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Sediment Transport Rate in the Dune Regime in Bed Levelling Experiments

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In this paper different methods of determining the sediment transport rate in the laboratory are presented. Different methods regarding investigations of bed levelling experiments on a transverse sloped bed are discussed and correlated. The studies were carried out in a straight flume in the Hydraulic laboratory at Darmstadt University of Technology. For morphodynamic model computations, particularly with scours, the natural development of the river geometry and for simulations of alternating bars, the knowledge of the transport processes in longitudinal and transverse direction are important. In two- and threedimensional morphological models the transverse transport is of much higher importance then in the classical one-dimensional coputations. Regarding the high relevance of the transverse transport the number of measurements is insufficient. There is a need for more detailed information supported by experimental data.

Investigations on sediment transport on a transverse sloped bed were conducted under different flow conditions. The analysis of the transverse transport relies on the knowledge of the longitudinal transport. The transport rates were determined by the propagation of present bed forms, observed in longitudinal bed profiles and by gathering the transported bed material at the end of the flume. A comparison of the aforementioned methods will be given. These are discussed with respect to the determination of transport rates.

I. INTRODUCTION

In investigations of hydraulic engineering topics the morphological evolution of the channel bed is often one important component. The river morphology, and in the laboratory the flume bed morphology, depends on the behaviour of the moving bed material. Therefore it is very important to know exactly how much material is transported and in which paths (direction) the sediments travel. To quantify the transported material it is inevitable to measure transport rates under various conditions to find representative approaches of sediment transport prognoses. In field observations normally some point measurements are conducted to quantify representative transport rates of the natural area of observation. Mostly these measurements are taken in addition to some common transport formula to get substitutional transport rates for the considered area. Contemporary morphodynamic-numeric models contain such expressions and are able to simulate the transported quantities under the knowlegde of the prevailing sedimentologic parameters. But the morphodynamic-numeric models need some calibration data too, in order to find the right amount of transported sediments. Here the aforementioned point measurements, sometimes coupled with a non contact measuring method, are useful.

In the laboratory the measurement of the transported material of a bounded area is common. Here the regional conditions make an integrated consideration of the transported material possible.

For measuring the amount of the bed load transport a separation of common methods could be made by differentiating in gravitational, volumetric and non contact (acoustical, tracer using or optical) methods. The most accurate method to get the quantity of the transported material is an integrated weight measurement. The weighing of the total transported material which was transported out of a flume with a movable bed arranged over the total length of the flume up to the outflow region yield an accurate total transport rate. If the bed morphology and its changing with time is known, then the different volumina of the bed form and its propagation gives agood estimate of the total transported volume. By knowledge of the porosity the sediment transport rate can be calculated. These two methods are applied in this investigation.

II. BED LEVELLING EXPERIMENTS IN THE LABORATORY

A current investigation in which the knowledge of sediment transport rates is necessary deals with the observation of bed levels in a channel section with a movable bed (*Wiesemann, Mewis, Zanke* 2004 [4]). This investigation, conducted in a 60m long tilting flume, includes experiments with prevailing bed-load transport and dunes (bed forms). The mobile bed was preformed previous to each experiment with a cosine in cross-section. The investigated sediment was a coarse sand with an representative diameter $d_m = 0.96$mm. The grading curve of the flume bed sand is given in Figure II-1.

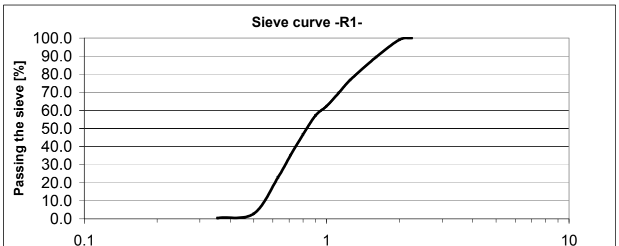

Figure II-1: Results of sediment analysis (sieve analysis).

The amplitude of the preformed cosine function decreases with time. This decay is observed by measuring longitudinal bed profiles at different positions in the cross section of the flume. The decaying amplitude was measured under the presence of bed forms. This decay is a degree for the transverse transport caused by the inclination of the bed and the affecting gravity component.

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. Possible disturbances caused by the inflow and the outflow conditions affect the evolution of bed morphology. By locating the measurement section in sufficiently long distance from the boundaries these interferences can be regarded as negligible.

Each run is short because the main goal was the bed levelling. No feeding of sediment at the inflow was necessary.

