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THREE-DIMENSIONAL MORPHODYNAMIC-NUMERICAL COMPUTATIONS OF INITIATION AND PROPAGATION OF RIVER DUNES

P. Mewis[1]

***Abstract**: The basic mechanism of morphodynamic instability has been identified by J.F. Kennedy (1963). The lag effect of the bed shear stress is a property of the dynamic equations underlying all three-dimensional morphodynamic simulations and has been investigated in several papers (*Fredsøe*, 1976, Richards, 1980 a.o.). In a more recent paper Colombini (2004) focused on the high sensitivity of the dune instability to the near bed flow structure.*

The dune bed for a laboratory and a lowland river case chosen from the river Elbe in Germany is simulated using the 3D morphodynamic numerical model SMOR3D. The model solves the three-dimensional hydrostatic momentum equations and has been applied for a wide range of problems, like e.g. alternate bar instability. It accounts for wetting and drying, bed- and suspended load and density driven currents.

The dunes that develop in the numerical simulation behave very similar to real dunes. The calculated dunes resemble the parameters of observed dunes. The bed shear stress for the bed load formula is calculated from the velocities at a certain elevation above the bed. In this context it is necessary to mention, that the numerical model results may not serve as a bed-form predictor by themselves.

***Keywords**: morphodynamic modeling; sediment transport; bed forms; river dunes; bed instability.*

INTRODUCTION

The definition of morphodynamic bed forms and the identification of the basic morphodynamic instability have been given by J.F. Kennedy (1963). Since this work the lag effect of the bed shear stress is known to be the mechanism responsible for the initiation of dunes at the river bed. After the initial work the instability mechanism has been discussed in a number of papers like that of J. Fredsøe (1974) or Richards (1980). The dune instability is a property of the three-dimensional dynamic equations underlying all threedimensional morphodynamic simulations carried out at present. Recent papers on this topic originate from Colombini (2004, 2008). Colombini focused on the high sensitivity of the dune instability on the near bed flow structure

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and used the jump height of bed material to obtain modified unstable regions that compare better with measurements.

LABORATORY OBSERVATION OF DUNES

Laboratory Flume Measurements with a movable bed have been carried out in the Hydraulic Laboratory of UT Darmstadt under supervision of the author. The tilting flume is 60 m long and 1 m wide. The experiments where focused on the transverse slope effect. However in several runs a dune bed evolved in the flume from a streamwise leveled bed. For the example shown here the bed material was coarse sand of 0.96 mm mean grain size, the flow depth 30 cm, discharge 180 l/s and the slope 0.0011. The dunes appeared over the entire length of the flume. In Fig. 1 and 2 longitudinal profiles of the bed obtained with a laser distance sensor are plotted. The dunes appeared quickly after the start of the experiment with an initial amplitude of about 1 cm after 3 min of experimental run.

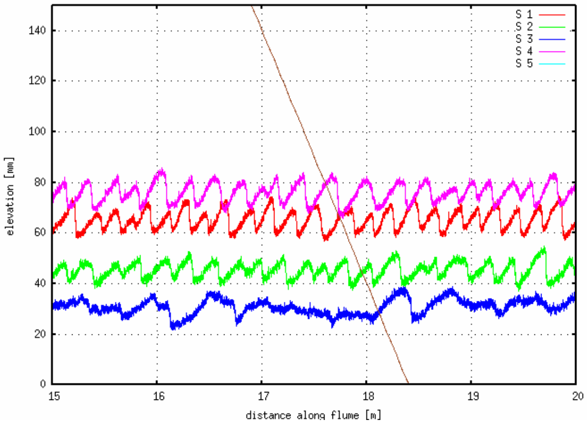

Fig. 1: Longitudinal bed profiles of the flume after 3 min. The dune height is about 1 centimeter.

