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“LABORATORY MEASUREMENTS OF SEDIMENT TRANSPORT ON TRANSVERSE SLOPED BEDS”[*]

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An experimental study on the time dependent decay of a transverse sloped bed in a straight flume is presented. The results are important for numerical computations with morphodynamic models particularly regarding the simulation of scours, the natural development of river geometry and for simulations of alternating bars. With respect to the relevance of this process there is a need for more detailed information supported by experimental data. Investigations in sediment transport on a transverse sloped bed were conducted in for different flow conditions. The studies were carried out in the laboratory of the Institute of Hydraulic and Water Resources Engineering at Darmstadt University of Technology. Measurements were carried out in a 60m long and 1m wide tilting flume with a transverse inclination of the bed of approximately 6°. The measurement section was 30m long. To achieve the relevant data of the bed topography, especially the bed level heights, the moving bed was measured by submerged Laser Distance Sensors (LDS). The time dependant decay of the prepared cosine-shaped bed was achieved by measuring five longitudinal bed profiles which were distributed in transverse direction. Additionally Ultrasonic Distance Sensors (UDS) and traditional point gauges yielded water level information. The results are comparable to those found in the technical literature but the magnitude of the downslope transport attempt differs from other approaches.

1 Introduction

Sediment transport transverse to the main flow affected by an inclined bed is an phenomenon which is not sufficiently investigated and described yet. The inclined bed affects the sediment transport. Following the gravity force the sediment particle moves downwards the bed slope. Quantitative knowledge of this effect is important for simulations of scouring and river morphology with numerical models.

There is still a lack of approaches describing the sediment transport in downslope direction transverse to the main flow field. Therefore some detailed investigations are necessary to develop approaches which are suitable for numerical investigations.

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Downslope transport is a very important factor for the appearance and development of bed forms and scours, particularly in river bends. Interaction between downslope transport and secondary flow is described in literature. This interaction reach an equilibrium condition at the final developed scour.

In this study experiments on sediment transport on a transverse sloped bed were conducted. The results are compared with those reported in the technical literature. For analyzing the downslope transport and the sediment transport direction an arrangement like that used by *Talmon*, van *Mierlo* and *Struiksma* 1995 [4] was applied.

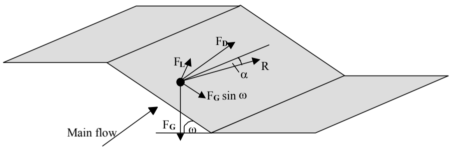
Processes and Parameters

A mobile bed was inserted into a straight flume. It was preformed before every experiment with a cosine in cross-section (fig. 2 left). An important advantage of this geometry is the conservation of the bed's shape throughout the deformation during the experiment. Only the amplitude decreases with time according to equation (2). This provides an improved accuracy in the measurements of the decaying amplitude, especially if bed forms are present.

During an experiment bed forms evolved from the initially plain bed. These bed forms moved on the bottom of the flume by permanent rearrangement. The evolution of bed forms continues until the geometry of bed forms is fully developed or reach an quasi-equilibrium-condition. The rearrangement and the development of bed forms influence the velocity profile. Conversely, the distribution of shear stress in the flume has influence on bed forms. The measured parameters in this investigation were the bed levels and the water levels. The experiment was controlled by adjusting the tilt of the flume, adjusting the flow discharge and positioning the sliding panel at the outlet of the flume. Thereby some changes, particularly in the hydraulic gradient and the mean water depth, were observable. The applied experimental setup was subject to disturbances, namely the inflow section with a transition to the measurement area with mobile bed material and the final, cosine-shaped board at the end of the bed material. These disturbances affect the evolution of bed morphology at the inflow and outflow sections. By locating the measurement area in sufficient distance from the boundaries these interferences could be regarded as negligible. The investigation include experiments with prevailing bed-load transport and experiments with noticeable fraction of suspended load. The flume was 60m long.

Direction of Sediment Transport on Transverse Sloped Bed

The force balance of transport in longitudinal and transverse direction specifies the actual sediment transport direction. In the experimental setup the forces affecting a grain are depicted in figure 1. In addition to the fluid drag force, the gravity force and the inclined bed turn the resulting force in downslope direction (fig. 2).



F_D = Fluid drag force
F_G = Gravity force
F_L = Lift force
$F_G \sin\omega$ = transverse component of gravity
R = Resulting force (transport direction)
ω = angle of transverse inclination

Figure 1: Forces acting on a grain on transverse sloped bed

2 Common Approaches Concerning Downslope Transport

A general approach for describing the sediment transport direction was presented by *van Bendegom* (1963) [1] based on the longitudinal coordinate of the flume. Compared to the longitudinal direction two more directions were measured. These are the direction of flow in the near bed region, which differs particularly in river bends from the longitudinal direction and the direction of the bed gradient. The original formulation assumes that the influence of a transverse sloped bed is directly proportional to the bed gradient.

