Conference Paper, Published Version

Goll, Annalena; Kopmann, Rebekka; Brudy-Zippelius, Thomas

Numerical modelling of bed formes (dunes) with TELEMAC3D and SISYPHE

Numerical modelling of bed formes (dunes) with TELEMAC3D and SISYPHE

Annalena GOLL,
Rebekka KOPMANN and Thomas BRUDY-ZIPPELIUS
Hydraulic Engineering Department
Federal Waterways Engineering and Research Institute (BAW)
Karlsruhe, Germany
Annalena.Goll@baw.de

***Abstract*— This paper presents simulations of dunes in an open channel flume with TELEMAC3D and SISYPHE. The simulations are compared to results of a laboratory flume situated at the BAW (German Federal Waterways Engineering and Research Institute), Karlsruhe, where three-dimensional sand dunes were produced and studied. The behaviour of the simulated dunes, their origin and movement has been studied. It shows that successful dune modelling can be done by using a calibrated parameter set. The distribution of the vertical layers has proved to be a crucial parameter when simulating dunes with TELEMAC3D and SISYPHE. Very fine spacing near the bottom is needed, scaling with the grain size of the sediment or the friction coefficient respectively. The distribution of bed shear stress influencing the bed forms is changed by the choice of number and spacing of the vertical layers. So far the produced bed forms move too fast and the bed load discharge is too high, even with a reduced pre-factor of the bed load transport formula. As this research is ongoing further insights are expected.**

I. INTRODUCTION

Recently there has been an immense advance in seizing the dynamics that lead to and govern the complex processes of river dune morphology. New measuring instruments allowed better and thorough experimental studies, e.g. [1], [2], [3] and [4]. High performance computer made detailed simulations possible, e.g. [5], [6], [7], [8] and [9]. High resolution simulations enabled to investigate long known phenomena like flow separation behind dunes [10], [11], and to give a realistic picture of dune movements [12], [9].

But still there remain questions concerning the challenge to adequately connect bed morphologies to the turbulent flow field and to find proper dune dimension definitions [13]. For example it has been shown that the form of the dunes effects the amount of turbulence of the flow [1], [14]. On the other hand there have been studies which name the choice of the turbulence model ambiguous concerning the morphodynamic computation [6]. Studies that try to evaluate computational models that are used to simulate the turbulent flows which govern the dune movement process found significant differences between the models [11].

Even so the achievements named above are immense it is so far not possible to predict dune movements for large river sections or forecast long-term developments. In general the aim therefore has to be to use data obtained from experimental flumes to calibrate models that can be used for large scale simulations and project work.

This paper presents calculations of morphodynamic and flow of a open channel laboratory flume situated at the BAW, Karlsruhe, where three-dimensional sand dunes were produced and studied. Morphodynamic simulations of the dune bed with TELEMAC3D and SISYPHE are compared to the flume data obtained by photogrammetry. This work is supposed to be a first step on the way to fit and validate the models and find parameter sets that can be used for long term and large scale predictions of dune movements.

II. EXPERIMENTAL SETUP

A. *Experimental Flume*

The experimental flume is situated at the German Federal Waterways Engineering and Research Institute (BAW), Karlsruhe. Details can be taken from [15].

The experimental open channel flume is 32m long and 2m wide. It has a rectangular cross section with one side-wall of glass with metal bars and one side-wall of plastic material. The bottom is constantly covered with sediment which has a steep grading curve (with mean diameters 1% 0.4275mm, 3% 0.605mm, 64% 0.855mm, 32% 1.2mm) and a total mean diameter of 0,94mm. The slope of the bed is 0.6‰. The water depth is regulated by a flow-governed weir at the outlet. For the presented calculations only runs with Q = 140 l/s and corresponding sediment input of 37 kg/h are considered. The water depth at the outlet is then 0.141m and the mean water depth is 0.175m.

B. *Measuring Device*

The following description of the measuring device is taken from [16]. For further details please refer to this paper.

The used measurement system has been developed by the BAW. It is a laboratory based three-dimensional photogrammetric measurement system for the monitoring of alluvial bed topography allowing for repeated, instantaneous recording of dune beds during water flow. It was initially developed to measure dry channel surfaces but has been further developed for subaqueous surfaces. The system consists of an automated camera orientation unit and is based on bar coded markers and a grid projection unit for identification of bed topography. Achievable vertical accuracies for bed elevation measurements are 1 mm for subaqueous measurements and 0.1mm for dry bed model measurements.

