Conference Paper, Published Version

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MEASUREMENTS OF TRANSVERSE SEDIMENT TRANSPORT AND THE EFFECT OF SUSPENDED LOAD

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ABSTRACT

The influence of a transverse bed inclination on the direction of the sediment transport is increasingly important for two- and three-dimensional morphodynamic-numerical computations. The natural cross-section, the bend scour of rivers as well as the appearance of bed-forms are strongly influenced. Still there is a lack of experimental data to quantify this important process. Moreover the role of suspended sediment in the transverse transport is not clear today. In this paper a mechanism is described that introduces transverse transport for the suspended fraction as well. Experiments in a laboratory flume are given that indicate the major role of the bed forms on the transverse transport. For the dune regime a different behaviour is measured than predicted by the known formulas.

Keywords: sediment transport, transverse transport, morphodynamic-numerical computation

1. INTRODUCTION

The sediment transport at a river bed is strongly influenced by an inclination of the bed. The weight of the particles exerts a force in the down-slope direction. For the moving particles this gives rise to a down-slope transport component. If the flow is directed parallel to the depth lines the down-slope transport takes place in the transverse direction.

The transverse transport has become much more important today, when two- and three-dimensional numerical models are used more frequently to compute the morphodynamic development of the river bed. In the traditional one-dimensional models only the longitudinal slope is described by the model which is several orders of magnitude less than the transverse slope of the bed. The scour depth in river bends has been investigated by a series of scientists giving empirical relationships for the combined effect of spiral flow and bed slope. For the natural cross-section of a river the transverse transport becomes important in determining the profile form.

In this paper measurement results on the transverse transport are presented, that have been obtained in the laboratory at the TU Darmstadt. The task was to obtain a comprehensive data set that gives trustworthy information on the magnitude of the transverse transport for a certain range of the major parameters involved, as there are fluid drag and grain size.

2. TRANSVERSE TRANSPORT IN BED-LOAD

2.1 Mathematical description of transverse transport

A general description of the influence of a bed inclination on the sediment transport should by of vectorial type. There is a major difference between the longitudinal and the transverse inclinations of the bed. In this paper only the transverse inclination is considered. The morphology is largely influenced by the transverse inclination because the small deviation in the direction of the transport will result in very pronounced bed level differences over a certain flow distance.

The transverse bed inclination is considered as proposed by Talmon et. al (1995) and depicted in figure 1 below. The flow is directed along the depth lines in a channel. The form aof the bed is that of a cosine function. This special form will decay in amplitude over time during an experiment.

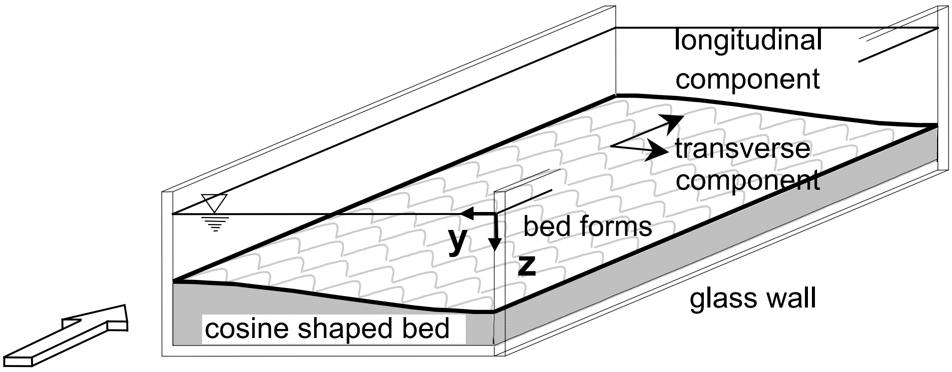

Figure 1: Sketch of the measurement flume section

For this situation a simple formula for the direction of the sediment transport α can be derived:

$$\frac{q_n}{q_s} = \tan(\alpha) = -\frac{1}{f(\Theta)}\frac{\partial z_b}{\partial y} \qquad (1)$$

where:

q_s = transport rate in flow direction; q_n = transport rate in transverse direction;
α = angle between long. and transverse dir.; y = transverse direction;
θ = Shields-number (also τ^* or Fr^*); z_b = bed level

Direct proportionality to the transverse bed slope is well accepted. The important unknown is the function *f(θ)* that indicates the influence of the transport intensity on the transverse transport fraction.

