2.0

0 100 200 300 400

BED LEVELLING RUN4, EXP. 3
r.m.s values of bed level, at $n=0.4W$

$z'_b$ [cm]

0.0
0.5
1.0
1.5
2.0

0 100 200 300 400

FIG. 4.3.5

BED LEVELLING RUN4 EXP. 3
ROOT MEAN SQUARE VALUES OF BED LEVEL

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BED LEVELLING RUN4, EXP.3
WATER LEVELS AT GAUGES

DELFT UNIVERSITY OF TECHNOLOGY
BED LEVELLING RUN4, EXP.3
WATER SURFACE LEVEL AS A FUNCTION OF TIME

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FIG. 4.3.7
### DATA: RUN 4 EXPERIMENT 4

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_{50})</td>
<td>median diameter</td>
<td>160 [(\mu m)]</td>
</tr>
<tr>
<td>(Q)</td>
<td>flow rate</td>
<td>0.0098 [m(^3)/s]</td>
</tr>
<tr>
<td>(Q_s) in</td>
<td>transport rate</td>
<td>4.01 [g/s]</td>
</tr>
<tr>
<td>(Q_s) out</td>
<td>transport rate</td>
<td>4.29 [g/s]</td>
</tr>
<tr>
<td>(a)</td>
<td>average water depth</td>
<td>0.07 [m]</td>
</tr>
<tr>
<td>(\Delta z_b)</td>
<td>deformation ampl.</td>
<td>0.05 [m]</td>
</tr>
<tr>
<td>(i)</td>
<td>base state ch. slope</td>
<td>(3.20 \times 10^{-3}) [-] for (t&gt;120) min</td>
</tr>
<tr>
<td>(T_{\text{meas}})</td>
<td>measuring period</td>
<td>330 [min]</td>
</tr>
<tr>
<td>(X)</td>
<td>fraction susp. load</td>
<td>0.50 [-] from run4 bend exp. (corrected)</td>
</tr>
<tr>
<td>(C)</td>
<td>Chézy</td>
<td>19 [(m^2/s)]</td>
</tr>
<tr>
<td>(U)</td>
<td>average velocity</td>
<td>0.28 [m/s]</td>
</tr>
<tr>
<td>(\theta)</td>
<td>average Shields val.</td>
<td>0.85 [-]</td>
</tr>
</tbody>
</table>
BED LEVELLING RUN 4, EXP. 4

Fig. 4.4.1 Bed level as a function of time

Fig. 4.4.2 Bed elevation differences

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BED LEVELLING RUN4, EXP.4

FIG. 4.4.3 TRANSVERSE BED PROFILES

FIG. 4.4.4 WIDTH-AVERAGED BED LEVEL

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BED LEVELLING RUN4, EXP. 4

r.m.s. values of bed level, at n = 0.4W

$z_b' [cm]$ vs. time [min]

Fig. 4.4.5

BED LEVELLING RUN4, EXP. 4

r.m.s. values of bed level, at n = 0.4W

$z_b' [cm]$ vs. time [min]

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BED LEVELLING RUN4 EXP. 4
ROOT MEAN SQUARE VALUES OF BED LEVEL

FIG. 4.4.5
BED LEVELLING RUN4, EXP.4

WATER LEVELS AT GAUGES

FIG. 4.4.6

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BED LEVELLING RUN4, EXP.4
WATER SURFACE LEVEL AS A FUNCTION OF TIME

DELFT UNIVERSITY OF TECHNOLOGY
APPENDIX 4.5  RUN 4 EXPERIMENT 5

DATA: RUN 4 EXPERIMENT 5

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{50}$ median diameter</td>
<td>160 $\mu$m</td>
<td></td>
</tr>
<tr>
<td>Q flow rate</td>
<td>0.0098 $m^3/s$</td>
<td>average of 5 experiments</td>
</tr>
<tr>
<td>$Q_s$ in transport rate</td>
<td>4.01 g/s</td>
<td>average of 5 experiments</td>
</tr>
<tr>
<td>$Q_s$ out transport rate</td>
<td>4.29 g/s</td>
<td>average of 5 experiments</td>
</tr>
<tr>
<td>a average water depth</td>
<td>0.07 m</td>
<td></td>
</tr>
<tr>
<td>$\Delta z_b$ deformation ampl.</td>
<td>0.05 m</td>
<td></td>
</tr>
<tr>
<td>i base state ch. slope</td>
<td>$3.08 \times 10^{-3}$ [-]</td>
<td>for t&gt;120 min</td>
</tr>
<tr>
<td>$T_{meas}$ measuring period</td>
<td>330 min</td>
<td></td>
</tr>
<tr>
<td>X fraction susp. load</td>
<td>0.50 [-]</td>
<td>from run4 bend exp. (corrected)</td>
</tr>
<tr>
<td>C Chézy</td>
<td>19 $m^3/s$</td>
<td></td>
</tr>
<tr>
<td>U average velocity</td>
<td>0.28 m/s</td>
<td></td>
</tr>
<tr>
<td>$\theta$ average Shields val.</td>
<td>0.82 [-]</td>
<td></td>
</tr>
</tbody>
</table>
BED LEVELLING RUN4, EXP.5