The advantage over existing measuring devices is the possibility to record continuously and instantaneously through the water surface, instead of emptying the flume to be able to record the dry bed topography. For the presented flume results a picture was taken every 20s of a selected area of the flume. After each run of 6h the complete flume was recorded as well.

III. Numerical Model

For the numerical computation, TELEMAC3D and SISYPHE (version v6p0) were used (for a detailed model description, please refer to http://www.opentelemac.org and http://docs.opentelemac.org).

The computational grid spans the complete experimental flume except the starting and ending part (flume meter 2 until 29.97) in x-direction and over the full 2m in y-direction. The mean horizontal mesh size of the unstructured sigma-mesh is 15cm. The vertical discretisation was subject to calibration and thus several discretisations were used: 10 respectively 20 vertical layers were unevenly distributed with fine spacing near the bed, coarsening towards the free surface according to the log-law. Additionally an extremely fine bottommost layer was added. The mean water depth of the flume is 0,175m.

At the inlet constant discharge and no sediment is given at the boundary. The sediment input is realised with the dredging and disposal module DredgeSim [17] coupled to SISYPHE to reproduce the conditions of the physical model, where the sediment input is alternated every hour from the left to the right hand side on the first half square meter of the flume input. Like in the experimental flume the water level at the outlet is kept constant.

Both pure hydrodynamic and coupled hydrodynamic and morphodynamic simulations were done. For the hydrodynamic computations without morphodynamics a preformed dune bed is chosen. Therefore a fully developed dune bed morphology is taken from photogrammetric measurements of the flume after 6h (see Fig. 1). For coupled morphodynamic simulations the calculations start from a plane bed.

A. *Numerical Configuration of TELEMAC3D*

Several configurations were tested [18]. As the turbulence modelling is of major importance when simulating bed forms, the choice of the turbulence model (and corresponding parameters) has been given special attention. The best results could be found with the mixing length model of Prandtl as the vertical turbulence model and the Smagorinsky model as the horizontal one.

The molecular viscosities (coefficients for diffusion of velocities) were set to 10^{-4} m^2/s to stable the simulations, as it seems that in case of flume experiments the turbulence models create too less turbulent viscosity. The scheme for advection of velocities is the explicit scheme with SUPG (Streamline Upwind Petrov Galerkin) in connection with the use of the wave equation.

B. *Numerical Configuration of SISYPHE*

The bed load transport formula was Meyer-Peter & Müller [19] with a pre-factor of 3. The slope effect formula of Soulsby [20] and the deviation formula of Talmon [21] were used, using parameter for deviation = 2. Bed load sediment was a four fraction grain mixture (with mean diameters 1% 0.4275mm, 3% 0.605mm, 64% 0.855mm, 32% 1.2mm) that yielded an overall mean diameter of 0.96mm. The friction coefficient was chosen according to $3D_{50}$ to 2.82mm.

IV. Results

Calibration and numerous test simulations have shown that dune modelling with TELEMAC3D and SISYPHE is very sensitive to the distribution of the vertical layers. With uniform distribution no dune formation or movement could be obtained. Only with unevenly distributed vertical layers which have fine spacing near the bed and coarse towards the free surface according to the log-law a dune-like formation could be produced. This experience has been stated before [6]. It also has shown that the correct dune height and the formation of dunes in general further depend on the choice of the distance of the first vertical layer.

This becomes obvious as the bed shear stress τ in SISYPHE is calculated from the velocities of first node above the bed surface according to:

$$\tau = \rho u_*^2 = \rho \left[\frac{\kappa}{\log(30\Delta / k_s)} \right] \left(u^2 + v^2 \right) \qquad (1)$$

where Δ is the distance between the bed and the first vertical layer. This is why the bed shear stress depends strongly on the ratio of this distance and the friction coefficient k_s.

Fig. 2 shows the flume bottom of 4 runs with different vertical layer distributions. The first 6–8m of each flume are influenced by the bed load input. Only two runs (10 layer fine, 20 layer fine) yield a dune formation with comparable to the dune heights of the physical model. Both runs have a very small first vertical layer (0.00138 times the water depth). The figure shows that a bigger first vertical layer results in a less dominant dune formation.

