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Dune simulation with TELEMAC-3D and SISYPHE: A parameter study.

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***Abstract*—This paper presents results of RANS simulations of dunes in an open channel flume with TELEMAC-3D and SISYPHE. Three-dimensional sand dunes were produced, studied and compared to the physical dunes of a laboratory flume situated at the BAW, Karlsruhe. Aim of the study is to create a parameter set for TELEMAC-3D and SISYPHE with which it will be possible to conduct explicit simulations of bed forms for selected river stretches. For comparison the parameters of dune height and length are used. Additionally the mean deviation of the probability density function of the bed forms, the mean skewness and the mean kurtosis were computed and compared to the data of the physical data set. Three different bed load transport formulas and four different slope effect and deviation formulas were used. The deviation formula of Apsley & Stansby in combination with the slope effect formula of Koch & Flokstra and the transport formulas of Engelund & Hansen as well as Yang & Lim showed the best results. The study shows that even though the height, length and kurtosis of the dunes can be matched quite well with the dunes of the physical flume, the skewness is not in the same area. A possible explanation is that the produced dunes are not dune-shaped but have the form of ripples.**

I. INTRODUCTION

Most of the more-dimensional calculations in engineering practice are 2D-hydrodynamic simulations. More and more morphodynamic tasks and for this a coupling to morphodynamic simulations is needed. In this case bed forms are only accounted for by empiric formulations, e.g. by changing the roughness coefficient. The actual depth of the river with dune peaks and deepenings is not reproduced. Following this the correct prediction of the available shipping capacity must be assigned with a higher uncertainty. Explicitly modelling of dune movement and behaviour could help to solve this task.

There have been different approaches to tackle this lack in morphodynamic modelling. One is LES of bed forms, where [1], [2] used detailed hydrodynamics to model the coherent structures of turbulence that are responsible for dune sediment transport. Additionally the sediment model included pickup, transport and deposition. In another approach [3] used roughness predictors by Engelund [4] adapted for supply limited situations and could show good agreement between prediction and measurements. It is in between these two methods, highly resolved and implicit integration, the task of this research project of the Federal Waterways Engineering and Research Institute falls.

In previous papers the capacity of TELEMAC-3D and SISYPHE has been shown [5], [6]. This paper provides further evaluation and analyses of the results. The hydrodynamic and morphodynamic programs are described in detail in [7] and [8].

II. FLUME EXPERIMENT

A. *Experimental setup*

The experimental flume is situated at the German Federal Waterways Engineering and Research Institute (BAW), Karlsruhe. It has been described in [9] and [10]. A stretch of 30m length and 2m width covered with nearly uniform sediment with a D50 of about 1mm provided the data for the comparisons presented here. Different runs without installation, groynes, slot groynes and partially fixed bed have been conducted.

B. *Numerical Model*

For the numerical computation, TELEMAC-3D and SISYPHE (version 6.1) were used (for a detailed model description please also refer to http://www.opentelemac.org and http://docs.opentelemac.org).

The computational grid spans the 30 x 2 m of the experimental flume. The horizontal mesh size is 6-16cm with a mean of 11cm. In total that gives 5750 nodes and 11000 elements. 10 layers are used in the vertical with a logarithmic distribution finer towards the bottom, which results in roughly 100.000 elements to be calculated.

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 [11] coupled to SISYPHE to reproduce the conditions of the physical model. Like in the experimental flume the water level at the outlet is kept constant.

C. *Statistical dune parameters*

The common approach to evaluate dunes is the use of dune lengths and heights. Longitudinal cross sections every 1cm of the topography are extracted and for each the slope is deducted. Afterwards a partial regression line is plotted for each profile and by the crossings of each of the profiles with these regression lines a mean dune length and a mean dune height is calculated.