Every run includes several measurements of longitudinal bed profiles of 30m length, which were measured by moving the Laser Distance Sensors (LDS) on a measuring carriage with mean flow velocity to minimize the disturbances to the flow conditions. This setup of devices enables a high resolved simulation of the movable flume bed (see Figure III-1).

The evolution of bed forms continues until the geometry of bed forms is fully developed or reaches a quasi-equilibrium-condition.

The aim of the described bed levelling investigation is to formulate a new approach for describing the transverse transport. Because of the correlation of longitudinal transport and transverse transport the knowledge of the longitudinal transport rate is essential for this experimental investigation. The longitudinal transport rate includes important information about the prevailing hydraulic and sedimentologic parameters. For an accurate formulation of the transverse transport the longitudinal transport component should be known. In the described bed levelling investigation the aim was to evaluate the sediment transport direction, therefore both components the longitudinal and the transverse one are necessary.

III. SEDIMENT TRANSPORT MEASUREMENTS

A. Measurements in the laboratory

The determination of the transport rates was conducted by weighing the transported material and by observing the morphology of the bed, checking the evolving and propagating bed forms.

Weighing the transported material by collecting the material at the end of the flume and determining its submerged weight leads to an exact total transport mass. This magnitude could be transferred with the known duration of the experiments into a transport rate. So this method does not give information about potential present time variations in the transport rate. If bed forms are present the gathered sediment mass at the end of the flume is subject to fluctuations caused by the propagating bed form crests (dune shape). On a 3D ripple bed this influence is not dominant but on a 2D dune bed the transport rate differs significantly with a propagation period of a single dune. This leads to a fluctuation in the total transport weight against the point of time when the experiment is stopped: Stopping the experiment before or after the dune crest is travelling out of the flume affects the total transport rate, because of the small number of dunes travelling out of the flume.

To avoid these dependencies the transport behaviour within the measurement section of the bed levelling has to be measured. By considering the propagation of the bed forms the transported volume could be determined. The measurement of longitudinal bed profiles yields the geometry of the travelling dunes. With an adequate algorithm the bed profiles could be analyzed. With known geometric parameters the propagation of the bed forms and hence the transport rate could be calculated.

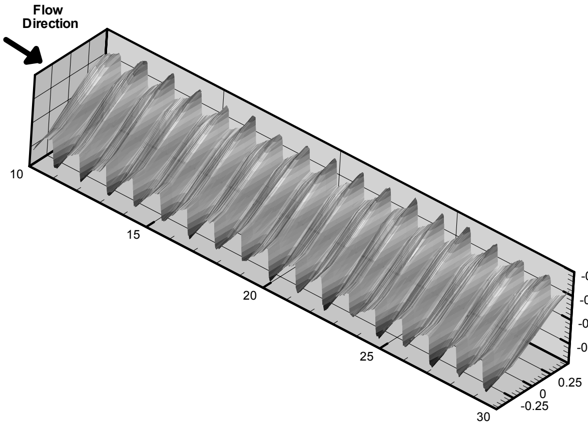

Figure III-1: Threedimensional depiction of measured flume bed. The dunes that developed are shown.

Figure III-1 shows the three-dimensional flume bed measured with five Laser-Distance-Sensors. The bed forms, here two-dimensional dunes, are depicted. At various time steps the bed levels at five transverse located points were measured. The evolution and rearrangement of the flume bed could be observed with this technique. For a more simple determination of the prevailing morphology the profiles were plotted in 2D as shown in Figure III-2.

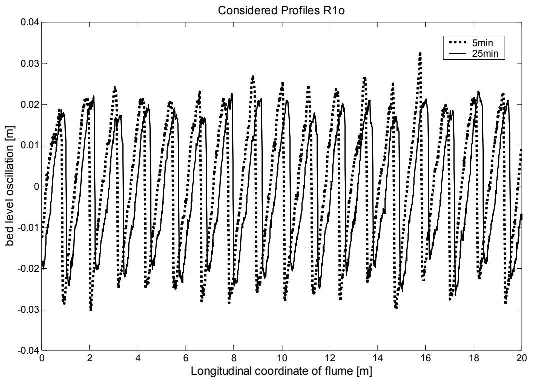

Figure III-2: Plotted longitudinal bed profiles.

In Figure III-2 the propagation of the dunes can be observed. A longitudinal bed profile at two different time steps is depicted. Beside the propagation of the bed forms the variation of bed form height is given, but the characteristic form of the bed forms remains the same.