2.2 Known formulas for transverse transport

The sediment transport on a transverse inclined bed has been investigated experimentally only by very few researchers. Because the change in the direction of the sediment transport is not large it is difficult to measure this effect. Therefore it is not surprising that a number of formulas exist, that try to describe the process, but the values they give scatter very much by an order of magnitude and even more.

Table -1: approaches for transverse transport (after Mewis 2002 and Sekine und Parker 1992)

source	f(Θ)	m (Exponent of Θ)
Engelund 1974	$\mu_d \approx \frac{1}{1{,}73}$	0
Engelund 1981	$\mu_d = \tan\varphi = 1{,}6\sqrt{\Theta}$	0,5
Hasegawa 1981	$\sqrt{\mu_d \mu_s}\sqrt{\frac{\Theta}{\Theta_c}}$	0,5
Ikeda 1982, Parker 1984	$\frac{\lambda\mu_d}{1+\alpha\mu_d}\sqrt{\frac{\Theta}{\Theta_c}}$	0,5
Struiksma, Olesen, Flokstra, de Vriend 1985	$f_s\ \theta$; $f_s = (1\text{-}2)$	1,0
Sekine und Parker 1992	$\frac{1}{0{,}75}\left(\frac{\Theta}{\Theta_c}\right)^{0{,}25}$	0,25
Talmon, et al 1995	$1{,}7\sqrt{\Theta}$	0,5
Wiesemann, Mewis, Zanke 2004	$1{,}0\sqrt{\Theta}$	0,5

The known formulas are summarised in table 1. For comparison the exponent for the shear stress is reproduced in th elast column. The formulas are based on different data sets partially obtained in air flow. The data sets are obtained with different techniques.

3. MECHANISM OF TRANSVERSE TRANSPORT IN SUSPENDED-LOAD

Already in Talmon et al (1995) the measurements indicated, that the suspended load is contributing to the transverse transport. In the measurements given below this can also be observed. The classical point of view is, that only bed-load has a transverse transport component because only the bed-load is in direct contact to the bed.

The classical point of view is generalized here by including the suspended load also. This derivation is mentioned already in 2001 by Mewis. The mechanism is as follows. The equilibrium sediment concentration is given by equilibrating the upward turbulent fluxes of sediment and the settling flux of the sediment. The settling takes place perfectly vertically, following the gravity. The turbulent fluxes that are lifting up the sediment are acting perpendicular to the mean isosurfaces of sediment suspension concentration. These are supposed to be located parallel to the bed and thus inclined to the gravity. Denoting the turbulent fluxes away from the wall with n and the settling flux with the letter g, we get the situation sketched in figure 3. Between the upward and downward fluxes we obtain a small shift along the bed, that is denoted with the letter C. This shift is directly proportional to the bed slope. Indeed this transport takes place at every depth where the concentration isolines are inclined. But ofcourse most important are the locations with the highest concentration, that is close to the bed, but not in direct contact with the bed.

Moreover the transverse transport will be enhanced by density currents induced by the density effect of the suspended sediments close to the bed in combination with the influence of the density stratification on the turbulence structure. To account for these currents is more complicated and not the matter of this derivation.

A mathematical derivation according to the mechanism scetched in figure 2 can easily be given if the settling velocity is known. To calculate the transverse displacement C it is sufficient to know the settling flux g. The relation to the longitudinal transport rate can be established when the longitudinal advection velocity of the sediment is known.

