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Published in:
Coastal Sediments 2019. Proceedings of the 9th International Conference

Link to article, DOI:
10.1142/9789811204487_0051

Publication date:
2019

Document Version
Peer reviewed version

Citation (APA):
Kærgaard, K., Mariegaard, J. S., Sørensen, O., Eskildsen, K. L., Drønen, N., Deigaard, R., & Fuhrman, D. R. (2019). Towards an Engineering Model for Profile Evolution: Detailed 3D Sediment Transport Modelling. In P. Wang, J. D. Rosati, & M. Vallee (Eds.), *Coastal Sediments 2019. Proceedings of the 9th International Conference* (pp. 577-590). World Scientific. https://doi.org/10.1142/9789811204487_0051

TOWARDS AN ENGINEERING MODEL FOR PROFILE EVOLUTION: DETAILED 3D SEDIMENT TRANSPORT MODELLING

KASPER KAERGAARD[1], JESPER SANDVIG MARIEGAARD[1], OLE SØRENSEN[1], KLAUS LANGGREN ESKILDSEN[1], NILS DROENEN[1], ROLF DEIGAARD[1], and DAVID R. FUHRMAN[2]

1. *DHI, Agern Alle 5, DK-2970 Hørsholm, Denmark. kak@dhigroup.com*
2. *Technical University of Denmark, Department of Mechanical Engineering, Section of Fluid Mechanics, Coastal and Maritime Engineering, DK-2800 Kgs. Lyngby, Denmark.*

Abstract: This paper describes a new morpho-dynamic 3D surf-zone model. The hydrodynamic model used for this purpose is the MIKE 3 Wave FM Model. This model solves the 3D Navier-Stokes equations on a 2D horizontal unstructured mesh with a sigma transformation describing the vertical coordinate. A recent solution to the well-known over-production of turbulence outside the surf-zone in RANS models has been applied and is shown to improve the predicted undertow profiles. The sediment transport is modelled using an advection-diffusion equation for the suspended load, together with a bed-load formulation. In the present paper the predicted surf zone hydrodynamics and sea bed evolutions are compared against experimental laboratory data.

Introduction

One of the most interesting features in the field coastal engineering/research is the shape of the coastal profile. It is highly dynamic and changes on both time scales of hours (storm-bar formation during severe storm events) and days/weeks (movement of storm bar volume back to beach during subsequent fair weather).

Deterministic modelling of coastal profiles has long eluded coastal researchers and engineers. While the deterministic models of cross-shore sediment transport have been relatively well described since the 1980s (e.g. Deigaard, 1986), the morphological response from the cross-shore transport has not lived up to the test when comparing modelled and measured changes to the coastal profiles. Furthermore, the modelled profiles tend to degenerate into an unrealistic shape if the models are kept running for the longer term (days to weeks).

Recent advances in computer power allowed Jacobsen and Fredsøe (2011) to correctly model the morphological development of the coastal profile during a lab experiment by Baldock (2011). This was achieved using a CFD model with a VOF description of the water/air interface for the hydrodynamic description (hereafter CFD-VOF model), an advection-diffusion equation for the suspended sediment together with a bed-load formulation and solving the Exner equation for the morphological update. This huge achievement has shown a possible way forward in the field of deterministic coastal profile modelling. The main issue with the approach of Jacobsen and Fredsøe (2011) is that the model is computationally very expensive. So much that it is not realistic to use this model in engineering design in many years to come; even when taking into account the continuing huge increases in computational power.

In the present study we explore the possibility of modelling the coastal profile using a model which is similar but much faster than the CFD-VOF model by Jacobsen and Fredsøe (2011).

Method

A wave phase resolving 3D model (MIKE by DHI 2019) is used to solve the hydrodynamic equations. This model solves the Navier-Stokes equations on a 2D horizontal unstructured mesh with a sigma transformation describing the vertical coordinate; thus, the vertical is discretized using a constant number of layers which move up and down with the surface elevation. The model therefore solves the same equations as the CFD-VOF model, main the difference being the description of the water surface and the numerical schemes used to solve the resulting system of equations.

The model does not contain an explicit model for wave breaking; rather the numerical scheme is responsible for dissipating the wave energy during breaking: When the wave front becomes steep enough the highest harmonics are poorly resolved on the computational mesh and gets dampened. This hydrodynamic model is coupled with a k-ε turbulence model for the sub-grid eddies.