Simulations over a preformed dune bed (Fig. 1) show the different bed shear stress that is produced due to the different vertical layer distributions (Fig. 3). Four different dunes of the preformed bed and the corresponding bed shear stress can be seen. The two vertical distributions where the first bottommost layers were refined (_fine) yield a bigger amount of bed shear stress. It seems that a higher bed shear stress is needed to form a distinctive dune bed. Decisive is the fact that not the simulation with the by trend highest bed shear stress (10layer_fine) produces the most similar bed forms to the flume experiment, but the run with slightly less bed shear stress (20layer_fine) (see Fig. 2 as well). The 20–layer run has only selective peaks of higher bed shear stress. Obviously dune formation and dune shape in TELEMAC3D and SISYPHE not only depend on the amount of produced shear stress but also on its distribution (Figs. 3a) and 3b)). This coincides well with existing research, e.g. [22], [23], [24] and [25], [26], [27], [28].

The height, length and the movement of the dunes in the physical model has been compared to the movement of the dunes in the numerical model. The results are shown in Fig. 4. Fig. 4a) shows one representative dune every 5 minutes over a period of 20 minutes, extracted of the continuously recordings of the physical model. Fig. 4b) shows an extracted dune of the numerical model with 20 vertical layers over a period of 20 minutes. It can be seen that the dunes move in a similar way. The slopes of the luv- and the lee-sides of the dunes are comparable. The dunes do not flatten and the dune crest moves in the same velocity in ratio to the dune valley. Nonetheless the complete dunes of the numerical model still move to fast. This affects the complete bed load discharge, which is approximately 3.7 times too big compared to the physical model. This is the case despite the reduction of the pre-factor of the Meyer-Peter & Müller transport formula down to 3. It has to be stated though, that the physical model is not in an equilibrium state as well, concerning bed load discharge.

Dune lengths and heights have been evaluated with a MATLAB routine. For this purpose longitudinal cross sections every 1cm of the topography are extracted and the slope is deducted. Afterwards a partial regression line is plotted and by the crossings of each of the profiles with this regression line a mean dune length and a mean dune height are calculated. Those mean parameters are used for comparing the calculated bottom surfaces with the results of the physical model. Nonetheless the complete plots of the flume bottom are taken into account as well, as the existence of three-dimensionality can not be reasoned from mean heights and lengths.

Fig. 5 shows the mean heights and lengths of the dunes of the numerical and the physical model. Measurements of several runs under same conditions of the flume experiment were taken into account to show the natural variability. It can be seen that the distribution of the 20 vertical layers produces dunes that are similar to the measured ones. The yielded dunes of the 10-vertical-layer model are too short; this leads to too steep luv-sides of those dunes. The plot of the complete flumes (Fig. 2) also shows that the 10-vertical-layer run has too high and sharp single peaks whereas the dunes of the 20-vertical-layer run are much more evenly distributed over the flume width. Both runs produce three-dimensional dunes, but their forms differ.

Even so dune heights and lengths could be reproduced very well it is questionable if the model can be used for proper predictions so far. Furthermore the evaluated time of the runs is only 6h. The bed forms might still change as equilibrium conditions are supposedly not reached yet.

V. CONCLUSION

This paper presents the insights that we have gained so far on the behavior of dune origin and movement with TELEMAC3D and SISYPHE. It has been shown that successful dune modeling can be done by using a carefully calibrated parameter set. In this process numerical schemes, grid distributions and sediment parameters link and gear into each other.

The distribution of the vertical layers has proved to be a crucial parameter when simulation dunes. Very fine spacing near the bottom is needed, scaling with the grain size of the sediment or the friction coefficient respectively. The distribution of bed shear stress influencing the bed forms is changed by the choice of number and spacing of the vertical layers. So far the found parameter set has to be calibrated for each case. A prediction is not possible yet.

The questions remains why the distribution of the vertical layers has such an immense influence on the bed forms and the bottom shear stress. Over the course of a dune the velocity profiles are stretched and compressed and are no longer logarithmic [25]. The calculation of the shear stress in TELEMAC3D follows Eq. (1). This logarithmic equation should provide the same bottom shear stress no matter where the velocity is extracted, but only if the velocity profile is logarithmic. As this is not the case over the dunes, it becomes crucial where on the profile the effective velocity is extracted. An additional finer discretisation further changes the course of the profile, as the profile is reproduced in more detail. As the extraction point turns out to be decisive in case of non-logarithmic profiles, the identification of this point with the actual correct velocity is of major interest. The presented results confirm this.