Furthermore the skewness and kurtosis of these longitudinal cross sections can be calculated from the same dataset. Skewness and kurtosis give additional information about the dune field. They are the third- and fourth-order distribution moments normalised by the variance. Using distribution moments (as skewness and kurtosis) will imply that the results are independent of the mean of a series of bed-form profiles, as well as the resolution of the recording [12].

If the elevation of the bed surface is expressed as $\alpha(x,y,t=t1)$ then the variance σ^2 of this data set is the 2nd order momentum of a spatial series:

$$\sigma^2 = \int_{-\infty}^{\infty} \alpha'^2 f(\alpha)\mathrm{d}\alpha = \langle \alpha'^2 \rangle \quad (1)$$

The standard deviation (square root of the variance) represents a characteristic vertical roughness scale for the bed surface, even though the dune with its specific height is resolved [13].

The skewness is the 3rd order momentum divided by the cube of the standard deviation σ:

$$Sk = \langle \alpha'^3 \rangle / \sigma^3 \quad (2)$$

It is a measure for the symmetry of a spatial series relative to the normal distribution. If the skewness is zero, the distribution around a sample mean is symmetric. Data more spread to the right of the mean has a positive skewness value and vice versa [12]. The general shape or form of the bed surface can be taken from this skewness value. Dune fields are associated with a negative skewness, which might represent a flattened crests and steeper troughs [13]. A negative skewness also represents a long, convex upwards stoss-side slope and a relatively steep and short lee-side face which are characteristic for dunes [12].

The kurtosis is the 4th order momentum divided by the standard deviation to the power of 4:

$$Ku = \langle \alpha'^4 \rangle / \sigma^4 - 3 \quad (3)$$

It is the measure for the peakedness/tailedness of a spatial series distribution, as it is the variation of the variance. The kurtosis value of a normal distribution is 3, so here this value is corrected to get a value of zero for a normal distribution. A positive value means more extreme fluctuations of the data set, whereas a negative kurtosis is the result of flat data [12]. Bed waves that are widely spread on a flat bed have a large and positive kurtosis, and a train of triangular, identical waves following each other will have a negative kurtosis [13]. One mean parameter has been calculated for the whole flume.

D. New formulae in SISYPHE

Several parameter sets have been tested. The use of further slope effect and deviation formulas as well as new bed load formulas promised better results. The slope effect and deviation model proposed by Apsley and Stansby [14] and Stansby et al [15] is based on the concept of the "effective" shear stress, which is a modified shear stress that includes a bed slope contribution. This formula has already been presented by Nicolas Chini at the 2009 TELEMAC User Conference.

The change of the transport angle (deviation) in x and y direction, which is used in the following presented calculations, is calculated as:

$$\theta_x^* = \theta\cos(\delta) - \lambda\frac{\partial z}{\partial x}\cos^2(\beta)$$
$$\theta_y^* = \theta\cos(\delta) - \lambda\frac{\partial z}{\partial y}\cos^2(\beta) \quad (4)$$

with $\cos\beta$ calculated as:

$$\cos\beta = 1/\sqrt{1 + (\partial z/\partial x)^2 + (\partial z/\partial y)^2} \quad (5)$$

In notation conform to the SISYPHE User Manual the deviation change would have the following form:

$$\tan\alpha = \theta\tan\delta - T\frac{\partial Zf}{\partial n} \quad (6)$$

with

$$T = \frac{\theta_o \cos^2\beta}{\tan\phi} \quad (7)$$

A new bed-load formula has been implemented into SISYPHE: the formula of Yang & Lim [16]. The formula is a total bed load approach, based on the concept that in natural flow condition there is often no sharp distinction between suspended and bed load transport. Following this both types of load are computed together and expressed in a total load transport parameter T_T. The formula as presented in their paper reads as

$$\theta_s = k\left(\frac{\gamma_s}{\gamma_s - \gamma}\right)\tau_o\left(\frac{u_*'^2 - u_{*c}^2}{\omega}\right) = k\,T_T \quad (8)$$

with k being a constant of 12.5. u_{*c} is the critical shear velocity for sediment movement, u'_* is the effective shear velocity and ω the grain settling velocity as proposed by [17]:

$$\omega = \frac{\nu}{d}\left(\sqrt{25 + 1.2d_*^2} - 5\right)^{1.5} \quad (9)$$

In notation conform to the SISYPHE User Manual the transport formula would have the following form:

$$\Phi_b = 12.5 \frac{d}{\rho_o \omega} \tau \ (\Theta' - \Theta_c) \qquad (10)$$

depending on the grain diameter, density, settling velocity, bottom shear stress and as well effective and critical shear stress.