To mitigate the problem with overproduction of turbulence under non-breaking surface waves (see e.g. Mayer & Madsen 2000), the solution proposed by Larsen & Fuhrman (2018) has been adopted using the coefficient $\lambda_2 = 0.12$, as defined in their paper. They developed a methodology for formally stabilizing two equation turbulence closure models in nearly potential flow regions (corresponding to $\lambda_2 > 0$), whereas $\lambda_2 = 0$ switches this new feature off, leading to a standard closure.

The sediment transport is modelled using an advection-diffusion equation for the suspended load, together with a bed-load formulation. The bed concentration is calculated from the bed friction velocity (U_f), based on the bed shear stress coming from the hydrodynamic module using the approach by Fredsøe and Engelund (1976). This bed concentration is assumed to represent the concentration at 2 * d from the bed; d being the diameter of the sediment. The concentration in the center of the first layer above 2 * d is calculated assuming a Vanoni profile from 2 d above the bed to the actual position of the layer, see Figure 1. This step is necessary due to the sigma transformation describing the vertical coordinate; this means the vertical thickness of the layers in the model will vary during the passage of a wave.

The Exner equation is solved for the morphological changes.

The model is thus quite similar to the CFD-VOF model but cannot describe the overturning process of the wave crest during plunging wave breaking. However, it runs much faster than the CFD-VOF model. A realistic simulation period is on the order of a (short) storm event.

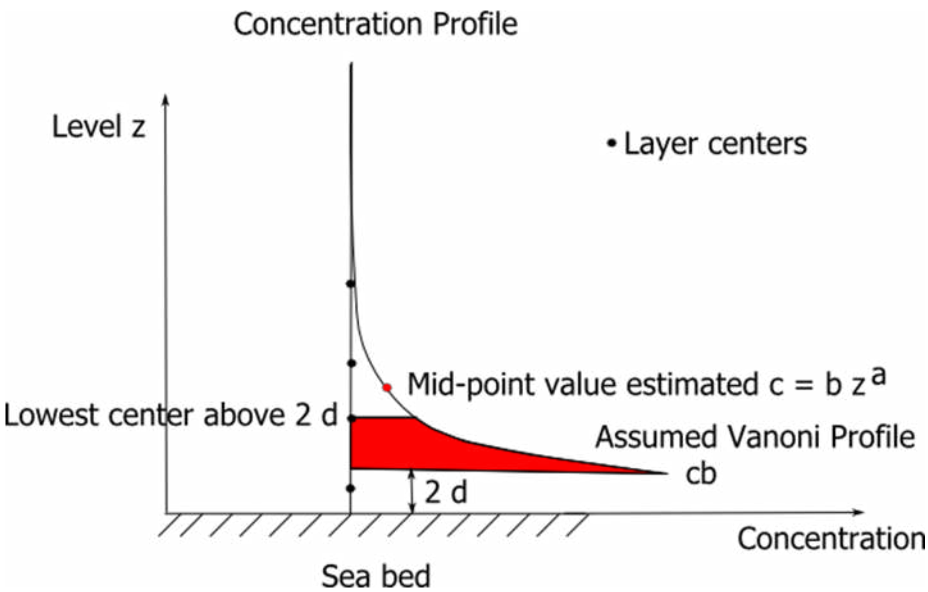

Figure 1: Integration of concentration profile

Model Results

Surf Zone Hydrodynamics

The first comparison is made against the classic experiment by Ting and Kirby (1996). Their experimental setup is shown in Figure 2. They looked at the wave breaking, undertow and turbulence generated by regular spilling and plunging waves. The spilling waves were H = 0.125 m and T = 2 s while the plunging waves had H = 0.128 m and T = 5 s, H being the wave height and T the wave period.

The MIKE 3 Wave FM model was run on a mesh with a horizontal resolution of 0.02 m and 12 equidistant vertical layers. Stream function waves were generated in a 5 m wide relaxation zone. The model was run with three different formulations for the turbulence:

- Standard: This is the standard implementation in MIKE 3 Wave FM. It is noted that this implementation only includes vertical gradients in the horizontal velocities in the production terms in the turbulence model for both the k and ε equations.
- $\lambda_2 = 0.0$: For this case the full strain rate tensor is used to calculate the production terms in the turbulence model for both the k and ε equations.
- $\lambda_2 = 0.12$: For this case the full strain rate tensor is used to calculate the production terms in the turbulence model for both the k and ε equations and the solution proposed by Larsen & Fuhrman was applied in the model using $\lambda_2 = 0.12$.