Even though an adequately simulation of dune height and length could be done the produced bed forms move too fast and the bed load discharge is too high. The reduction up to a very low value of the pre-factor in the Meyer-Peter & Müller bed load transport formula did not solve that problem. It can be reasoned that the dune movement is not bound strictly to the right dune geometry, at least in the numerical model. This is why calibration parameters must be found which affect only the dune movement but not the geometric dimensions. More investigation is needed to understand the connection between the different calibration parameters in order to get an optimal parameter set.

VI. OUTLOOK

Further investigations are needed to extract a case independent parameter set for dune origination and movement. Especially a rule for a proper distribution of vertical layers would be a big step in direction of dune prediction. As this research is ongoing further insights are expected.

So far the numerical model only considers bed load transport. This assumption was made as dune movement mainly happens through bed load transport, not in suspension. Observations of the physical model show that part of the transport is happening through bed load that is thrown into the flow by turbulence “bursts” hitting the dune. This is a long known effect that has been studied intensively before, e.g. [29], [30], [31] and [32]. Even so this transport method is the minor one, the disregard of it might be crucial. The necessity of a proper choice of a correct bed load transport model in connection with a matching turbulence model becomes obvious. Further research in this direction is in progress.

Moreover it is necessary to understand the complex processes of dune movement to successfully simulate dune movement with numerical models. Through the close co-operation between the research of the flume experiment and the numerical simulations at the BAW a very fruitful exchange of knowledge, understanding and discussion is possible. One next step are detailed measurements of the flow field above fixed (and prior to this naturally formed) dunes. This will help to specify the validation of the hydrodynamic part of the simulations which is essential for a successful morphodynamic simulation.

ACKNOWLEDGEMENT

We thank Martin Henning for fruitful discussions and for providing the data of the flume experiments.

REFERENCES

[1] T.B. Maddux, J.M. Nelson, and S.R. McLean. Turbulent flow over three-dimensional dunes: 1. Free surface and flow response. *Journal of Geophysical Research (Earth Surface)*, 108:20, December 2003.

[2] T.B. Maddux, S.R. McLean, and J.M. Nelson. Turbulent flow over three-dimensional dunes: 2. Fluid and bed stresses. *Journal of Geophysical Research (Earth Surface)*, 108:17, December 2003.

[3] J.G. Venditti, M.A. Church, and S.J. Bennett. Bed form initiation from a flat sand bed. *Journal of Geophysical Research (Earth Surface)*, 110(9):19, February 2005.

[4] S.R. McLean, J.M. Nelson, and L. Gary. Suspended sediment in the presence of dunes. In Dohmen-Janssen and Hulscher, editors, *River, Coastal and Estuarine Morphodynamics: RCEM 2007*, pages 611–618. Taylor & Francis Group, London, 2008.

[5] W. Yue, C.-L. Lin, and V.C. Patel. Large-eddy simulation of turbulent flow over a fixed two-dimensional dune. *Journal of Hydraulic Engineering*, 132(7):643–651, July 2006.

[6] S. Giri and Y. Shimizu. Numerical computation of sand dune migration with free surface flow. *Water Resources Research*, 42:19, October 2006.

[7] T. Stoesser, C. Braun, M. García-Villalba, and W. Rodi. Turbulence structures in flow over two-dimensional dunes. *Journal of Hydraulic Engineering*, 42:14, 2008.

[8] K. Bhaganagar and T.-J. Hsu. Direct numerical simulations of flow over two-dimensional and three-dimensional ripples and implication to sediment transport: Steady flow. *Coastal Engineering*, 56(3):320–331, 2009.

[9] M. Nabi. Computational modelling of three dimensional bedform evolution. In *Proceedings of River Flow 2010*, 2010.

[10] V.C. Patel and C.-L. Lin. Turbulence modeling in flow over a dune with special reference to free surface and bed roughness effects. *Proceedings of The Sixth International Conference on Hydroscience and Engineering*, 6:1–10, June 2004.

[11] K. el Kheiashy, J. McCorquodale, I. Georgiou, and E. Meselhe. Three dimensional hydrodynamic modeling over bed forms in open channels. *International Journal of Sediment Research*, 25(4):431 – 440, 2010.