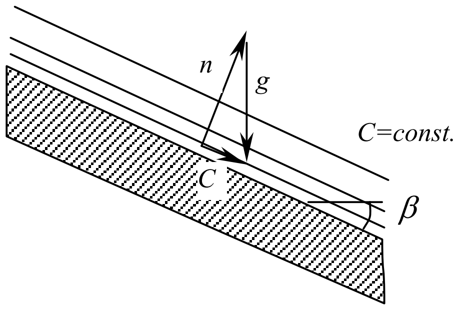

Figure 2: Sketch of the mechanism of transverse transport in suspended load, with *g* the gravity or settling effect and *n* the turbulence effect, that is acting perpendicular to the bed, resulting in a transverse transport of *C*.

Because the lifting turbulence induced flux and the settling flux equilibrate except for a the small transverse displacement $C = w_S \sin\beta$, we need to know only the settling flux. At the same time the particles are moved with the mean current by bU, where b is the ratio between the sediment and the depth averaged velocities. Here we assume that the sediment settling velocity can be calculated via the drag coefficient c_D of the sediment particles for coarse material and high Reynolds number. The ratio between the streamwise and the transverse transport:

$$\frac{q_t}{q_l} = \frac{w_S}{bU} \cdot \sin\beta = \sqrt{\frac{4r_f}{3c_D}} \frac{1}{b\sqrt{\theta}} \sin\beta \approx \frac{1}{\sqrt{\theta}} \tan\beta \qquad (2)$$

The measured square root dependency from the shear stress is well reproduced. Thus the suspended sediment behaves well in line with most findings known in the literature.

The magnitude is largely dependent on *b*. Using a commonly accepted value of *b* of about 0.5, a c_D of 0.4 and a friction factor r_f of 0.005 a factor of four remains when compared with the measured results. The discrepancy is increasing to 12 when using the w_s formula for fine sand. It can be argued that the sediment advection velocity it overestimated for the ripple regime when setting *b* to 0.5. If *b* is set to 0.13 the results are met very well.

4. MEASUREMENT OF TRANSVERSE TRANSPORT IN THE LABORATORY FLUME

4.1 Measuring Devices

The measurements where carried out in a 60 m long flume in the hydraulic laboratory of the TU- Darmstadt. Because of the length of the flume no sediment feeding at the entrance to the flume was necessary. The disturbances introduced at the entrance and at the end of the flume where limited to a range of few meters into the flume. The measurement section was placed in the middle of the flume away from the disturbances.

As shown in figure 3 the bed levels have been measured at five locations in the transverse direction using laser distance sensors during the experimental run. The values of the bed elevation have been averaged over a reach of twenty meters. This way bed forms have been eliminated from the results. The sediment transport capacity has been measured in a settling tank arranged at the outlet of the flume, thus accurately measuring the total mass of sediment transported in one experimental run.

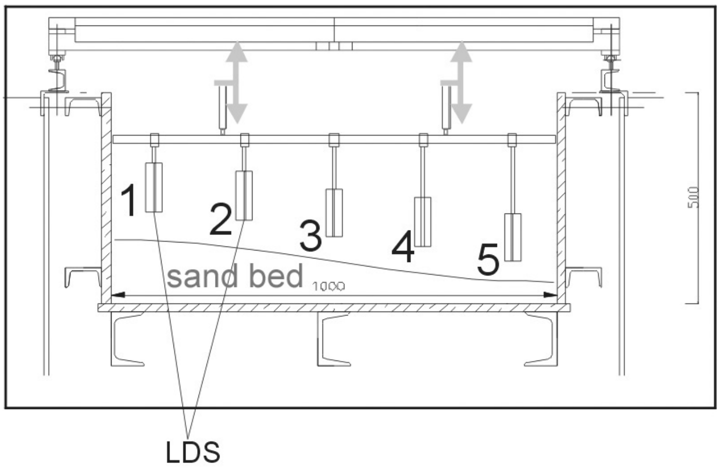

Figure 3: The bed levels were measured using five laser distance sensors (LDS)

4.2 Experiments

Two different series of experiments have been carried out. One with fine sand of 0,25 mm mean grain size, the second with coarse sand of 0,96 mm grain size. Table 2 summarizes the experimental conditions.