The measured and modelled surface elevation is compared in Figure 3. It is seen that for *standard* and $\lambda_2 = 0.12$ the wave becomes slightly too large before breaking slightly too far offshore. The energy dissipation in the broken wave is too low compared with the experiments with both the maximum modelled surface elevation being larger than the measured ones from around x = 20 m. For the $\lambda_2 = 0.00$ the waves break too late due their height being too low. This is due to the overproduction of turbulence in the zone before breaking resulting in unphysical wave dissipation, in line with the results by Larsen & Fuhrman (2018).

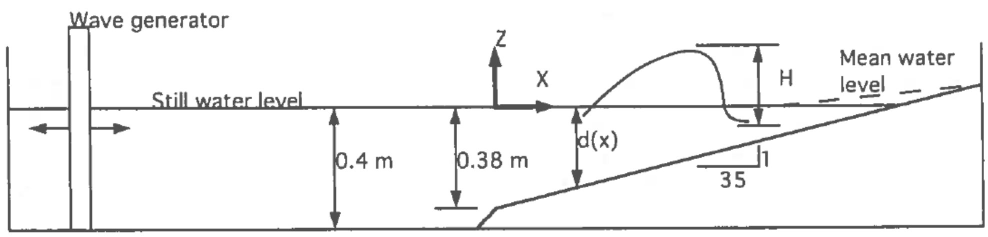

Figure 2: Experimental setup from Ting & Kirby (1996)

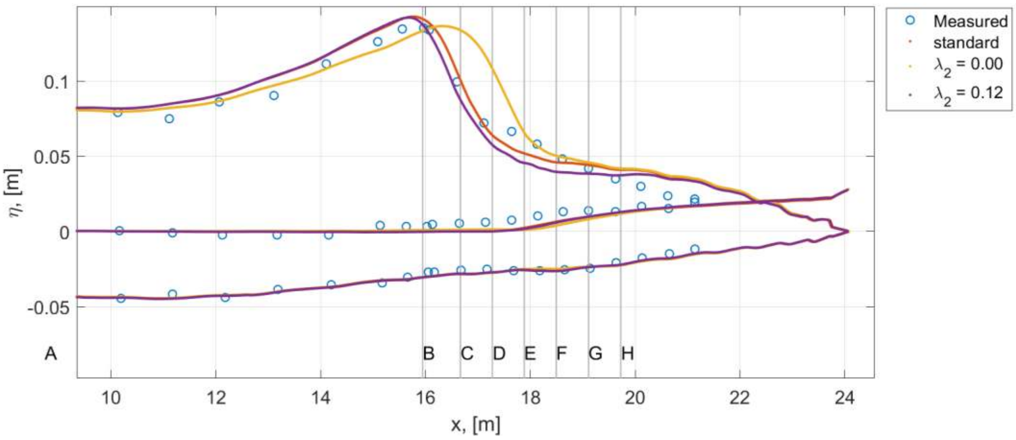

Figure 3: Comparison between measured and modelled surface elevation. The top line shows the maximum minus the mean surface elevation, the center line shows the mean surface elevation and the bottom line shows the minimum minus the mean surface elevation.

The modelled and measured undertow is compared in Figure 4, Figure 5 and Figure 6 together with the predicted undertow from the CFD-VOF model by Jacobsen (2011); for the locations shown in Figure 3.

From Figure 4, Figure 5 and Figure 6, it is seen that the MIKE 3 WAVE FM model does a fair job a predicting the undertow at profiles A, B, F, G and H. At F, G H and E the MIKE 3 WAVE FM model matches the measured undertow better than the CFD-VOF model. At locations C, D and E the MIKE 3 WAVE FM model over-predicts the undertow velocities in the lower part of the water column and the CFD-VOF model does a better job at matching the measurements at these locations. Using $\lambda_2 = 0.12$ clearly improves the undertow profile around the point of breaking while inside the surf-zone there is little difference between the *standard* and $\lambda_2 = 0.12$ results. The differences observed for $\lambda_2 = 0.0$ are likely also due to the change in breakpoint observed in Figure 3.