B. Analyzing the transported material

For an explicit consideration of various methods an exact analysis of the transported material is necessary. In addition to the density of the grains the porosity of the bed layer is important to evaluate the transported mass from the measured volumina. For this purpose the non-compacted density of the bed layer is the basis for the assumed porosity of a travelling dune. This approach seems to be the obvious one because of the poured condition of the dune bed. Whether the primary inserted bed layer was possibly compacted, the continuing rearrangement of the bed layer leads to a loose fill.

C. Bed form geometry

For a complete consideration of the transported volumina in addition to the bed form propagation speed the knowledge of the length and the height of the bed forms is necessary. The applied zero up- and down-crossing method to the zero crossing of the longitudinal bed profiles yield information about the geometry of the dunes. With known length of the profiles and the number and positions of zero-crossings the length and height are given. It is important to know whether the dune form is nearly a triangle or a more rounded one.

By determing the rms-values of each bed profile the the volume of the dunes can be determined in a more direct way.

A more detailed analyzis concerning maxima and minima between the zero-crossings lead to the bed form height. With an adequate algorithm the profiles could be analyzed with respect to these aims. In Figure III-3 a longitudinal bed profile is shown. The average bed level value is the basis to apply the zero-crossing method.

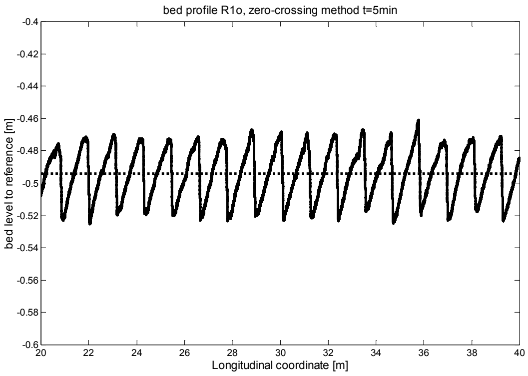

Figure III-3: Longitudinal bed profile R1o, t = 5min. Oscillating bed levels. The dotted line is the average bed level value.

The applied measurement technique yields high resolved data. So it is possible to evaluate the typical dune profile by summing up all values multiplicated with the longitudinal distance for each value of the bed profile. For that purpose the average value of the minima values of the bed profile has to be indentified.

The determined typical dune profile of this investigation is characterized with a factor $\beta_F = 0.55$.

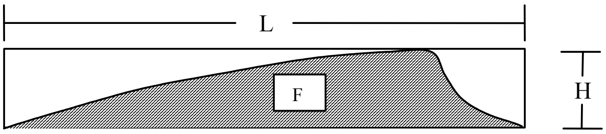

Figure III-4: bed form (dune). Sketch of determination of the form faktor β_F.

The dune form factor β_F , proposed by *Führböter* 1967 and here applied according to *Zanke* 1982 [6] is formulated as

$$\beta_F = F/(H \cdot L), \tag{1}$$

in which H = bed form height, L = bed form length, F = cross section (area) of dune.

is the relation of the present dune profile to the product of length and height. Hence the form factor for a triangle form is 0.5 and with a present parabolic form the dune about 0.66. Other investigations which dealed with sediment transport determination from dune profile propagation used different form factors due to the prevailing bed form properties. Calculations described in *Zanke* 1982 [6] were conducted with a form factor of 0.6 for a good agreement. With the flume width of 0.5m the calculated dune height and length is transferred into the sediment transport volume.

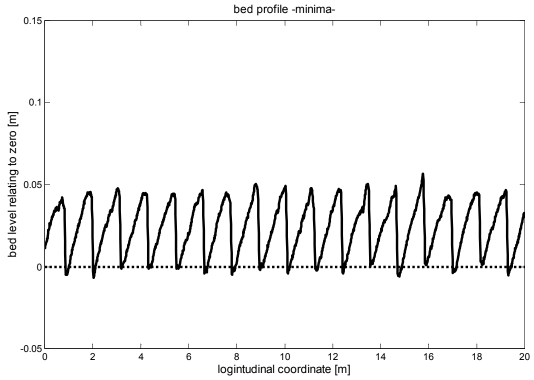

Figure III-5: Shifted bed profile R1o, t = 5min. Average minimum value is set to zero.

In Figure III-5 the average value of the minima is set to zero. The area above this zero line was evaluated.