The formulation of *van Bendegom* can be simplified for the case where no general longitudinal direction of the channel or flume exists and the longitudinal slope is negligible. This leads to the following formulation:

$$\frac{q_y}{q_x} = \tan(\alpha) = -\frac{1}{f(\theta)}\frac{\partial z_r}{\partial y} \tag{1}$$

α = angle between sediment transport direction and longitudinal direction.
$f(\theta) = \frac{F_D}{G}$ „weight-function“ - to be determined -
θ = Shields parameter
y= longitudinal direction or main flow direction
x= direction orthogonal to longitudinal direction or main flow direction
q_y= sediment transport in transverse direction
q_x= sediment transport in longitudinal direction
z_r = depth under reference level

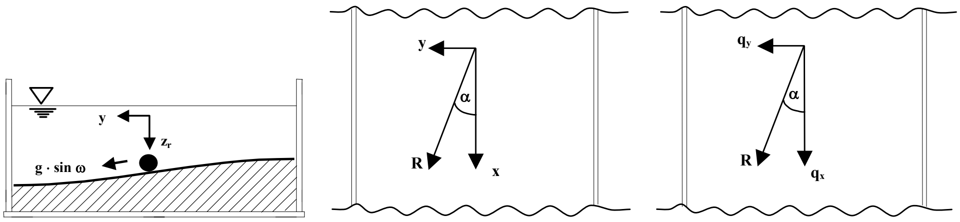


Figure 2.: Cross section of flume with cosine-shaped bed profile and top view with depiction of transport directions

The initial bed was preformed with a cosine cross sectional shape prior to every run. This shape is due to the first order solution of the mathematical formulation by *Talmon, van Mierlo und Struiksma* (1995) [4] which describes the decay of the initial bed gradient (Eq. 2) at the point of time t=0.

$$\frac{h_y}{h_{or}} = 1 + \frac{a_i}{h_{or}} \cdot e^{-t/\left(\left(\frac{P}{\pi}\right)^2 \frac{1-P}{1-\mathrm{X}_0} \frac{f(\Theta)}{F(\Theta)}\right)} \sin\left(\pi \frac{y}{B}\right) \qquad (2)$$

B =	flume width
h_{or} =	mean water depth in the origin
h_y =	local water depth at a point at a time
a_i =	initial amplitude of „first order solution“ (sine-shape of bed)
P =	porosity of sand bed
X_0 =	fraction of suspended load

3 Laboratory Experiments

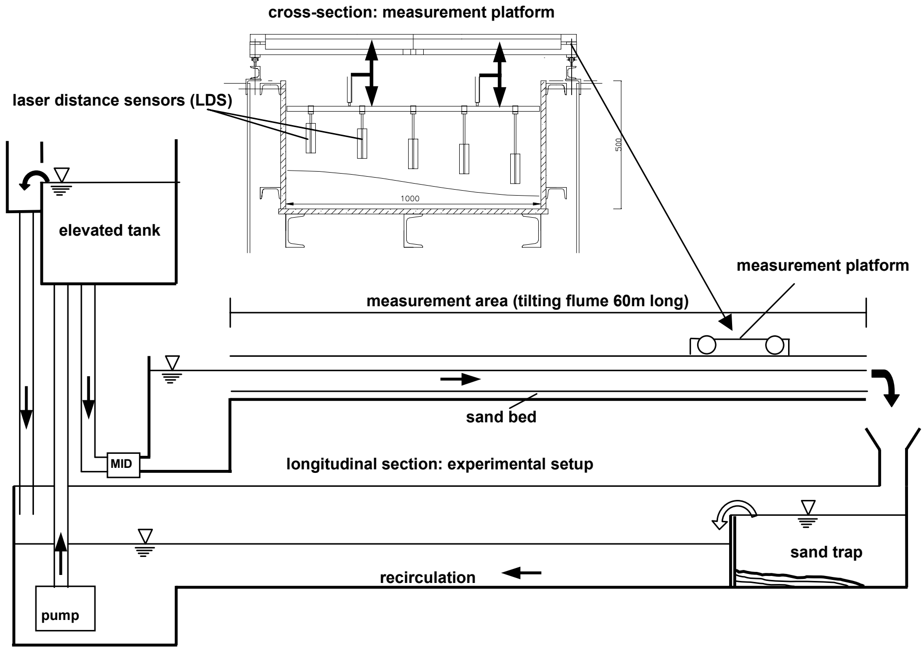


Figure 3: Experimental setup (longitudinal section) with depiction of measurement platform and installed Laser Distance Sensors (cross-sectional view).