III. RESULTS

A. *Skewness and kurtosis*

Figs. 1 and 2 show the dune height and length of several configurations. In the diagrams it is not indicated which parameter configurations were used, as the diagrams are supposed to show only the variation of results that were gained with minor changes in TELEMAC-3D and SISYPHE. The used parameter variations are slope effect and deviation formula (where most runs used either Koch & Flokstra plus Apsley & Stansby or Soulsby plus Talmon as slope effect plus deviation formula) and variations in TELEMAC-3D (such as solvers and most importantly time step variation). For details about the used formulas see SISYPHE User Manual [18].

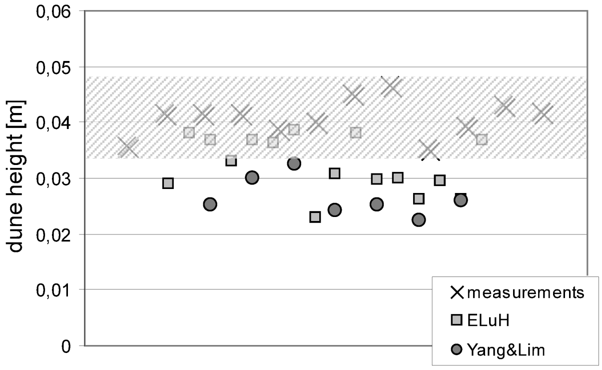

Figure 1. Dune length for different runs with Engelund & Hansen and Yang & Lim as transport formula compared to measurements.

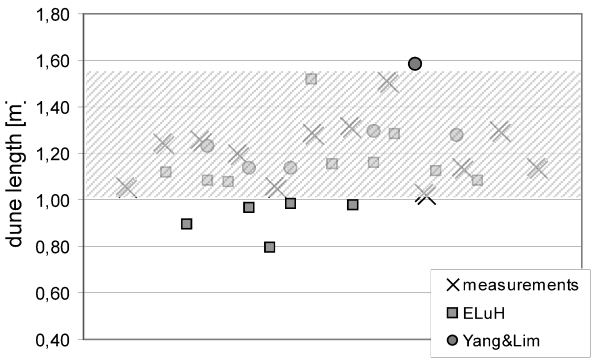

Figure 2. Dune heights for different runs with Engelund & Hansen and Yang & Lim as transport formula compared to measurements.

Additionally Figs. 3 and 4 show the skewness and kurtosis values of the same runs. In Fig. 5 the same data is plotted against a diagram taken from [12]. It can be seen that the kurtosis values can be matched for some runs, but that the skewness is off. Comparing it to the results from [12] it can be shown that the results of the simulations are mostly more similar to the ones of a riffle bed and that the skewness and kurtosis values of the experiments match the runs from fine sand dune runs presented by [12].

Ripples often have two sides that have the same length. This means that their stoss-side is much shorter as the one of dunes, which gives them a skewness that is much more close to zero. They will have less transport over their stoss-side and have no superposition. Due do this ripples can be even curved inwards instead upwards like dunes. This tends to results in a positive skewness for ripples whereas dunes will have a negative one [12].

In our numerical model we have obviously none or very limited existence of superposition due the limitations of the mesh size. Superpositioning ripples cannot be reproduced, as they are too small to be captured with our mesh. This might be a reason why it is not possible to reproduce the right curvature of our dunes and why most of the presented runs have a positive skewness. Due to this tests with finer resolutions will be conducted.