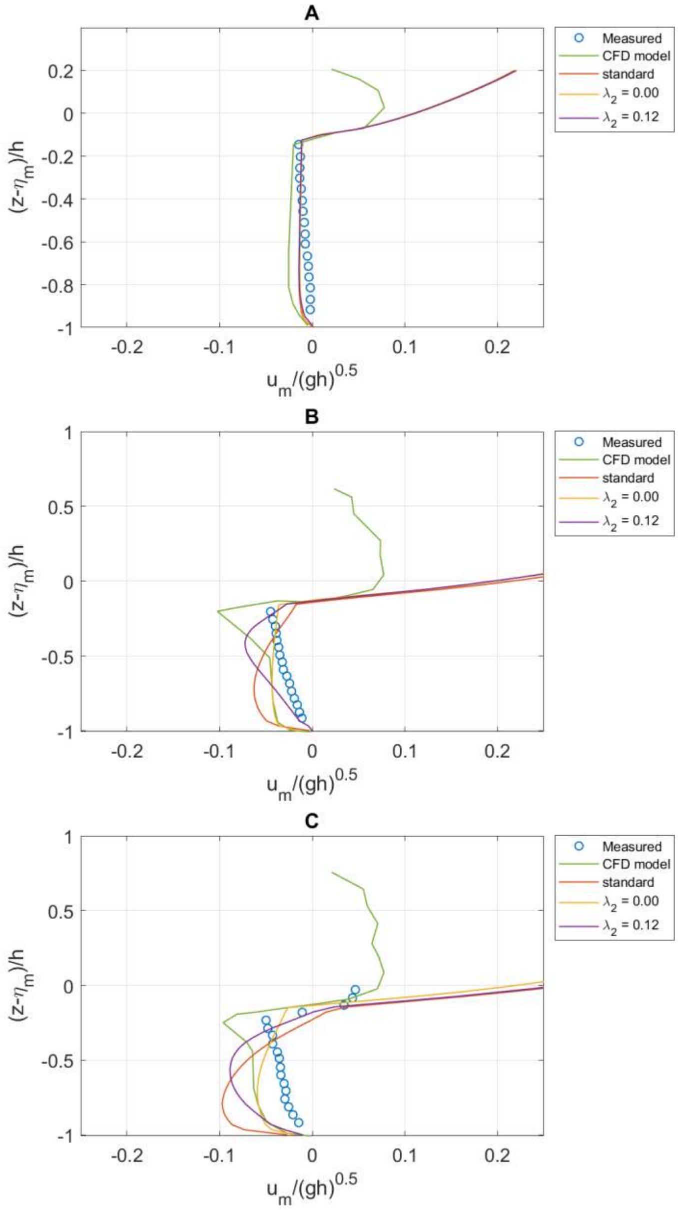

Figure 4: Comparison between measured and modelled undertow. Locations: See Figure 3.

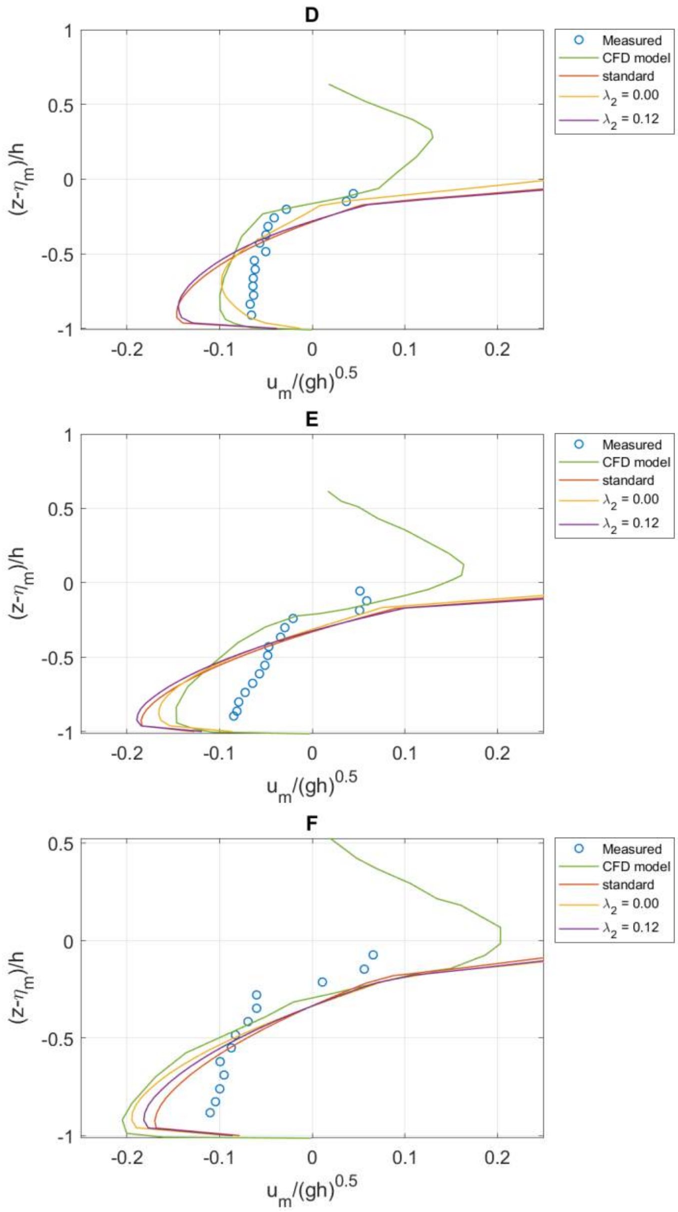

Figure 5: Comparison between measured and modelled undertow. Locations: see Figure 3