Table 2: Hydraulic conditions for the experiments

experiment	d_m [mm]	h [m]	U [m/s]	Θ [-]
Series R0	0.25	0.3	0.22-0.64	0.11-0.57
Series R1	0.96	0.3	0.48-0.77	0.12-0.53

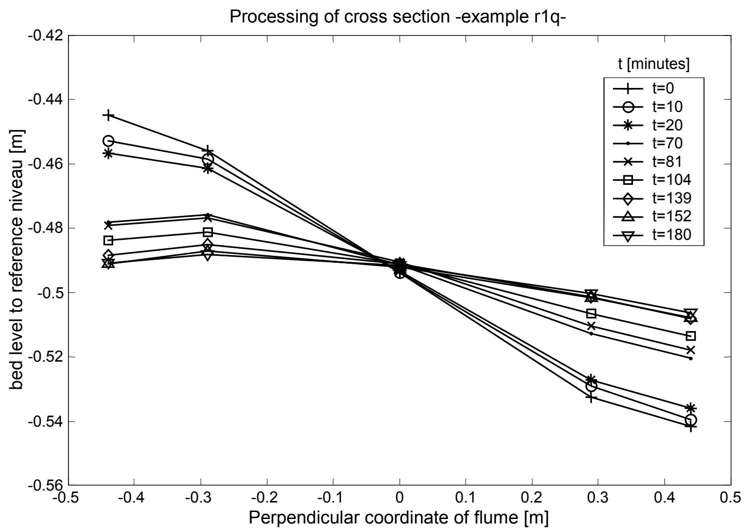

Figure 4: Transverse profile development for experiment r1q

The values measured by the five laser distance sensors gave a decay for each of the experiments. The cosine shape of the bed was conserved, as depicted in figure 4, but the amplitude decreased. The decay of the decrease was well to be observed in the plot of the time development of the mean elevations of each of the five longitudinal profiles, as given in figure 5. This decay and the longitudinal transport rate where used to calculate the value of the inverse function *1/f(θ)* for each experiment. Now a high value of *1/f(θ)* corresponds to a large transverse transport and a low value to a low transverse transport.

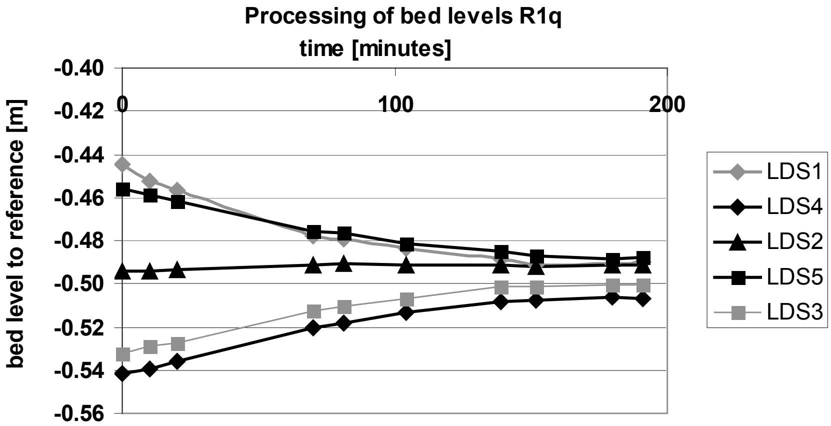

Figure 5: Time development of the averaged five longitudinal profiles

Major problems appeared in the measurements due to the presence of dunes. In this case the amount of material measured at the end of the flume varied largely when a dune approached the end of the flume. For this case simply the dune propagation speed and the dune dimensions were used to calculate the overall sediment transport rate. Also the pore fraction of the material at the bed was a value to be measured precisely for accurate results.

4.3 Fine sand

The results of the first series of experiments with fine sand material of 0.25 mm mean grain size are shown in figure 6. In this series 11 experiments covering a range of the particle Froude number from 0,11 to 0,57 were carried out. The bed was covered by three-dimensional ripples. These ripples had very steep slopes and the flow patterns close to the bed have been very complex in that the flow turned in the ripple troughs to the side or into the opposite direction in an unsteady manner. The sediment motion was dominated by the individual return flows and eddies developing in the troughs of the ripples. No piece of flat bed was present. The transport regime was clearly suspension.