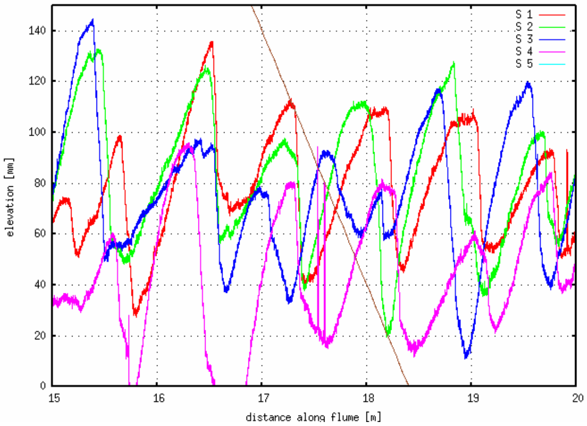

Fig. 2: Longitudinal bed profiles of the dunes after 120 min indicating a dune height of about 8 centimeter.

The inclined black line in the plots indicates an inclination of 1:10. From Figure 1 it can be seen, that the lee sides of the dunes were already inclined steeper than 1:10. The dune steepness is

1:15. The dunes are already in the nonlinear stage after 3 min. of experimental run. In the following Figure 2 both the height and length have increased. The dune length was estimated by means of autocorrelation plots and is plotted over time in Figure 3.

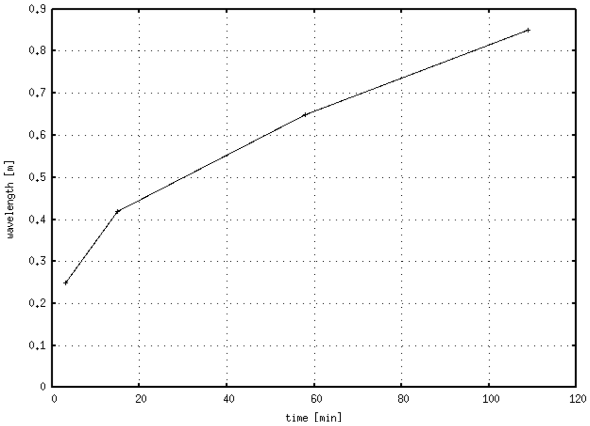

Fig. 3: Time development of the dune length for the flume experiment.

The first profiles taken after 3 min. already showed dunes of about 25 cm length. With time not only the dune height but also the length increased. Important to note is the initial dune length of about 25 cm. This seems to be the wave length that should correspond to the values given by the linear instability problem. The length reached almost 90 cm at the end of the experiment. This wave length is still not the equilibrium wave length. These parameters agree well with other laboratory experiments on dunes. The increase in dune length is a common property of the dunes.

LINEAR STABILITY ANALYSIS

The linear stability analysis results in propagation speed and growth rate of bed disturbances. While the propagation is a constant shift of the form, the growth rate results in a more or less rapid exponential growth of the amplitudes of the small harmonic dunes with time. The maximum growth rate is commonly accepted as the wave that will “appear” from background white noise perturbations.

The flow velocity exhibits a phase shift over a bed disturbance, often called the friction effect or the advective instability and has been described in many papers already, including Mewis (2004). The phase differences of the flow velocity over the water column for two real situations are plotted in the figures below.

A stability analysis for the system river flow and movable bed has been carried out. The analysis is similar to the work of Fredsøe 1974, Richards (1980) or of Colombini (2004). The rotational momentum equations and the continuity equation are linearized and the harmonic perturbation is solved for. The equations cannot be solved analytically but lead to a one dimensional vertical problem while the longitudinal direction is represented by harmonic functions. This task has been solved by the author in a 1D program utilizing a variable space step in the vertical direction for a sufficiently high resolution close to the bed. In the calculations reproduced here the hydrostatic pressure assumption has been used. For the turbulent eddy viscosity a mixing length approach is applied. After a coordinate transformation for the vertical coordinate the one dimensional vertical problem has been solved numerically.