Another method to determine the bed form geometry is the Fast Fourier Transformation (FFT). For application of this method a couple of algorithms exist. In this case a MatLab-implemented routine was used to find the periodic components of the bed profile.

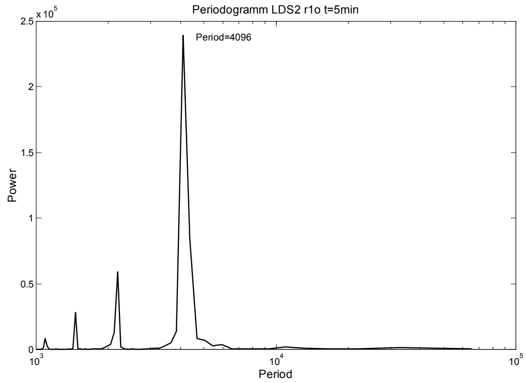

Figure III-6: From FFT determined period of measured longitudinal bed profile.

In Figure III-6 the results of the FFT of the bed profile is shown. The FFT lead to a main period of 4096 data points. This number of data points could be converted in the length of the prevailing bed forms and results in a dune length. For the Laser Distance Sendor LDS2 in run R1o at running time t = 5min the dune length was 1.06m. The length of the dunes resulting from the FFT-analysis is comparable to the length of the auto-correlation and the zero-crossing method, but the resulting length from zero-crossing and auto-correlation do correlate better, here a dune length of 1.15m was evaluated. The resulting bed form length shows significant variations in the consideration of all measured bed profiles of an experiment. Because of the leaping variation in length by considering all bed profiles over the whole time period of one experiments the FFT was not applied in the analysis of the bed levelling experiments.

D. Determination of dune propagation velocity

Based on the investigations of *Kühlborn* 1993 [1] the bed form propagation velocity could be determined from auto-correlation of adjacent longitudinal bed profiles of one time step of bed levelling measurements. The auto-correlation is expressed as:

$$R_{yy}(\Gamma) = \frac{1}{n-m-1} \sum_{i=1}^{(n-m)} \left[y(x_i, t) \cdot y(x_i + \Gamma, t + \Delta t) \right] \quad (2)$$

Ryy (Γ) = autocorrelation at position Γ

n = number of measuring points

m = number of measuring steps of lateral offset

Γ = lateral offset of autocorrelation

x, y = coodinates of height and horizontal location Δt = time interval

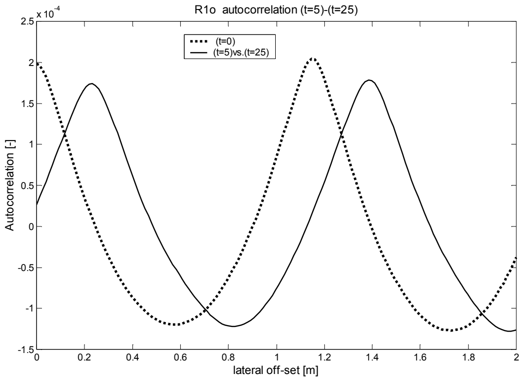

Figure III-7: Auto-correlation function of two bed profiles. Time 5min versus 25min.

The auto-correlation yields the period of the lateral staggered profiles (see Figure III-7). A maximum in the auto-correlation indicates that the staggered profile is in accordance to that one at the beginning of the considered time interval.

With the knowledge of the time step and the lateral distance belonging to the maximum value in the auto-correlation function the propagation velocity is given. With the known dune propagation velocity the transport volumina can be evaluated.

For a simple procedure to verify the evaluated propagation velocities, the longitudinal bed profiles are in depicted Figure III-8. The ordinate in Figure III-8 is the time. The bed profiles are depicted with the average value to the belonging time, so the oscillations of the profiles still exist, but their average value is set to the associated time of measurement. By connecting the dune crests a straight lines with a specific inclination result. This inclination yields the propagation velocity of the bed forms as well.

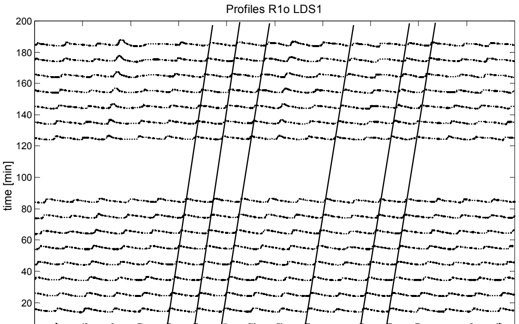

Figure III-8: Plotted longitudinal bed profiles of LDS1 (run R1o), straight line connection for progation velocity determination

A comparison of randomized testings of plotted profiles and auto-correlations with associated dune propagation velocity lead to a good conformance. So the dune propagation method to determine the velocity is verified.