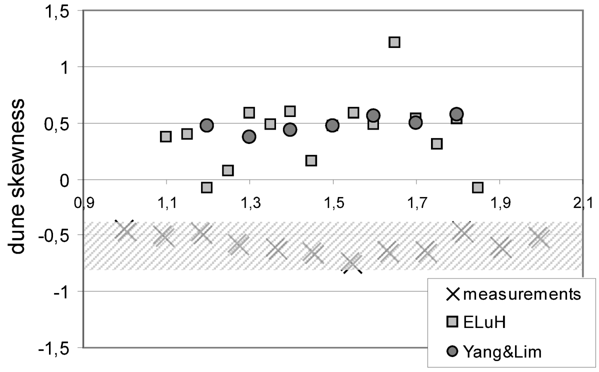

Figure 3. Dune skewness for different runs with Engelund & Hansen and Yang & Lim as transport formula compared to measurements.

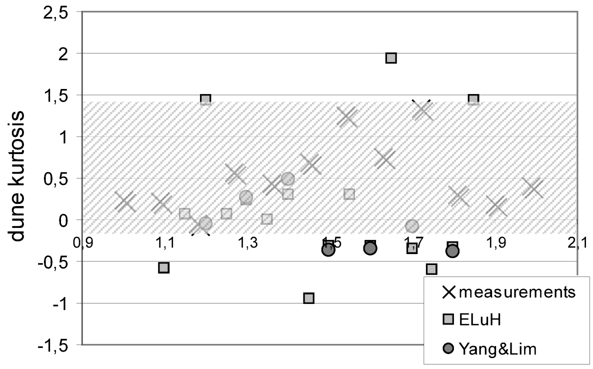

Figure 4. Dune kurtosis for different runs with Engelund & Hansen and Yang & Lim as transport formula compared to measurements.

Dunes have a flattened crest which will also result in a negative skewness value. As outlined by [13], this is due to the interaction of the dunes with the free surface and local flow acceleration. For ripples there is no flattening, as they do not interact with the free surface. Following this, the ripple-like form of our numerical dunes might be derived of a lacking reproduction of the flow field, namely the insufficient penetration of the dune influence towards the free surface.

For selected results the evaluated instant of area and time step has been varied (results not shown). From this it was possible to see that the results of skewness and kurtosis still slightly differed over time in the last hours of the run. A stable state of dune forms might not be reached yet. If a different area is chosen for evaluation, the values of skewness and kurtosis change. From this follows, that there are regions of different dune forms in the flume. The inflow is highly affected by the input measure and the output area as well might be disturbed by instabilities. The extent of the "undisturbed" area changes depending on the propagation speed of the newly added material, which changes with every bed load and slope effect formulation.

B. *Selected results*

Figs. 6 a), 6 b) and 7 show the overall best results compared to the measurements. They were gained with the bed load formulas of Engelund & Hansen and Yang & Lim. It can be seen, that even though the bottom topography matches the measurements quite well (Fig. 6 b), the values of skewness (and height as well) are not in the same range (Fig. 6 a).

C. *Time step dependency*

From Fig. 8 (a and b) we see very clearly that the time step influenced the results. The calculations have the same configuration but with time steps of 0.01s $\boxed{1}$, 0.1s $\boxed{2}$ and 0.5s $\boxed{3}$. On the left side runs of a setting with slope formula of Soulsby and deviation of Talmon are shown, whereas the runs on the right hand side have Koch & Flokstra as slope formula and the deviation formula of Stansby & Apsley. With a time step of 0.01s both settings result in a bottom formation that looks similar to the measurements of the physical flume (S10W1T2). In the graphs below (Fig. 8 b) the corresponding mean values of dune height and length, deviation, skewness and kurtosis are plotted against the time step. It can be seen that these mean values do not differ strongly between the 0.1s and 0.01s runs. The values of the 0.5s run on the other hand change in an obvious way. The same tendency can be observed in the plots of the bottom formation as well (Fig. 8 a).