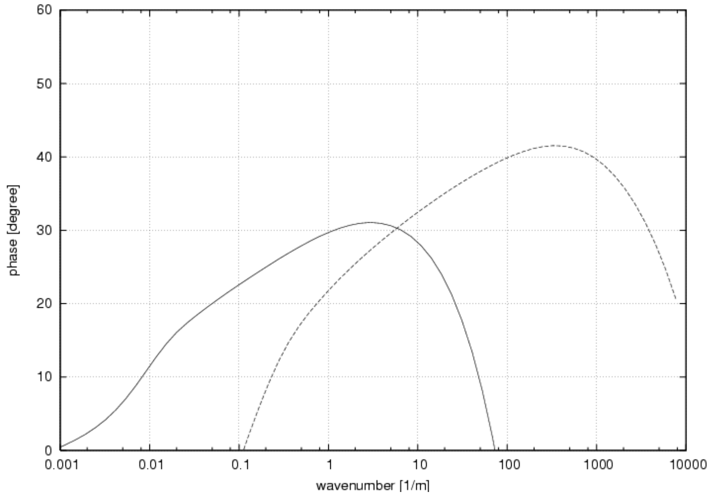

Fig. 4: Phase angle for small amplitude disturbances between bedform and maximum flow velocity for a wide range of wavenumbers.

The phase shift between the flow velocities and the bed disturbance reaches values of forty degrees. A shift of 90 degrees means that the maximum flow velocity is located in the middle between trough and crest of the bed disturbance leading to no propagation, but rapid growth. A large shift indicated a large growth rate in height of the bed-form, when compared to the propagation of the bed-form. The two lines in Figure 4 are the phase shift of the flow velocity. They are computed for the parameters of the lowland river Elbe and for the laboratory flume. The vertical resolution was 50 nodes in the vertical, close to the 3D computation shown below. The maximum phase angle for the two cases is corresponding to relatively short waves of about 2 m wavelength for the real river and only about 3 cm for the laboratory flume. Such short waves have not been observed. Therefore modifications that increase the wave length are wanted.

Different mechanisms that increase the wave length have been reported. Accounting for suspended load (Fredsøe, 1974) is not appropriate in the test cases. One possibility not followed here is assuming a loading law with adaptation or step length (Shimizu und Giri, 2006) for the bed load. Increasing the bed slope effect in the computation of the critical velocity and the sediment transport rate computation will also suppress short wave disturbances. The utilization of the flow velocity at certain distance from the bed is tested here (Colombini 2004).

Colombini (2004) proposed that not the shear stress directly at the bed should be used in the calculation of the sediment transport rates, but at an elevation corresponding to the upper limit of the bed-load layer. This is in agreement with the findings that the shear stress within the bed load layer is transmitted partially by the sediment grains and not only by the water.

The phase shift of the shear stress is largely dependent on the elevation above the mean bed level. To illustrate this in Figure 5 the isolines of 0, 10, 20, 30 and 40 degrees phase shift of the flow velocity are drawn in the plane of wave number and elevation above the mean bed level given in meter. The values are a result of the 1D stability analysis using 50 nodes in the vertical direction. From Figure 5 it becomes clear that the phase changes rapidly very close to the bed. Between 0.01 and 0.0001 m the phase lead of the flow disturbance increases from 10 to 40 degrees. The maximum of the phase shift drawn in figure 5 is restricted to a thin layer of fluid of less than 0.2 mm in height. Because the mean diameter of the sediment grains is larger than this distance the flow structure close the wall interacts with the rough sediment surface. The grain jump height (Colombini 2004) and also the roughness elements themselves strongly influence the phase shift.

Also very important to note is the increasing wave length of the maximum growth rates with increasing elevation above the bed. In Figure 5 the maximum angle is indicated by the broken line. At an elevation close to the mean grain size of the sediment the wave number is about 10 to 20 m^{-1}. The corresponding wavelength of 0.3 to 0.6 m agrees much better with the laboratory observations. The same is true for the river Elbe case.