[12] N. Ruether, N.R.B. Olsen, and R.S. Eilertsen. 3d modeling of flow and sediment transport over natural dunes. In *4th International Conference on Fluvial Hydraulics, River Flow 2008*, Cesme/Izmir, Turkey, 2008.

[13] S.E. Coleman and V.I. Nikora. Fluvial dunes: initiation, characterization, flow structure. *Earth Surface Processes and Landforms*, 36:39–57, October 2010.

[14] J.G. Venditti. Turbulent flow and drag over fixed two- and three-dimensional dunes. *Journal of Geophysical Research (Earth Surface)*, 112(11):21, November 2007.

[15] Leichtweiss Institut für Wasserbau. Konzipierung eines flussbaulichen Systemmodells für die Bundesanstalt für Wasserbau. Technical report, Leichtweiss - Institut für Wasserbau, Technische Universität Braunschweig, Abteilung Wasserbau, Professor Dr.-Ing. habil. Andreas Dittrich, 2004.

[16] M. Henning. Literaturrecherche zum Geschiebetransport und Morphologie alluvialer Gewässer unter besonderer Berücksichtigung von Transportkörpern. Bericht 966, Leichtweiss-Institut für Wasserbau, Braunschweig, July 2008.

[17] C. Maerker and A. Malcherek. Die Analyse von Baggern und Verklappen. Teil 1: Das Softwarepaket DREDGESIM. *Korrespondenz Wasserwirtschaft*, 10, 2010.

[18] A. Goll. Numerical modeling of bed load transport by dunes - Numerische Modellierung von Geschiebetransport durch Dünen. Master's thesis, Universität Stuttgart, January 2011.

[19] E. Meyer-Peter and R. Müller. Formulas for bed-load transport. *Proceedings of the 2nd Meeting of the International Association for Hydraulic Structures Research*, 1:39–64, 1948.

[20] R. Soulsby, J. Damgaard, and R. Whitehouse. A sloping duct for the study of sediment transport. *Proceedings of the 25th International Conference of Coastal Engeneering, Orlando, Florida*, 1:3913–3920, 1996.

[21] A.M. Talmon. *Bed topography of river bends with suspended sediment transport*. PhD thesis, Technische Hogeschool Delft, 1992.

[22] F. Engelund and J. Fredsøe. Sediment ripples and dunes. *Annual Review of Fluid Mechanics*, 14:13–37, 1982.

[23] S.R. McLean. The stability of ripples and dunes. *Earth Science Reviews*, 29:131–144, 1990.

[24] S.E. Coleman, V.I. Nikora, S.R. McLean, T.M. Clunie, T. Schlicke, and B.W. Melville. Equilibrium hydrodynamics concept for developing dunes. *Physics of Fluids*, 18(10):1–12, October 2006.

[25] P. Mewis. Are 3d morphodynamic simulations without dunes reasonable? In *Marine Sandwave and River Dune Dynamics*, 2004.

[26] M. Colombini. Revisiting the linear theory of sand dune formation. *Journal of Fluid Mechanics*, 502:1–16, 2004.

[27] P. Claudin and B. Andreotti. A scaling law for aeolian dunes on Mars, Venus, Earth, and for subaqueous ripples. *Earth and Planetary Science Letters*, 252:30–44, November 2006.

[28] A. Fourrière, P. Claudin, and B. Andreotti. Bedforms in a turbulent stream: formation of ripples by primary linear instability and of dunes by nonlinear pattern coarsening. *Journal of Fluid Mechanics*, 649:40, April 2010.

[29] K. Narahari Rao, R. Narasimha, and M.A. Badri Narayanan. The bursting phenomenon in a turbulent boundary layer. *Journal of Fluid Mechanics*, 48(02):339–352, 1971.

[30] R.G. Jackson. Sedimentological and fluid-dynamic implications of the turbulent bursting phenomenon in geophysical flows. *Journal of Fluid Mechanics*, 77(3):531–560, 1976.

[31] M. Lapointe. Burst-like sediment suspension events in a sand bed river. *Earth Surface Processes and Landforms*, 17:253–270, May 1992.

[32] R. Kostaschuk. A field study of turbulence and sediment dynamics over subaqueous dunes with flow separation. *Sedimentology*, 47(3):519–531, 2000.