For all runs the courant criterion is followed and the courant number ($c = ui\Delta t / \Delta x$) is below 1. This is checked even though this criterion is not a hard criterion for semi-implicit schemes. Further investigations will be done concerning this issue.

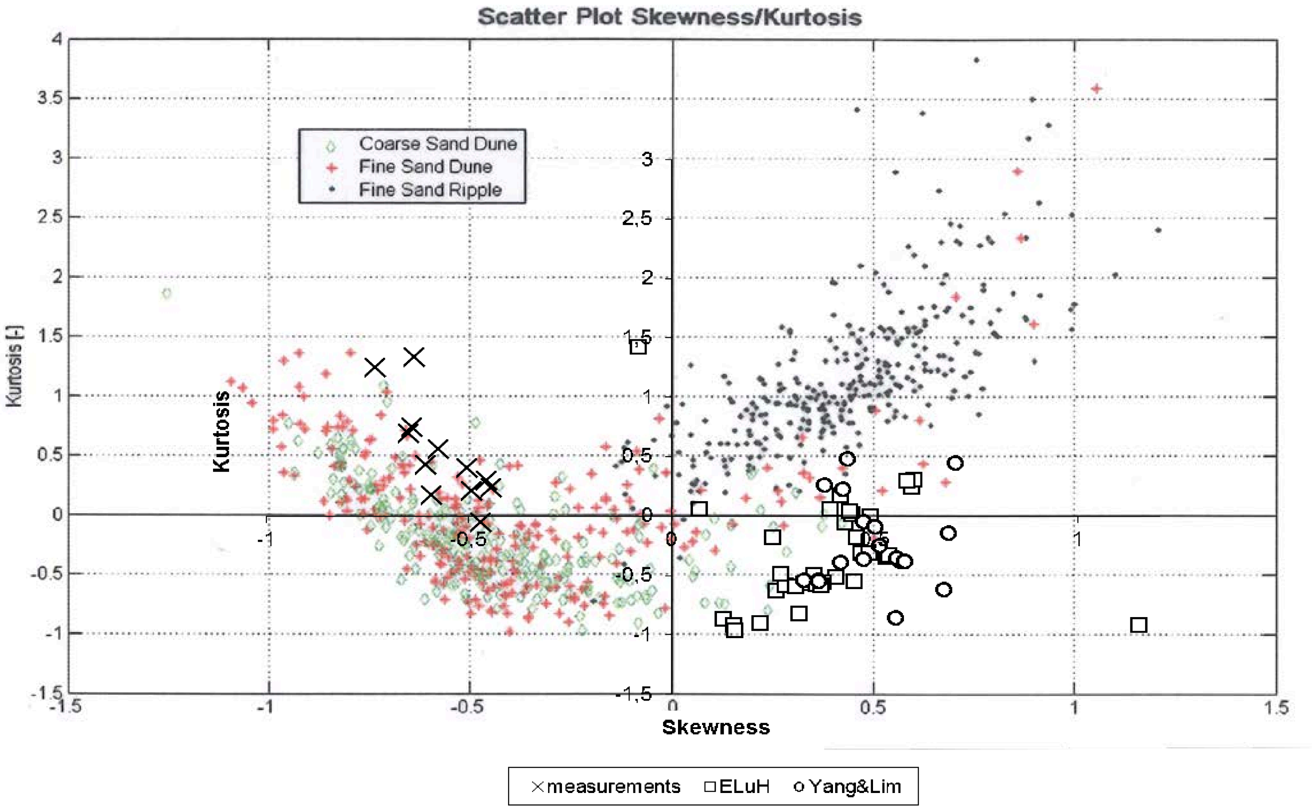

Figure 5. Dune skewness against kurtosis plotted against a diagram from [12].