In these plots the flow velocities are plotted. The effect of an inclined bed on the initiation of motion and on the sediment transport rates is thus not included. They will additionally increase the wavelength of the maximum growth rate in the sediment transport rate computation.

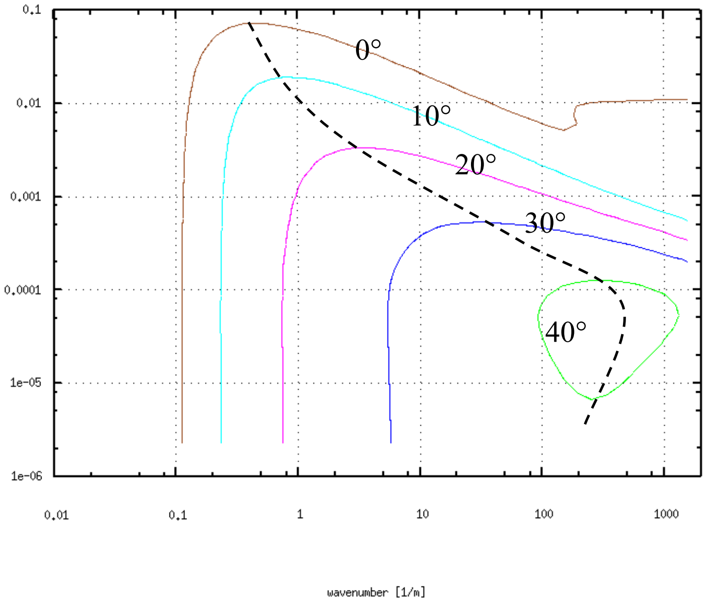

Fig. 5: Phase angle between flow velocity and bed form for small amplitude disturbances over a wide range of wave numbers and different elevations above the mean bed (y-axis) given in meters. Parameters of the laboratory flume case.

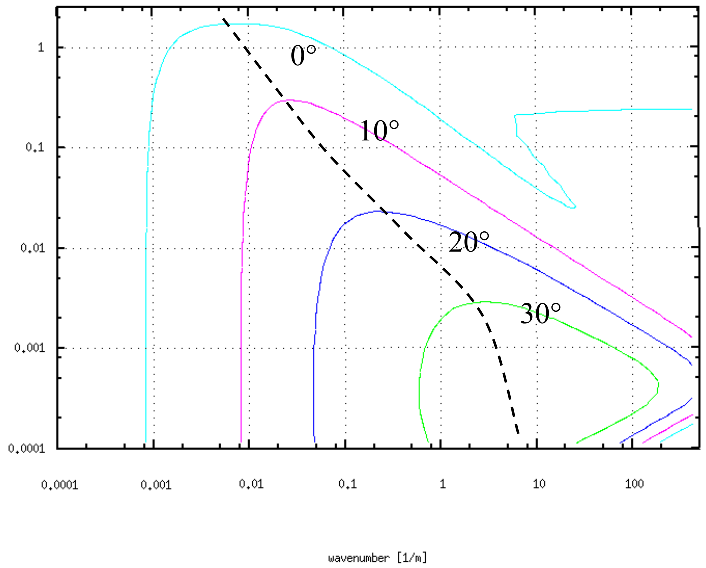

Fig. 6: Phase angle between flow velocity and bed form for small amplitude disturbances over a wide range of wave numbers and different elevations above the mean bed (y-axis) given in meters. Parameters of the river Elbe case.