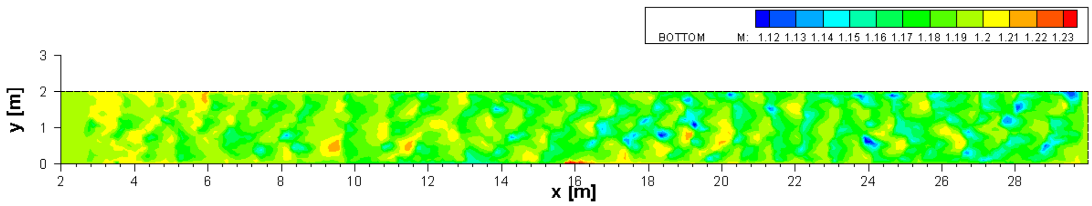

Figure 1. Pre-formed bed obtained from photogrammetric measurements of the flume after 6h, used for numerical simulations.

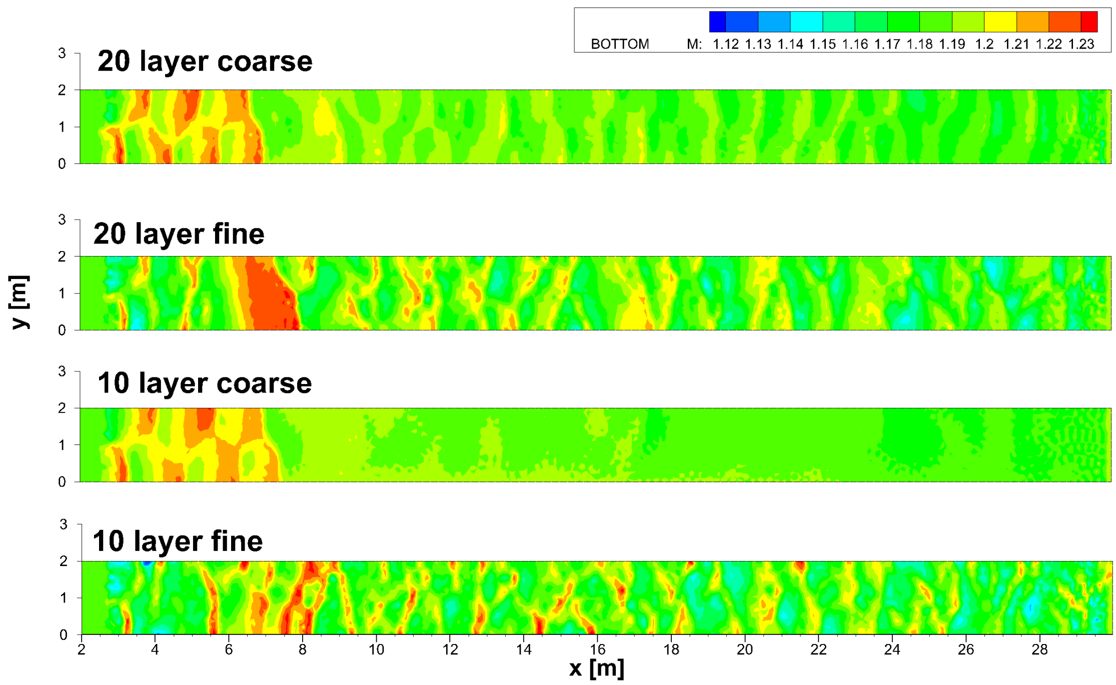

Figure 2. Calculated bed forms after 6h with different vertical layer distributions, start from level bed.