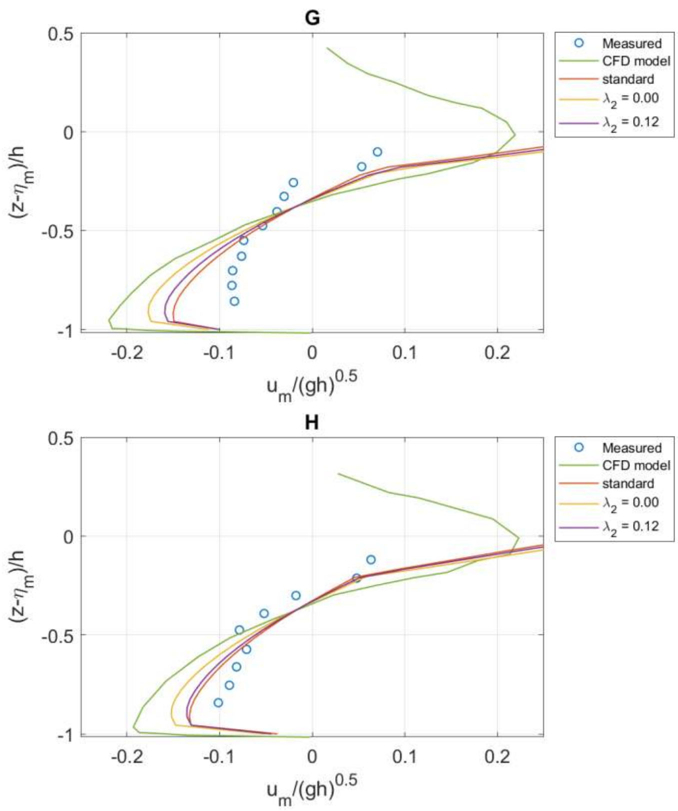

Figure 6: Comparison between measured and modelled undertow. Locations: See Figure 3

Figure 7 compares modelled total kinetic energy (tke) between the different turbulence models in profiles A, B and C. It is seen that at the point of breaking the effect using λ_2= 0.12 is a large reduction of the turbulence in the upper part of the water column in line with the results in Larsen & Fuhrman (2018). This is the reason for the improved undertow profiles around the point of breaking: The smaller turbulence in the upper part of the water column means that the eddy viscosity is also smaller. This means that there is less resistance for the undertow to flow offshore in this region in the λ_2= 0.12 case which in turn causes the undertow to flow offshore in this region rather than closer to the bed as is the case for the *standard* and $\lambda_2= 0.0$ cases.

Figure 8 and Figure 9 compare measured tke with the modelled ones at profile D, E, F, G & H. Reasonable comparisons are observed for D, G & H while the model overpredicts the tke for profiles E & F. As suggested by Larsen & Fuhrman

(2018), more research is needed to resolve these issues.