E. Transport rate

The comparison of the different methods in the investigation of the bed form geometry favourite the application of the auto-correlation method coupled with the zero-crossing method. In addition to these operations the transport rates q_G could be determined by using a method proposed by *Führböter* 1967. The following method was applied according to *Zanke* 1982 [6]:

$$q_{G,\text{average}} = H \cdot u \cdot \beta_F \tag{3}$$

in which H = bed form height, u = propagation velocity and β_F = form factor, due to prevailing bed forms (eq. 1).

Including the density and porosity of the bed layer the analysis leads to transport rates corresponding to the aforementioned technique. In Figure III-9 the evaluated transport rates from the dune propagation method considering the rms-values are shown. The dimensionless transport rates (eq. 4) are depicted versus the dimensionless shear stress Θ, the integral Shields parameter.

$$q_{bed}^{*} = \frac{q_{bed\,s}}{\sqrt{(s-1)gd^3}} \tag{4}$$

$$\Theta \equiv \frac{\tau}{(s-1)\rho g d} \tag{5}$$

here are d = diameter of particles, τ = total bed shear stress, g = gravity, s = relative density of sand, ρ = fluid density, $q_{bed\,s}$ = longitudinal sediment transport rate. This is a formula based on integral parameters (water depth h, Shields parameter including form drag of bed forms, water level gradient).

A good agreement of determined transport rates over a range of increasing dimensionless shear stress is given. The good correlation of the determined transport rates is another argument for the verification of this method. In order to get a similar transport rate to other results the total values of the dune propagation with the rms-analysis were modificated with a small parameter. So the quantatitive magnitude of the sediment transport is in the same range as the sand trap measurements but the correlation of all considered experiments is better.

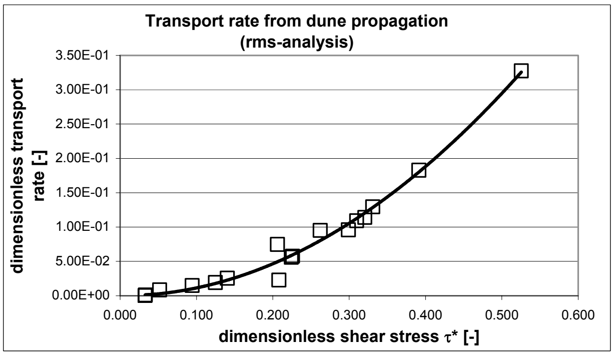

Figure III-9: Evaluated transport rate values versus the dimensionsless shear stress values (Shields parameter).

Because of the fairly good correlation the dune propagation method should compared to other methods. In addition to the determination of the dune propagation velocity the analysis of the bed form geometry, based on observations of minimum and maximum value between the zero-crossing points, yields the transported volumina.

In the bed levelling investigation the evaluation of the sediment transport direction of the series R1 (coarse sand, d_m = 0.096mm) was conducted with the data of eight experiments. The sediment transport data of these experiments, determined with the dune propagation, with the transport formula of Zanke 1999 [7] and with weighing up the sediments collected in the sand trap, are compared in Figure III-10, Figure III-11 and Figure III-12.

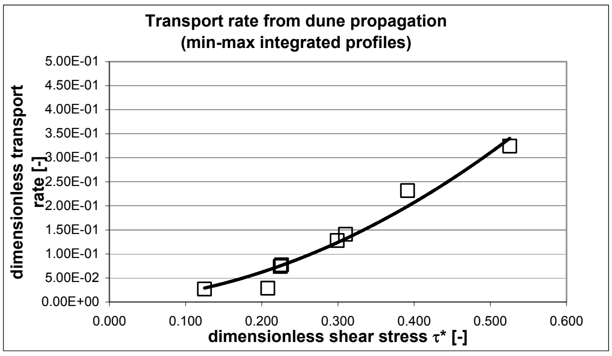

Figure III-10: Dimensionless transport rate versus dimensionless shear stress. Transport rates evaluated from dune propagations.