FIG. 4.5.1 BED LEVEL AS A FUNCTION OF TIME
FIG. 4.5.2 BED ELEVATION DIFFERENCES

DELFT UNIVERSITY OF TECHNOLOGY
BED LEVELLING RUN4, EXP.5
r.m.s values of bed level, at n=-0.4W

FIG. 4.5.5
DELFT UNIVERSITY OF TECHNOLOGY
BED LEVELLING RUN 4, EXP. 5

WATER LEVELS AT GAUGES

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FIG. 4.5.6
BED LEVELLING RUN4, EXP.5

WATER SURFACE LEVEL AS A FUNCTION OF TIME

FIG. 4.5.7

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## APPENDIX 5.3 RUN 5 EXPERIMENT 3

### DATA: RUN 5 EXPERIMENT 3

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{50}$ median diameter</td>
<td>160 [µm]</td>
<td></td>
</tr>
<tr>
<td>$Q$ flow rate</td>
<td>0.0037 [m$^3$/s]</td>
<td></td>
</tr>
<tr>
<td>$Q_s$ in transport rate</td>
<td>4.24 [g/s]</td>
<td>preceeding bend exp.</td>
</tr>
<tr>
<td>$Q_s$ out transport rate</td>
<td>4.24 [g/s]</td>
<td>preceeding bend exp.</td>
</tr>
<tr>
<td>$a$ average water depth</td>
<td>0.033 [m]</td>
<td></td>
</tr>
<tr>
<td>$\Delta z_b$ deformation ampl.</td>
<td>0.02 [m]</td>
<td></td>
</tr>
<tr>
<td>$i$ base state ch. slope</td>
<td>6.0*10$^{-3}$ [-]</td>
<td>preceeding bend exp.</td>
</tr>
<tr>
<td>$T_{meas}$ measuring period</td>
<td>110 [min]</td>
<td></td>
</tr>
<tr>
<td>$X$ fraction susp. load</td>
<td>0.50 [-]</td>
<td>from run5 bend exp.</td>
</tr>
<tr>
<td>$C$ Chézy</td>
<td>16 [m$^1$/s]</td>
<td></td>
</tr>
<tr>
<td>$U$ average velocity</td>
<td>0.22 [m/s]</td>
<td></td>
</tr>
<tr>
<td>$\theta$ average Shields val.</td>
<td>0.75 [-]</td>
<td></td>
</tr>
</tbody>
</table>
**BED LEVELLING RUN5 EXP.3**

**FIG. 5.3.1** BED LEVEL AS A FUNCTION OF TIME

**FIG. 5.3.2** BED ELEVATION DIFFERENCES

DELFT UNIVERSITY OF TECHNOLOGY
BED LEVELLING RUNS EXP.3
r.m.s. values of bed level, at n=-0.3W

$z_b' [\text{cm}]$

0.0 0.5 1.0 1.5 2.0

0 20 40 60 80 100 120 140 160 180

time [min]