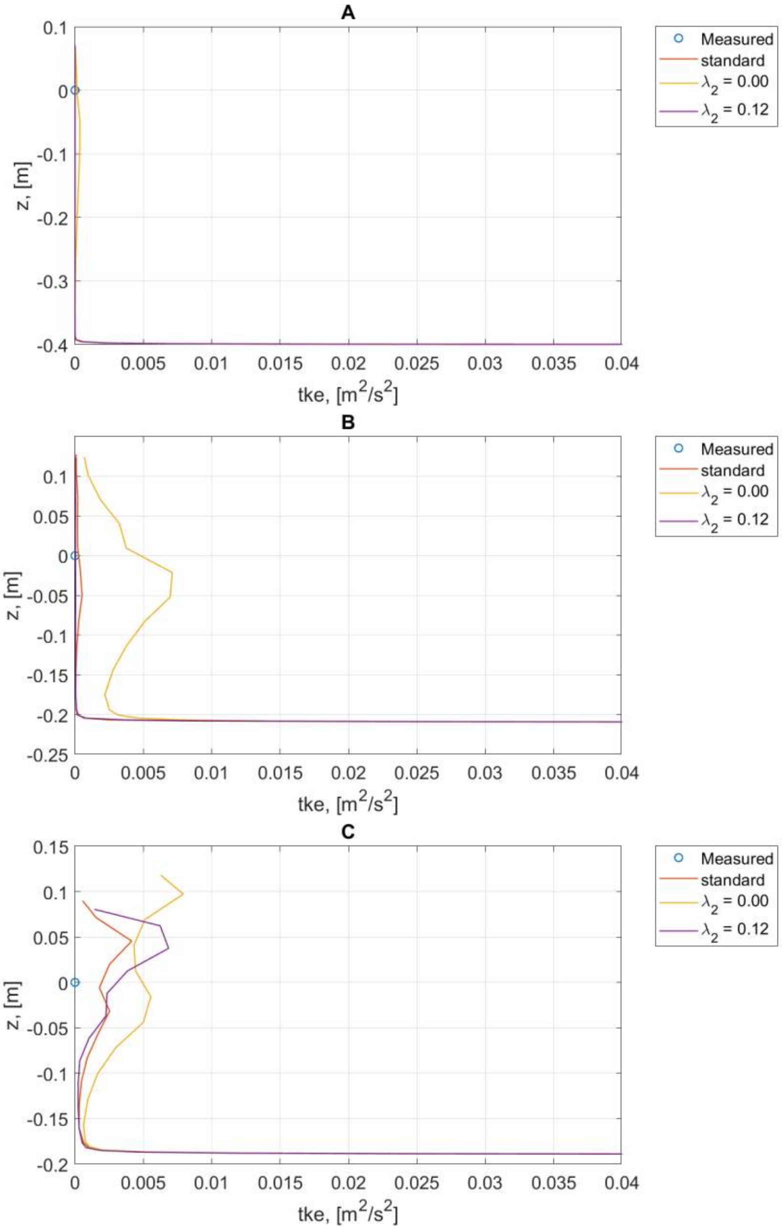

Figure 7: Comparison between modelled tke at locations A, B and C shown in Figure 3.

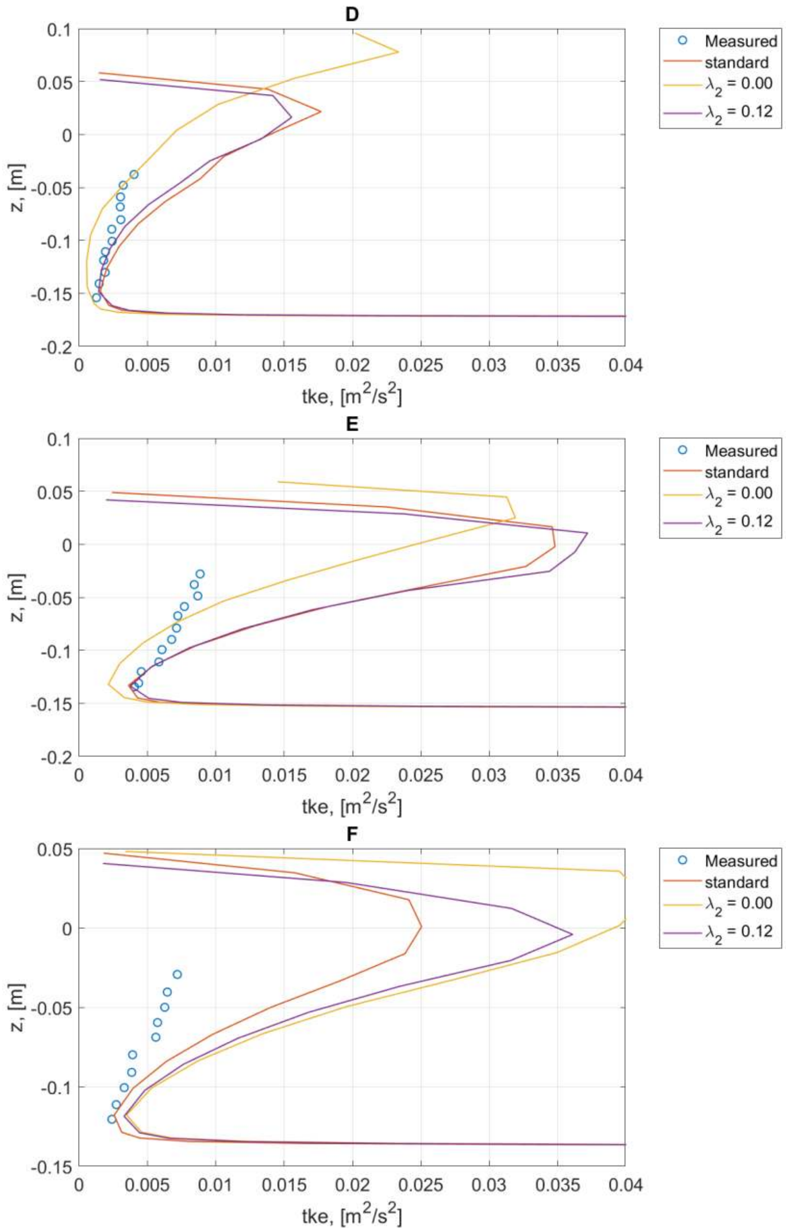

Figure 8: Comparison between modelled and measured tke at locations D, E and F shown in Figure 3.