The results of this series of experiments is plotted in figure 6. With increasing shear stress at the bottom the inverse function *1/f(θ)* is decreasing and so is the transverse transport rate. The individual results form a straight line except of two points at high particle Froude numbers θ. The function *f(θ)* consists of θ with the exponent ½. This is in perfect agreement with most findings of other researchers and more importantly with the suspended load function given above. The complete function is $1/(1\sqrt{\theta})$. This is 1.7 times less than the value given by Talmon et al (1995). When compared to the formula 2 the use of an advection velocity of 0.082 times the mean velocity would perfectly match the measured values. For the ripple bed with many return flows and turbulent eddies this is not unlikely.

Two experiments are out of the line. The transverse transport is two times smaller for these. During these two experiments dunes have been observed in the laboratory flume. Thus the longitudinal flow velocity was much higher close to the bed and the effect of the suspended load fraction much smaller.

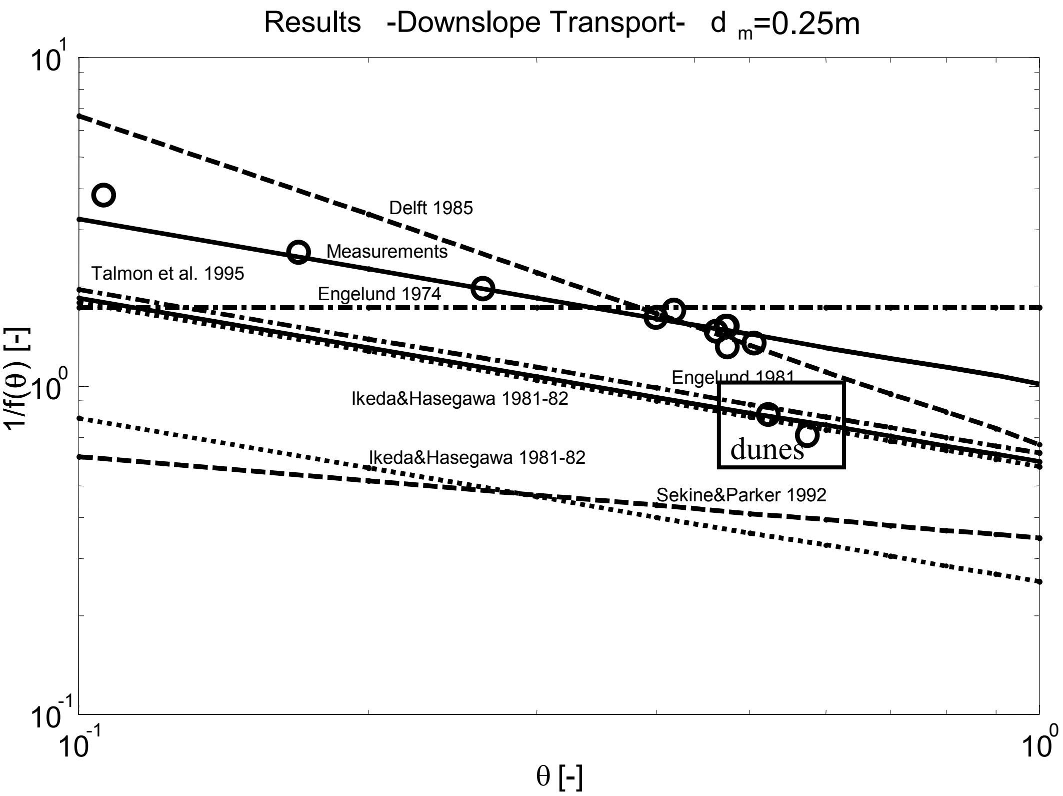

Figure 6: Comparison of results and existing approaches. Fine sand (0,25 mm).