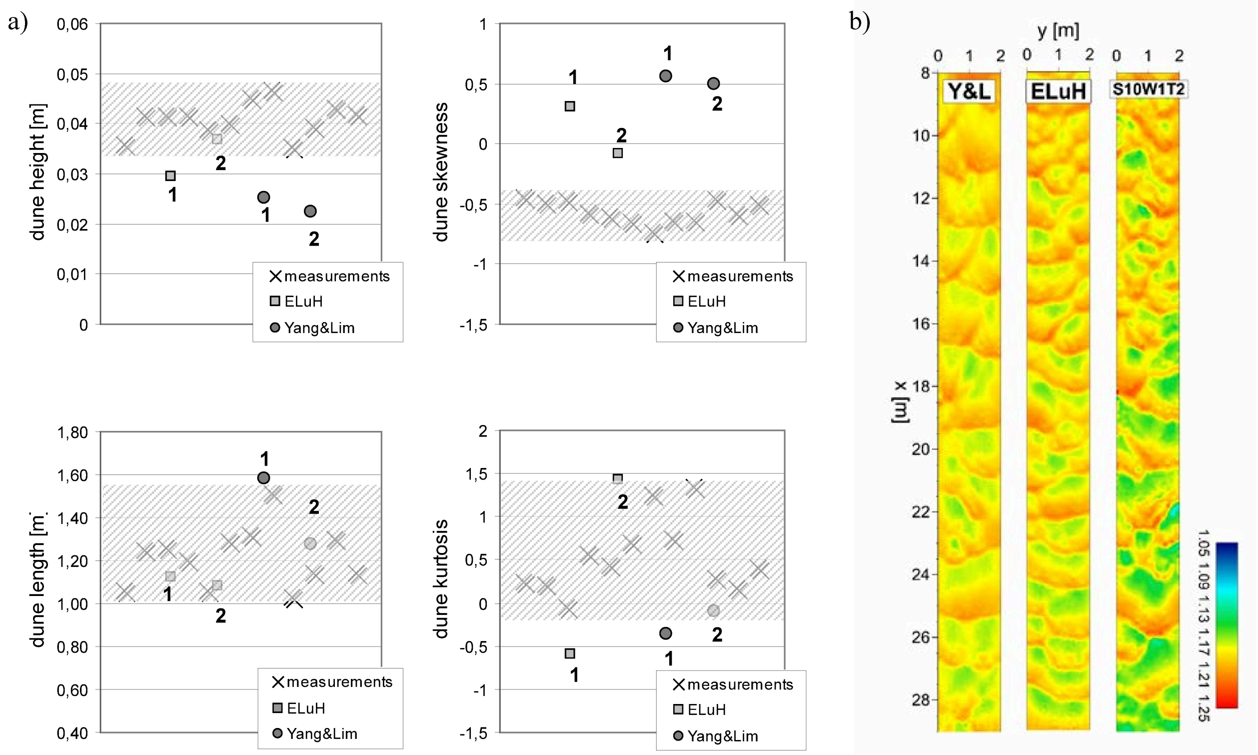

Figure 6. a) best runs in comparisons to measurements – 1: slope Koch&Flokstra and deviation Apsley&Stansby – 2: slope Soulsby and deviation Talmon. b) plots of bottom topography of run 1 for the two bed load transport formulas.