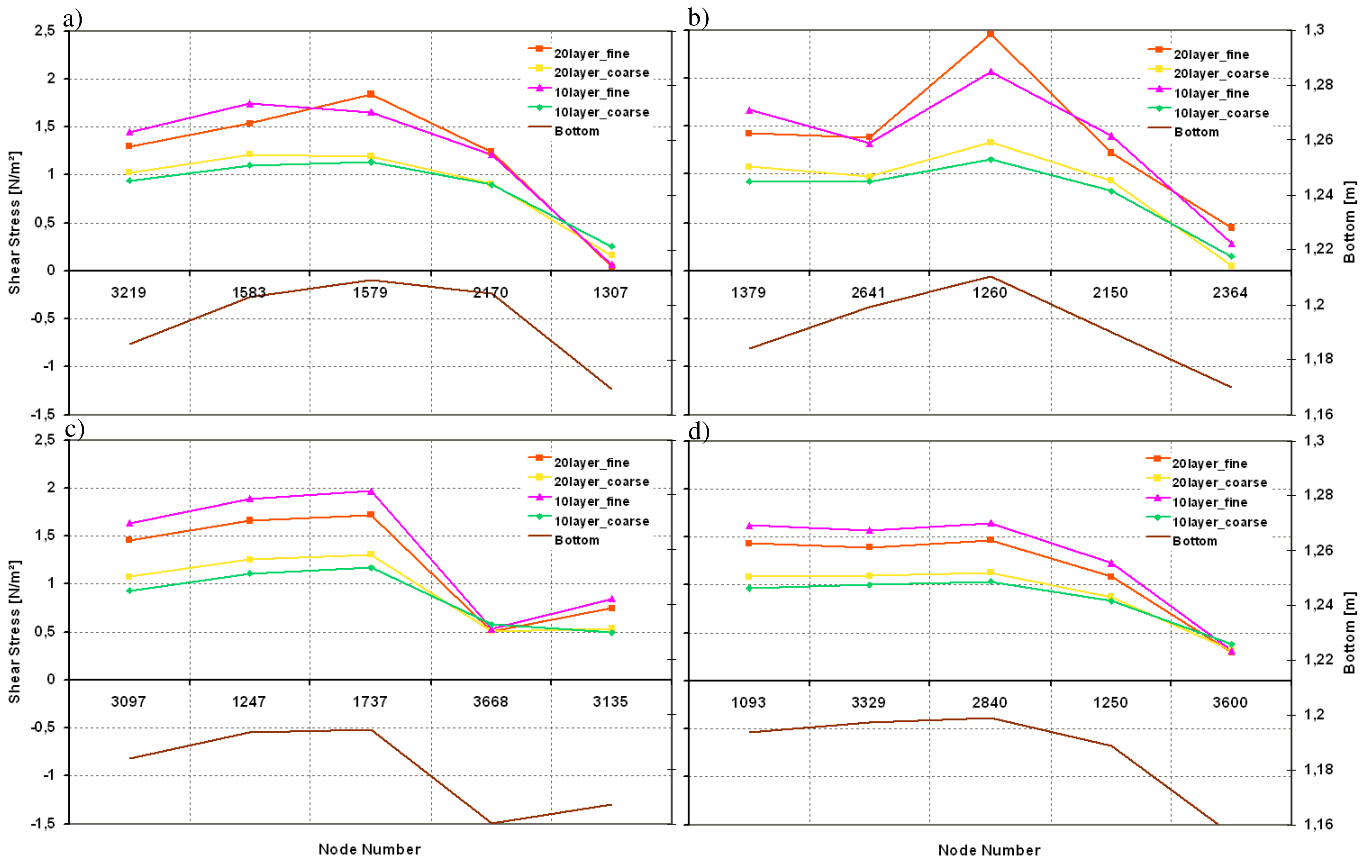

Figure 3. Simulated bed shear stress distributions over 4 different dunes of the pre-formed bed (Fig.1) for different vertical layer distributions.