NUMERICAL MODEL SMOR3D

SMOR3D is a three-dimensional flow and morphodynamic model that is based on an unstructured FE grid and utilizes the hydrostatic pressure assumption in the vertical. The model has been applied for a wide range of problems in coastal and river engineering already. Wetting and drying, suspended load and density driven currents have been simulated. In morphodynamic computations the model accounts for a mean grain size of the bed material. The well known Meyer-Peter, Mueller bed-load equation is used. The bed slope effect is accounted for in the sediment transport computation and the computation of the critical velocity. The alternate bar instability and river meandering have been modeled with SMOR3D as well. To obtain stable and reliable results the model is run using upwinding in the computation of the advective terms and also in the computation of the bedload.

To demonstrate the different growth rates of different wave length a 100 m long but narrow canal of 4 element width has been simulated using SMOR3D with 38 layers utilizing the sigma coordinate system in the vertical. The longitudinal node spacing is 0.5 m. A variable wave length seeding is made by prescribing a bed undulation of 1 mm amplitude by 0.001*sin(x/(0.15+x/150)*6.283). Thus the seeding consists of waves ranging from a length of 0.20 m to about 1.5 m over the 100 m long model domain.

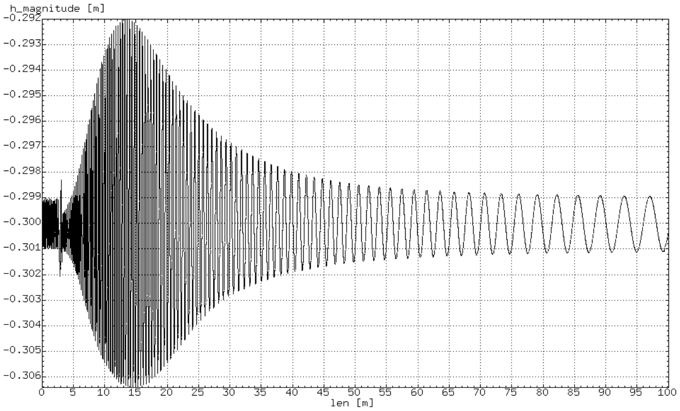

Fig. 7: Bed evolution of variable wave length disturbances for the laboratory example, when using the flow velocity directly at the bed. The fastest growing waves have a length of 0.4 m.

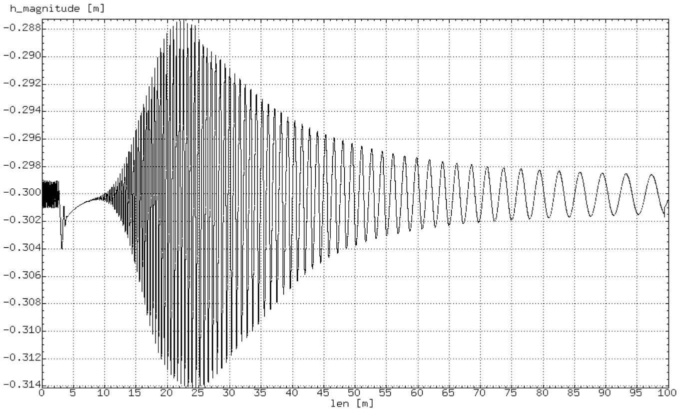

Fig. 8: Bed evolution of variable wave length disturbances for the laboratory example, when using the flow velocity 0.5 mm above the bed. The fastest growing waves have a length of 0.6 m.

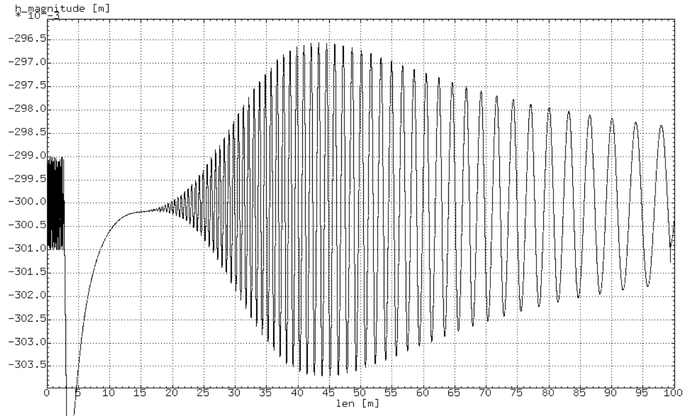

Fig. 9: Bed evolution of variable wave length disturbances for the laboratory example, when using the flow velocity 1.5 mm above the bed. The fastest growing waves have a length of 1.3 m..