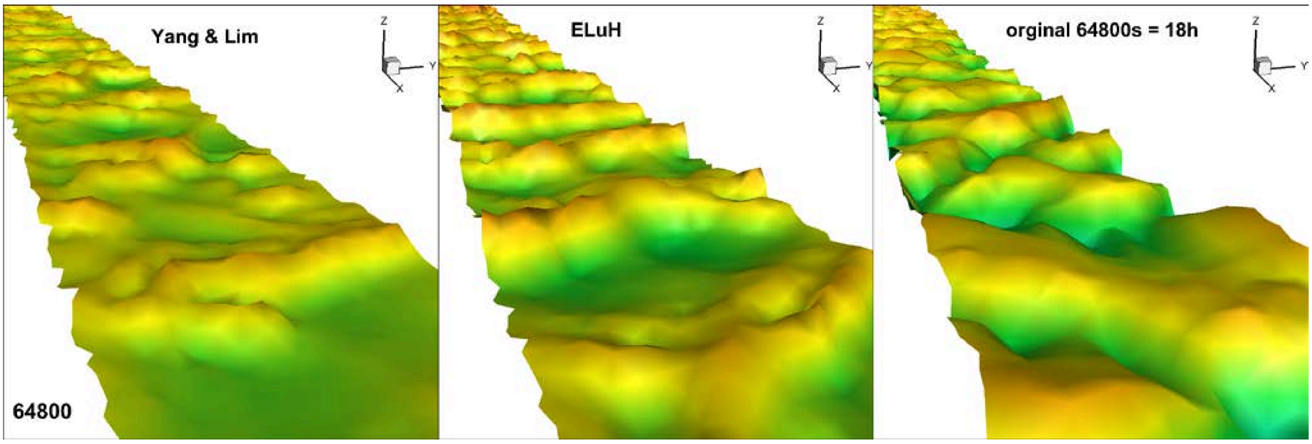

Figure 7. Comparison of simulated and physical flume bottom after 18h, 3D plot, same data set as figure 6 b)

D. Changed boundary conditions (input area)

The input of sediment still is one of the major challenges in this study. Even in the physical flume experiment the development of dunes was sensitive towards the sediment input method. In the numerical experiments this proved to be an even bigger issue. The dune form and also transport strongly depended on input volume and position. A reduced input volume (compared to the physical experiments) was chosen, which delivered better results due to the insufficient transport in the inflow area. Obviously the input method in the numerical model, being near to the boundary and subject to less developed flow conditions, created a fragile boundary condition. [19] states as well "…that even distant boundary conditions, which should normally be physically insignificant, may considerably influence numerical solution."