Experimental Procedure and Analysis

The experimental arrangement is depicted in fig. 3. There was no sediment feeding at the flume entrance. This was possible because of the length of the flume. The investigations were carried out under different flow conditions, in a 60m long and 1m wide tilting flume, in a measurement section of about 30m length with a transverse inclination of the bed of approximately 6° at the centerline. For every run the total amount of transported sediment, the decay of the preformed bottom and the appropriate waterlevels were measured. Before each run some prearrangements must be executed. First the initial bed was precasted. After calibration and installation of the needed devices, Laser Distance Sensors (LDS) and Ultrasonic Distance Sensors (UDS), the test was running under choosed conditions. The relevant data of bed levels and water levels were acquired and documentations were made at time intervals of 15min to 5hours, depending on the experiment condition (see fig. 4).

The measured water depth differences between the right and left side of the flume was compared to that computed with equation 2. The unknown function f(Θ) has been adjusted by hand.

In this investigation the experimental setup was chosen due to the awareness of former experiments conducted in a 2m wide and 40m long flume with a measurement area of 27m length. In this series of experiments the influence of the conditions near the inlet and the final wooden board at the end of the sand bed and the sand trap respectively influenced the measurement section during all runs. Therefore considerable erosion near the inlet as well as some disturbances at the end of the sand bed were observed. These given facts led to longitudinal bed profiles which where not parallel in their process. Therefore an analysis of differences in the bed elevations and of the decay of the transverse bed gradient is not explicit practicable. Accordingly for each run with nonparallel bed profiles several bed level differences existed and this led to a dispersion of results. To reach a better reliability of the results the experiments were displaced in a 60m long flume with sufficiently long distances to the boundary disturbances like inlet and outlet. The measurement area started 17.5m downstream and ended 47.5m downstream. Longitudinal bed profiles were measured over this length and the process was parallel for the most part.

Experimental results

To analyze the data the total sediment transport rate was used. No distinction was made between suspended and bed load transport (see *Talmon et al*. 1995 [4]).

In the presence of ripples it is difficult to distinguish between suspended and bed load transport.. Because of the fairly good agreement of the experiments estimating a total sediment transport rate, the suspended load transport appears to be involved in the downslope transport. Furthermore the bed gradient seems to have influence on the suspended load transport. This interrelationship has to be proved by further investigations.

Table 1. Overview of parameters of conducted experiments

Overview of experiments $f(\Theta) = a\,(\Theta)^{\frac{1}{2}}$

run	Q	LDS	d_m	h_m	I	Θ	a
[-]	[l/s]	[-]	[mm]	[m]	[-]	[-]	[-]
run0e	150	outer	0.25	0.296	0.00064	0.460	**1.16**
run0e	150	inner	0.25	0.296	0.00064	0.460	**1.00**
run0f	150	outer	0.25	0.295	0.00066	0.473	**1.28**
run0f	150	inner	0.25	0.295	0.00066	0.473	**1.10**
run0i	150	outer	0.25	0.304	0.00064	0.473	**1.10**
run0i	150	inner	0.25	0.304	0.00064	0.473	**0.95**
run0j	68	outer	0.25	0.154	0.00135	0.504	**1.15**
run0j	68	inner	0.25	0.154	0.00135	0.504	**1.04**
run0k	125	outer	0.25	0.301	0.00054	0.398	**1.29**
run0k	125	inner	0.25	0.301	0.00054	0.398	**0.98**
run0l	57	outer	0.25	0.156	0.00110	0.416	**0.99**
run0l	57	inner	0.25	0.156	0.00110	0.416	**0.91**
run0m	78	outer	0.25	0.299	0.00023	0.169	**1.19**
run0m	78	inner	0.25	0.299	0.00023	0.169	**0.95**
run0n	100	outer	0.25	0.302	0.00036	0.263	**1.23**
run0n	100	inner	0.25	0.302	0.00036	0.263	**0.98**
run0p	164	outer	0.25	0.303	0.00064	0.472	**1.05**
run0p	164	inner	0.25	0.303	0.00064	0.472	**0.95**