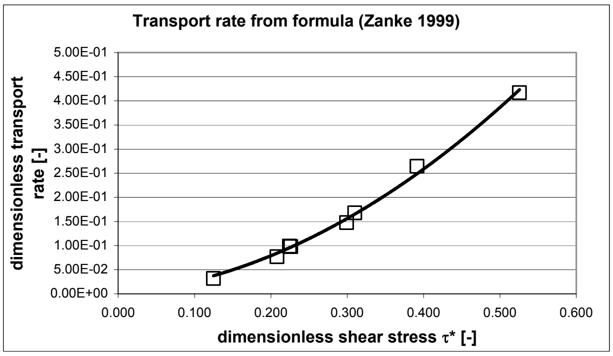

Figure III-11: Dimensionless transport rate versus dimensionless shear stress. Transport rates evaluated from transport formula of Zanke 1999.

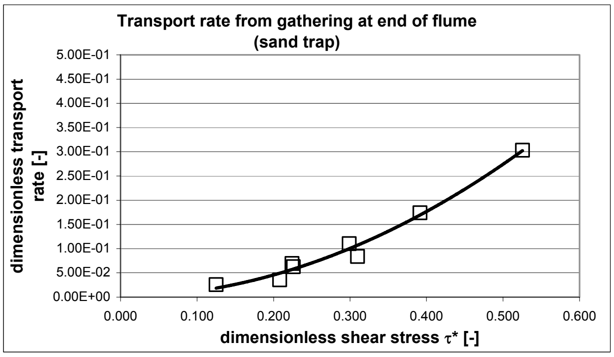

Figure III-12: Dimensionless transport rate versus dimensionless shear stress. Transport rates evaluated from the gathered total sediment transport mass (sand trap).

A comparison of the three different methods of sediment transport rate determinations is given in Figure III-13. Both methods, the dune propagation method and the sand trap (weighing) method vary from the calculations with the formula of *Zanke* 1999.

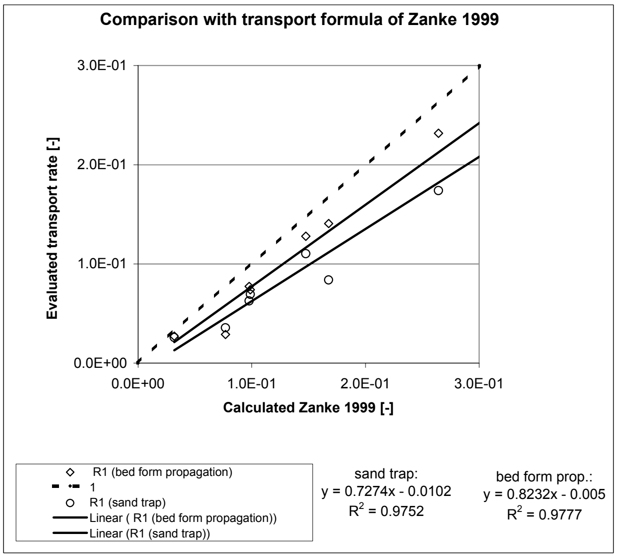

Figure III-13: Comparison of transport rate determination methods.

With regard to the bed levelling experiments and the combined determination of transverse transport rates the dune propagation method yields better results concerning the correlation of a transverse transport approach (cp. Wiesemann, Mewis, Zanke 2006 [5]). This could be attributed to the location of analyzing the bed profiles. In that case the longitudinal transport rate and the transverse transport rate are determined from the same measurement section and both from analyzing the bed profiles.

Further experiments must be conducted to get more data which support the concluded results.

IV. CONCLUSION

In the presented investigation it was shown that sediment transport rates could be determined by considering the prevailing bed forms and their propagation successfully. In experimental investigations with a movable bed and with the need for determining the transport rates gathering the transported material at the end of the flume is an accurate procedure. These integral measurements do not give information about the variation of transport rates and include the conditions of the total experimental setup with all disturbances at inflow and outflow sections. By considering the transport rates within the section where different but associated measurements are conducted the results of the transport rate determination could be better referred to that process which is measured too. In the present investigation the measured bed levels and hence the decay of a previous formed transverse slope was measured. The dune propagation method enables a direct association of measured longitudinal transport rates and the evolution and rearrangement of the bed morphology in the same measurement section.

V. APPLICATION OF SEDIMENT TRANSPORT ANALYSIS

The described determination of sediment transport rates considering the dune propagation is suitable for all laboratory experiments in which bed forms are present. To get reliable results the prevailing bed forms should have two dimensional character and should be stable in their characteristic form. Increasing dune heights do not lead to sigificant inaccuracies but a similarity of the dunes (stability of profile form) should be present.

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