BED LEVELLING RUNS EXP.3
r.m.s. values of bed level, at n=0.3W

$z_b' [\text{cm}]$

0.0 0.5 1.0 1.5 2.0

0 20 40 60 80 100 120 140 160 180

time [min]
BED LEVELLING RUN 5 EXP. 3

WATER LEVELS AT GAUGES

FIG. 5.3.6

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BED LEVELLING RUNS EXP.3

WATER SURFACE LEVEL AS A FUNCTION OF TIME

DELFT UNIVERSITY OF TECHNOLOGY
APPENDIX 5.5 RUN 5 EXPERIMENT 5

DATA: RUN 5 EXPERIMENT 5

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>d&lt;sub&gt;50&lt;/sub&gt;</td>
<td>median diameter</td>
<td>160 [μm]</td>
</tr>
<tr>
<td>Q</td>
<td>flow rate</td>
<td>0.0037 [m&lt;sup&gt;3&lt;/sup&gt;/s]</td>
</tr>
<tr>
<td>Q&lt;sub&gt;s in&lt;/sub&gt;</td>
<td>transport rate</td>
<td>4.24 [g/s]</td>
</tr>
<tr>
<td>Q&lt;sub&gt;s out&lt;/sub&gt;</td>
<td>transport rate</td>
<td>4.24 [g/s]</td>
</tr>
<tr>
<td>a</td>
<td>average water depth</td>
<td>0.033 [m]</td>
</tr>
<tr>
<td>Δz&lt;sub&gt;b&lt;/sub&gt;</td>
<td>deformation ampl.</td>
<td>0.02 [m]</td>
</tr>
<tr>
<td>i</td>
<td>base state ch. slope</td>
<td>6.04×10&lt;sup&gt;-3&lt;/sup&gt; [-]</td>
</tr>
<tr>
<td>T&lt;sub&gt;meas&lt;/sub&gt;</td>
<td>measuring period</td>
<td>180 [min]</td>
</tr>
<tr>
<td>X</td>
<td>fraction susp. load</td>
<td>0.50 [-]</td>
</tr>
<tr>
<td>C</td>
<td>Chézy</td>
<td>16 [m&lt;sup&gt;4&lt;/sup&gt;/s]</td>
</tr>
<tr>
<td>U</td>
<td>average velocity</td>
<td>0.22 [m/s]</td>
</tr>
<tr>
<td>θ</td>
<td>average Shields val.</td>
<td>0.75 [-]</td>
</tr>
</tbody>
</table>
(bed level measurements are not processed)
BED LEVELLING RUN5 EXP.5
WATER LEVELS AT GAUGES

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FIG. 5.5.6
BED LEVELLING RUN5 EXP.5

WATER LEVEL AS A FUNCTION OF TIME

FIG. 5.5.7

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APPENDIX 5.5  RUN 5 EXPERIMENT 6

DATA: RUN 5 EXPERIMENT 6

<table>
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<th>unit</th>
<th>comment</th>
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<tbody>
<tr>
<td>$d_{50}$</td>
<td>median diameter</td>
<td>160</td>
<td>[$\mu$m]</td>
</tr>
<tr>
<td>Q</td>
<td>flow rate</td>
<td>0.0037</td>
<td>[$m^3$/$s$]</td>
</tr>
<tr>
<td>$Q_s$ in</td>
<td>transport rate</td>
<td>4.24</td>
<td>[g/$s$]</td>
</tr>
<tr>
<td>$Q_s$ out</td>
<td>transport rate</td>
<td>4.24</td>
<td>[g/$s$]</td>
</tr>
<tr>
<td>a</td>
<td>average water depth</td>
<td>0.033</td>
<td>[m]</td>
</tr>
<tr>
<td>$\Delta z_b$</td>
<td>deformation ampl.</td>
<td>0.02</td>
<td>[m]</td>
</tr>
<tr>
<td>i</td>
<td>base state ch. slope</td>
<td>6.11*10^{-3}</td>
<td>[-]</td>
</tr>
<tr>
<td>$T_{ meas}$</td>
<td>measuring period</td>
<td>180</td>
<td>[min]</td>
</tr>
<tr>
<td>X</td>
<td>fraction susp. load</td>
<td>0.50</td>
<td>[-]</td>
</tr>
<tr>
<td>C</td>
<td>Chézy</td>
<td>16</td>
<td>[$\frac{m^1}{s}$]</td>
</tr>
<tr>
<td>U</td>
<td>average velocity</td>
<td>0.22</td>
<td>[m/$s$]</td>
</tr>
<tr>
<td>$\theta$</td>
<td>average Shields val.</td>
<td>0.76</td>
<td>[-]</td>
</tr>
</tbody>
</table>
BED LEVELLING RUN5 EXP.6

FIG. 5.6.3 TRANSVERSE BED PROFILES

FIG. 5.6.4 WIDTH-AVERAGED BED LEVEL

DELTFT UNIVERSITY OF TECHNOLOGY
BED LEVELLING RUN5 EXP.6
r.m.s. values of bed level, at n=0.3W

$z'_b [cm]$ vs time [min]

BED LEVELLING RUN5 EXP.6
r.m.s. values of bed level, at n=0.3W

$z'_b [cm]$ vs time [min]
BED LEVELLING RUNS EXP.6

WATER LEVELS AT GAUGES

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FIG. 5.6.6
BED LEVELLING RUN5 EXP.6

WATER SURFACE LEVEL AS A FUNCTION OF TIME

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FIG. 5.6.7