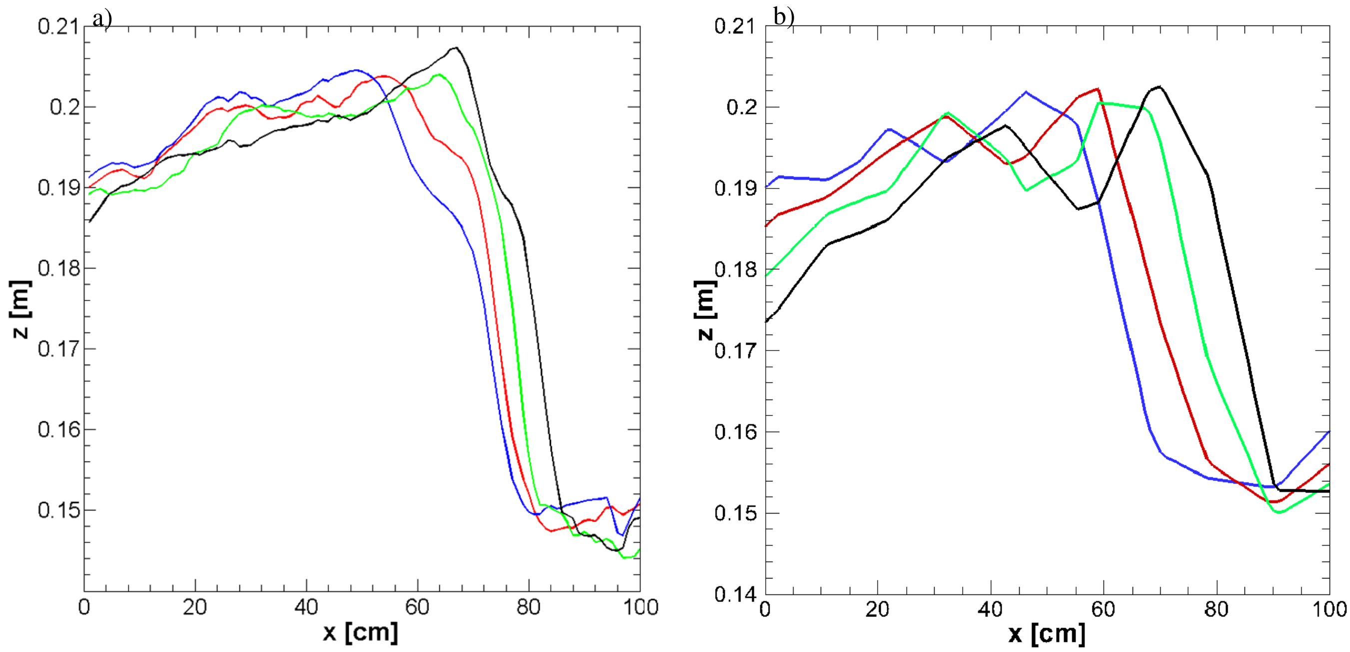

Figure 4. a) Dune movement in the physical model. b) Dune movement in the numerical model after 5 (blue), 10 (red), 15 (green) and 20 minutes (black).

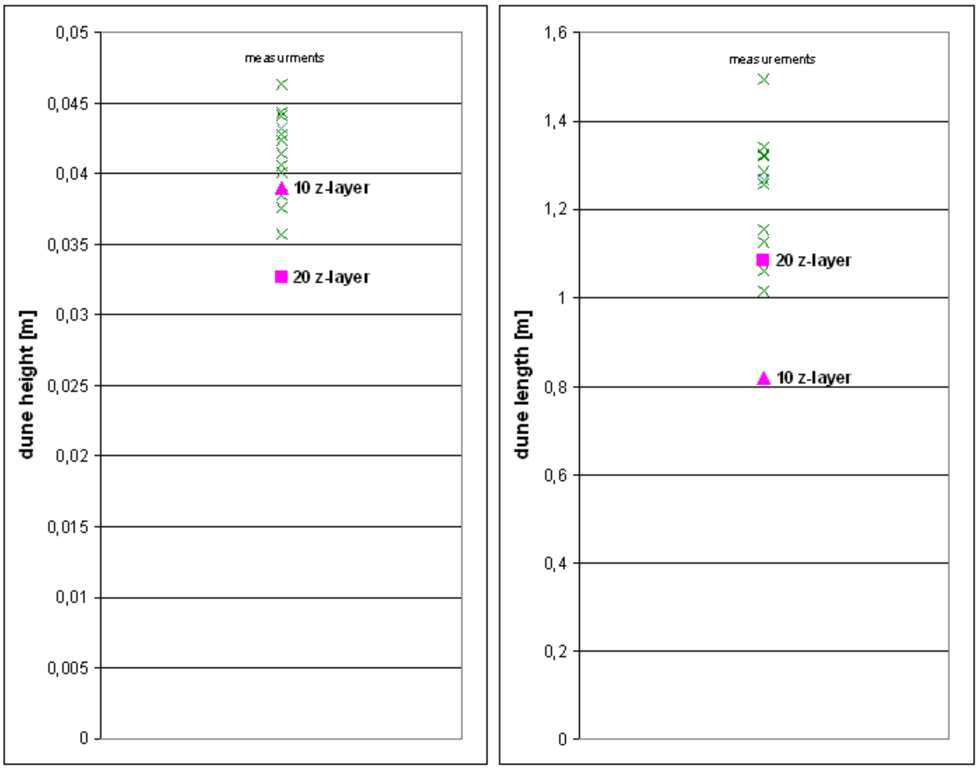

Figure 5. Comparison of measured (crosses) and simulated (square and triangle) a) dune length and b) dune heights.