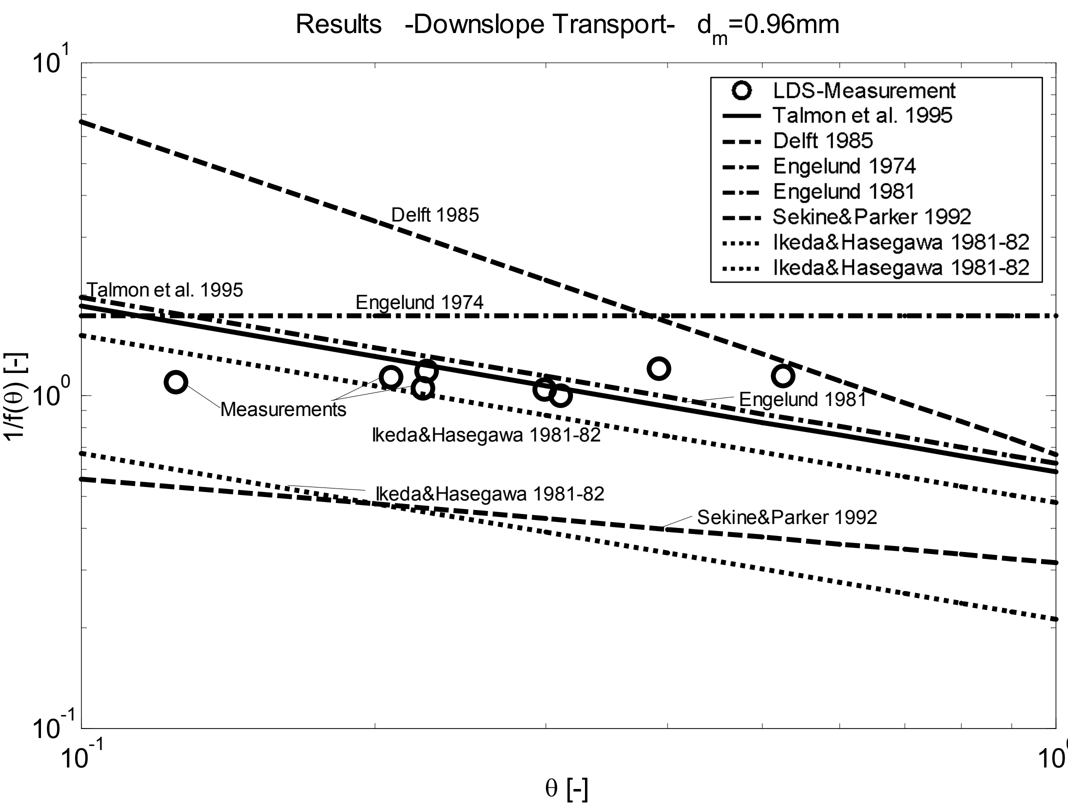

Figure 7: Comparison of results and existing approaches. Coarse sand (0,96 mm).

4.4 Medium sand

For the medium sand material a total of 8 experiments covering a Froude number range form 0,12 to 0,53 have been carried out. No ripples developed and only dunes have been observed in these experiments. The dunes developed right at the beginning of the flume. Recognizing this bed form regime the dunes have been formed prior to the start of the experiment, to get reliable results right from the starting time. It has been proofed that the characteristic dimensions of the dunes did not change during the experiments.

The measured values exhibit no dependency from the transport parameter θ. E.g. for this grain size the ratio of longitudinal and transverse transport is a constant and independent from the flow velocity. The function $f(\theta)$ is close to unity. This is the first time that the no dependency on θ result is observed (with the exception for the formula of Engelund). Here it is argued, that the transport conditions at the dune crests significantly differ from those of the fine material of the first test series. On the dune crests conditions similar to sheet flow prevail with a moving layer of sediment of several particle diameters height. This is possibly the reason for the no dependency result.

5. CONCLUSIONS

Accurate measurements of the decay of a transverse slope in a laboratory flume are presented. The results indicate

- a strong influence of the bed forms on the transverse transport,
- a participation of the suspended load on the transverse transport,
- no dependency of the transverse transport on θ for the dune regime.

The strong dependence on the bed forms indicate that this complex process has to be further investigated individually for different bed form regimes.

ACKNOWLEDGMENTS

The Authors acknowledge the German Research Foundation for funding part of the work described in this paper.

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