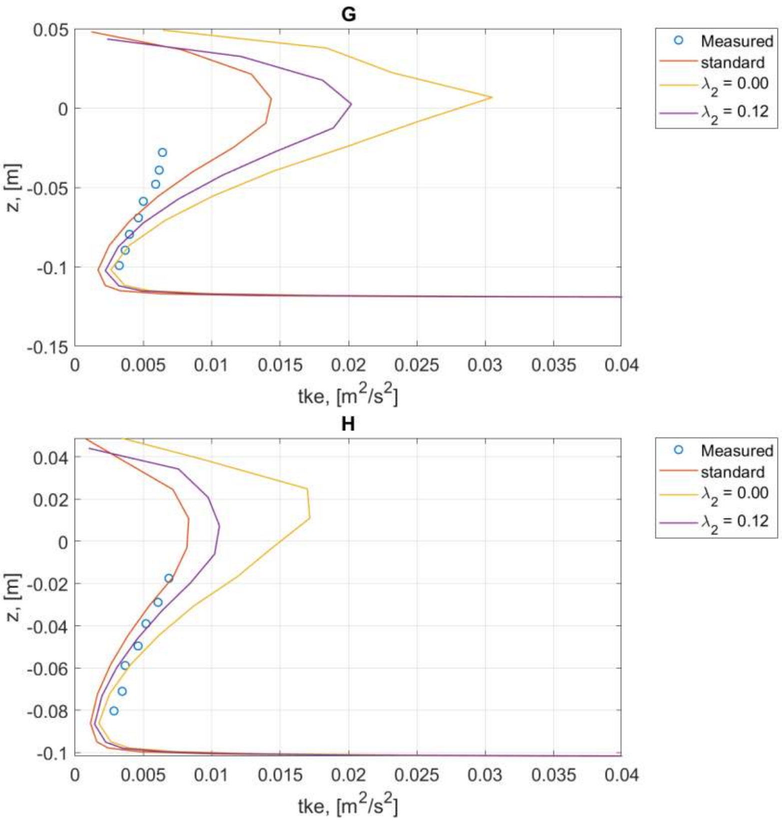

Figure 9: Comparison between measured and modelled tke at locations G and H shown in Figure 3.

Surf-zone Seabed Morphology

The surf-zone seabed morphology predicted by the model is compared to the experimental data from Baldock (2011) in the following. A medium sand with d_{50} = 0.25 mm was installed in a 100 m long wave flume at UPC, Barcelona. The offshore water depth was 2.5 m and a range of different wave conditions were run and the morphological response was measured. In the present study the RE1 case which has random waves generated with H_s = 0.44 m and T_p = 4.2 s at the offshore boundary. In the model a JONSWAP spectrum has been applied with standard parameters (γ= 3.3, σ_A = 0.07 and σ_B = 0.09). The model was run for the same cases as for the Ting & Kirby test.

Figure 10 and Figure 11 compares the predicted and measured seabed profiles. It is seen that for both $\lambda_2 = 0.0$ and $\lambda_2 = 0.12$ the model for both does a good job at predicting the height of the outer bar, while the trough becomes too wide and too shallow thereby causing the inner bar to be displaced towards the shoreline compared with the measurements. The erosion in the swash zone is slightly exagerated in the model compared with the experiements, this could be due to sheet flow or porosity effects on the sediment transport in this zone.

It is stressed that there is no calibration of the model to obtain this result. The main model parameter which needs to be carefully chosen is the horizontal and vertical mesh. In the present model 20 vertical non-equidistant layers are used while in the horizontal quadrilateral elements with a size of 0.1 m is used. The vertical layers are chosen such that there are 10 layers distributed logarithmicaly in the bottom 10 % of the water colum and 10 layers equally distributed in the top 90 % of the water column. The model took 10 hours to run on a 16 core computer.