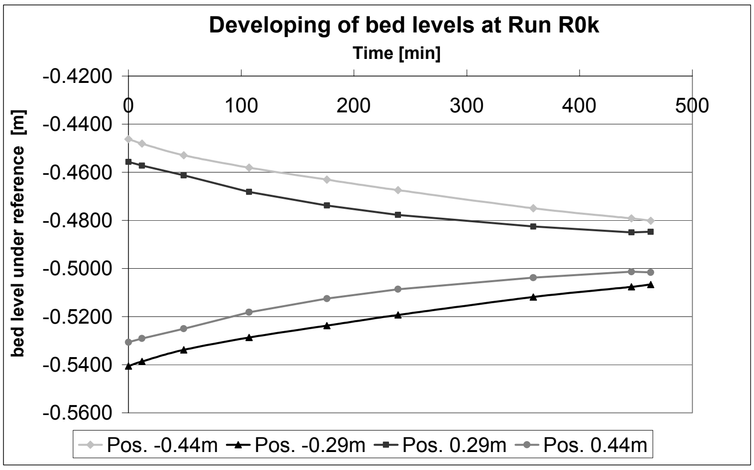


Figure 4: development of bed levels over time at different positions in the transverse direction, run R0k

The bed levels were measured at four points which leads to two bed level differences. With two pairs of Laser Distance Sensors, inner and outer differences are obtained. The locations are shown in fig. 2 and fig. 4.

Table 1 shows the results of the experiments. For each run both inner and outer values are given. Because of the secondary flow the sediment transport is not only affected by the transverse bed gradient. The different direction of main flow leads to a stronger erosion in the region near the vertical walls of the flume. Therefore the analysis of bed elevations seems to be more reliable if the inner bed level difference is used. As to be seen in table 1 the inner and outer differences differ. This is attributed to the influence of secondary flow. Furthermore factor *a* has to be modified, because of the secondary flow effects. Some measurement data of the secondary flow is required. Velocity measurements with corresponding directions and fluctuations in different points in a cross-section are necessary to obtain approaches of secondary flow effects.

4 Discussion and conclusions

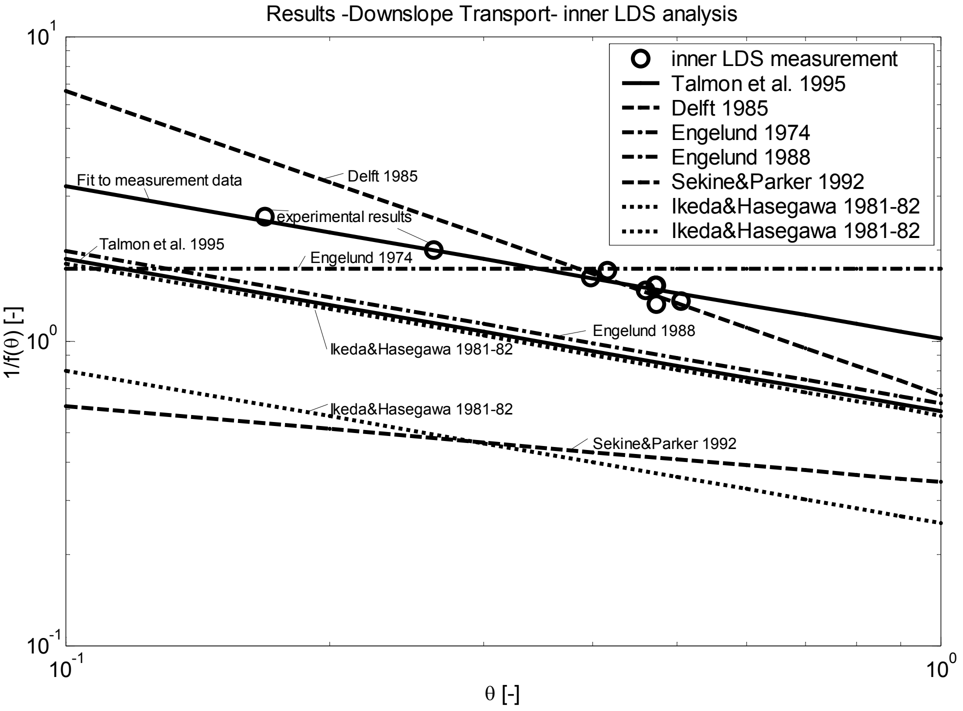


Figure 5: Comparison of measured data with existing approaches

The results as given in table 1 are plotted in fig. 5. With our measurements the exponent of ½ as proposed already by Engelund, Ikeda and Hasegawa and Talmon et al. could be verified. In contract to the other formulations we obtained a different factor in the function f(Θ). The factor a is 1, as given in equation 3. This relationship is valid for a bed with ripples.

$$f(\Theta) = 1.0\,\Theta^{\frac{1}{2}} \tag{3}$$

At the moment the role of the suspended load in the transverse transport remains unclear.

In this investigation it was necessary to consider the total sediment transport rate in the analysis to make the results with and without prevailing suspended load comparable to those with bed load transport only. In addition it seems to be necessary to consider the bed forms, because results of some more recent experiments with dunes lead to other values of parameter *a*.

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