In Figures 7 to 9 longitudinal bed profiles after a certain time of model run are plotted. The time instant plotted is not the same. The maximum growth rate at the early linear stage is easily visible. From one Figure to the next the distance from the bed where the flow velocity is evaluated is increased. The maximum amplitudes in Figures 7 to 9 belong to increasing wave lengths.

Also important to note is the damping of the short waves in the last figures. This indicates a suppression of short waves when using flow velocities at a small distance above the bed. The longest waves of the seeding grow slowly with time, but are overrun by the faster evolving shorter waves with maximum growth rate. This is in agreement with the graph of the stability analysis where the zero phase line belongs to k_x equal to 0.1 or about 60 m wave length.

EXAMPLE OF LOWLAND RIVER ELBE

The development of the dune bed for idealized conditions and using a real river reach of the river Elbe in Germany is simulated using the 3D morphodynamic numerical model SMOR3D. The Elbe is a waterway with a maintained waterdepth of 1.6 m. The bed material has a mean grain size of about 2 mm in the part simulated here. The average slope is about 0.00013. At almost all places the bed is covered with dunes of different dimensions. Typical are dunes, that are about 0.5 m high and about 6 m long. In some sections transport bodies of larger dimensions develop that heavily disturb the maneuvering of the ships.

To simulate the typical dunes of the lowland river a very high resolution of the numerical model is required. The grid is refined to an element edge length of 0.5 m. Per dune length 20 grid points are used. This resolution is necessary to be well above the limit of the numerical model accuracy. Because of the high resolution only a narrow section of 1 kilometer length is simulated. In the numerical model the dunes develop as shown in Figures 10 and 11. The simulation was seeded with 20 m long bed waves with a height of 2 cm. The initially harmonic dunes rapidly grow and deform into asymmetric form. During this time each of the prescribed bed waves divides into three to four shorter waves. As these waves grow they unite again into longer waves when reaching the final height of 0.6 m. This height seems appropriate for the 3 m deep Elbe case. The lee sides of the dunes are steep the luv sides rounded. The flow separation at the dune crest is not perfectly modeled. The bed is slightly bended upwards at these locations despite the upwinding in the transport equations. Nevertheless this seems to influence the results not significantly. Using the flow velocities at 1.5 mm above the zero level results in 10 to 15 m long bed waves, as shown in Figure 10.

Clearly the bed grain size is larger than this elevation where the flow velocities are computed. At present the grain size influences only the bed friction factor in the simulations. The resolution of the flow models can be excessively in theory. In practice we are already in between the grains of the bed sediment or even slightly above. Thus the grain size of the bed sediments is important for the velocity profile close to the bed. The larger the grains the larger the pressure drag, that influences the flow velocities differently from the turbulent profile extended down to the zero level z_0 for a rough wall or even closer to the wall into the laminar sublayer. Thus the grain size effect has to be investigated further, including the jump height effect described by Colombini 2004.