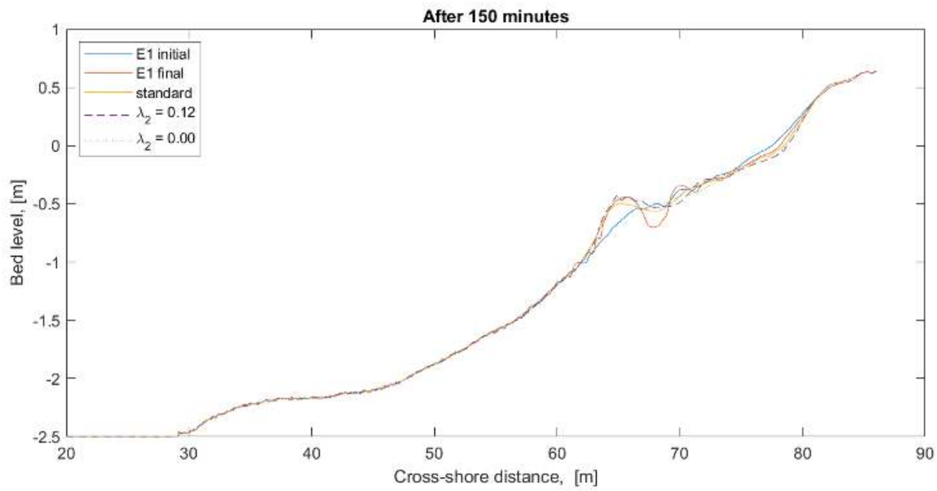

Figure 10: Comparison between measured and modelled seabed profile.

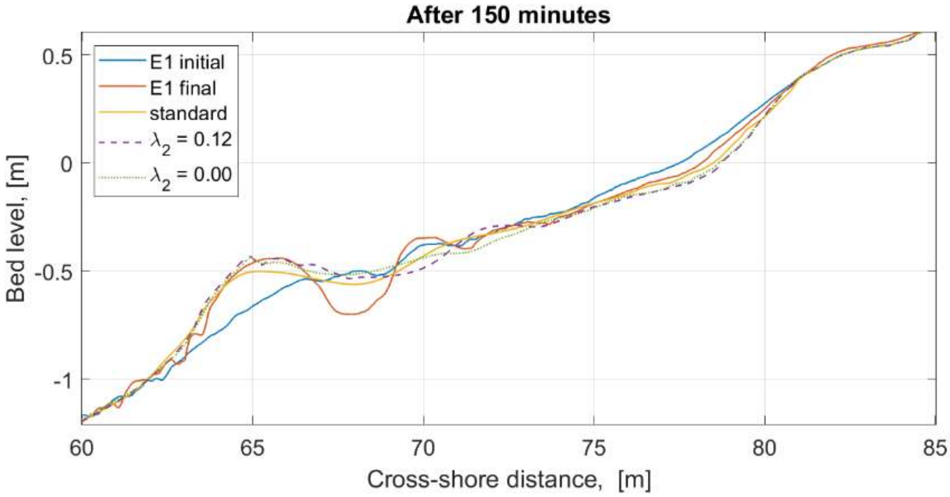

Figure 11: Zoom of Figure 10

Discussion

The present paper presents results for the new MIKE 3 Wave FM model in the surf-zone. It is seen that the accuracy of the model predictions regarding surface elevations and undertow profiles is of the same quality as similar models, i.e. NHWave and SWASH. Furthermore, the model includes a 3D sand transport model coupled with a morpho-dynamic model. The results show that the model does good job at predicting the position and the height of the offshore bar while the trough becomes too wide and the inner bar therefore is located too close to the shore when compared with measurements.

However, the model still represents a massive improvement over existing tools which cannot accurately predict offshore bar dynamics without careful calibration of the model parameters which vary depending on the sediment and the forcing conditions. For the present model there are no calibration parameters other than choosing adequate horizontal and vertical mesh resolutions.

The computational effort to run the model is large, but much smaller than a CFD model using a Volume of Fluid (VOF) method to describe the free surface. It is therefore realistic to run the model to make detailed investigations of the morpho-dynamic behavior of the coastal profile during a short storm or during the peak of a storm. The fact that the model requires no calibration other than choosing adequate horizontal and vertical mesh resolution presents a major improvement over existing models for predicting coastal profile changes during extreme events.

Conclusion

The new MIKE 3 Wave FM model has been extended to include 3D sand transport and morpho-dynamics. The model represents a new scientific and engineering tool which can be used to make predictions on the surf-zone morpho-dynamic on a time scale of hours.

Acknowledgements

This research was funded by the Innovation Fund Denmark as part of the Core Research Program 2016-2018. DRF also acknowledges support from the Independent Research Fund Denmark (SWASH project, Grant no. 8022-00137B).

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