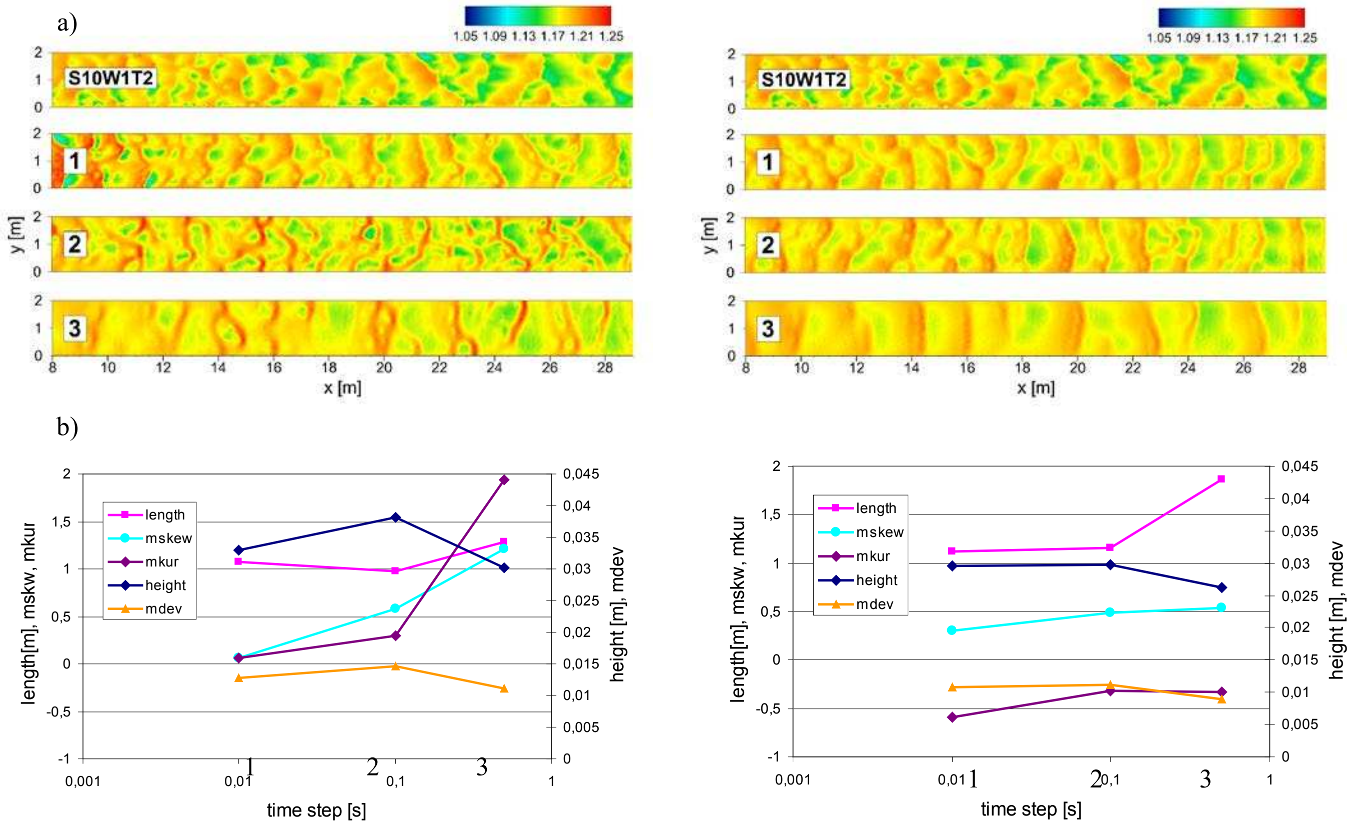

Figure 8. $\boxed{1}$: t=0.01, $\boxed{2}$: t=0.1 and $\boxed{3}$: t=0.5 – left side: slope effect formula of Soulsy and deviation of Talmon – right side: slope effect formula of Koch & Flokstra and deviation of Apsley and Stansby a) bottom formations. b) mean values of dune height and length, deviation, skewness and kurtosis.

IV. CONCLUSIONS AND OUTLOOK

It was shown that explicit dune modelling with TELEMAC-3D and SISYPHE can be done. The correct shape parameters of these dunes are subject to several influencing factors such as bed load transport formula, slope effect and deviation formulas, morphodynamic time step as well as hydrodynamic parameters. A new transport formula by Yang & Lim [16] is presented for SISYPHE as well as the adaptation of the Apsley & Stansby [14] deviation formula for version 6.1. Both new formulas show good results for dune simulations.

Even though the presented results are promising, it is possible that they originated only from carefully calibrated numerical flaws and are not reproducible with other boundary condition or models. In their paper [20] state that dunes do not result from a linear instability of the code, whereas ripples can arise from such faults. Following this, the question would be if the here presented dunes are not dunes but ripples and the product of a linear instability, or if they are proper dunes with some faults in form and shape and that the correct shape can just not be reproduced in RANS. On the other hand there is research [21] that says that both ripples and dunes are the result of a primary instability (e.g. a linear instability of the code), which would make a linear stability analysis of the code interesting in both cases. But even this approach might have limitations: [22] state that “the complex evolution of bed forms is clearly a nonlinear process” which would conclude that a linear stability analysis could not asses this phenomenon. Nonetheless an analysis should bring further insights.

Other next steps will be further examination of flow parameters such as the turbulence model and the advection scheme of velocities, which are thought to be of major importance when modelling three-dimensional bed forms. So far the k-epsilon turbulence model and the SUPG advection scheme were found to deliver the best results. Further insights are expected from high resolution measurements which will be conducted over the fixed bed of a natural formed dune bottom. The calibration of the hydrodynamic model TELEMAC-3D with this new data set promises good results.

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