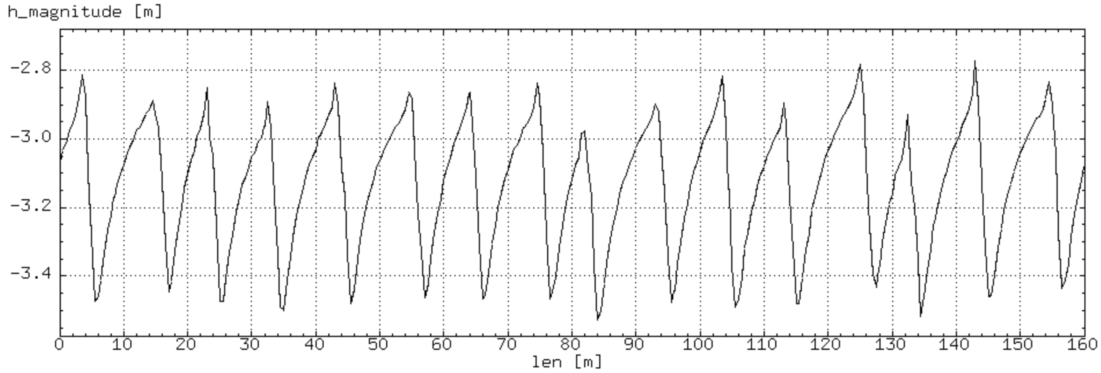

Fig. 10: Bed profile for the Elbe case when the velocity at an elevation of 1.5 mm above bed is used in the calculation of sediment transport. Seeding wave length was 20 m.

If the flow velocities at 6 mm above the bed are used the tendency is clearly to longer bed waves as shown in Figure 11. The crest is longer in this calculation and tends to become wavy again. It may become unstable at shorter wave length corresponding to the maximum growth rate and develop a new dune by splitting the long dune into two new individual dunes.

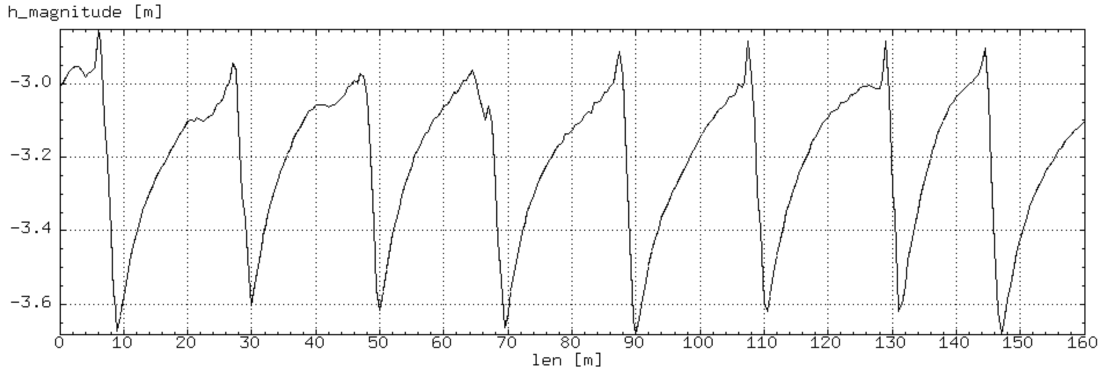

Fig. 11: Bed profile for the Elbe case when the velocity at an elevation of 6 mm above bed is used in the calculation of sediment transport. Seeding wave length was 20 m.

CONCLUSIONS

Linear stability analysis indicates a significant influence of the near bed region on the dune instability. The velocity profiles influenced by the sediment properties become important. The grain size itself is important not only for the computation of the friction coefficient but also for the jump height or more general the height at that the flow induces the shear stress acting on the grains.

The dynamics of dunes could be simulated using the three-dimensional morphodynamic - numerical model SMOR3D. It could be shown that the behavior and the dimensions are very similar to observed dunes. The initiation of the dunes is also represented quite realistic by shifting the position of the shear stress computation from the flow velocity upwards above the bed.

For real applications of the simulation technique the predictability of the bed-form development has to be tested and improved further. In this context it is necessary to mention, that the numerical model results may not serve as a bed-form predictor by themselves. The coexistence and the limits of existence of different bed-forms have still to be investigated.

However the simulation technique is a way to improve our knowledge of the river system. It provides a basis for larger scale morphodynamic computations and it may also be of use for short term predictions of shoals in the river and probably also of local scours within the river bed, despite of the stochastic nature of the phenomenon.

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