OFFSHORE SAND PITS: VERIFICATION AND APPLICATION OF A HYDRODYNAMIC AND MORPHODYNAMIC MODEL

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Abstract: Within the framework of the SANDPIT project a number of benchmarking datasets were defined. These tests are used to establish the efficacy of morphodynamic models in predicting the behavior of large-scale mining pits and so to contribute to improve coastal zone management. This paper discusses the results of a verification of WL | Delft Hydraulics' Delft3D-model using field data collected by Rijkswaterstaat, in and around an offshore pit in the North Sea some 10 km off the Dutch coast near Hoek van Holland. The main focus was on assessing the quality of hydrodynamic and morphological model predictions made in depth-averaged and 3-dimensional mode. The comparison has shown that the model is able to give satisfactory predictions of the depth-averaged velocities inside and outside the pit. Moreover, the 3D model provided very accurate predictions of the longshore and cross-shore vertical velocity profiles. Although depth-averaged velocities predicted in 2DH and 3D mode were comparable, the morphological predictions showed significant differences that are primarily ascribed to the complex 3-dimensional velocities that occur.

INTRODUCTION

Coastal erosion is expected to increase in many European countries owing to sea level rise. This will lead to an increased demand for sand for the nourishment of beaches and dunes. Mining of sand from the middle and lower shoreface (depths of 10 to 30 m) in large-scale mining pits will be required to meet this increased demand in future. It is expected that large-scale mining by dredging artificial sand pits or by removing existing sand banks will have a significant impact on the near-field and far-field morphology (increased coastal erosion).

The SANDPIT-project of the 5th framework of the EU Community Research Program, which commenced in April 2002, aims to address this problem. The general objective of the SANDPIT-project is to better understand and reliably predict the morphological behavior of large-scale sand mining pits and the associated sand transport processes at the middle and lower shoreface and the surrounding coastal zone. A balance is established between 'basic research on physical processes', including experimental research and mathematical modelling, and the 'development of practical engineering models' to be used in daily coastal zone management. The topics of research in the SANDPIT-project are listed below (more information can be found on the SANDPIT web-site: http://sandpit.wldelft.nl).

Research on sand transport:

- execution of field and laboratory experiments to fill missing gaps of existing databases,
- improvement of detailed research sand transport models,
- improvement of practical sand transport models using the results of field/laboratory experiments and of detailed process models,

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- implementation of practical sand transport models in a community sand transport model,
- implementation of community sand transport model in morphodynamic models.

Research on morphology:

- application of improved morphodynamic models to evaluate the morphological behaviour of sand banks at middle and lower shoreface (before and after removal of bank),
- application of improved morphodynamic models to evaluate the behaviour of sand mining pits at middle and lower shoreface.

Practical guidelines:

- integration of all results into practical guidelines and tools for use by various types of end-user, such as coastal managers, consultants, contractors and modellers.

Benchmark Datasets

As part of the project a number of benchmark tests were defined. These tests are used to establish the efficacy of morphodynamic models in predicting the behaviour of large-scale mining pits and so to contribute to improve coastal zone management. The benchmarking tests consist of two small-scale laboratory experiments and two field experiments. The laboratory experiments were carried out in flumes with constant flow combined with waves over a trench constructed in a moveable bed. Data consists of detailed hydrodynamic, sediment and morphology measurements. The field experiments consist of a trench that was dredged in the North Sea bed near Scheveningen in March 1964 for which backfilling was monitored, and the PUTMOR experiment in which detailed hydrodynamic and morphological data was collected in and around an offshore pit in the North Sea some 10 km off the Dutch coast near Hoek van Holland.

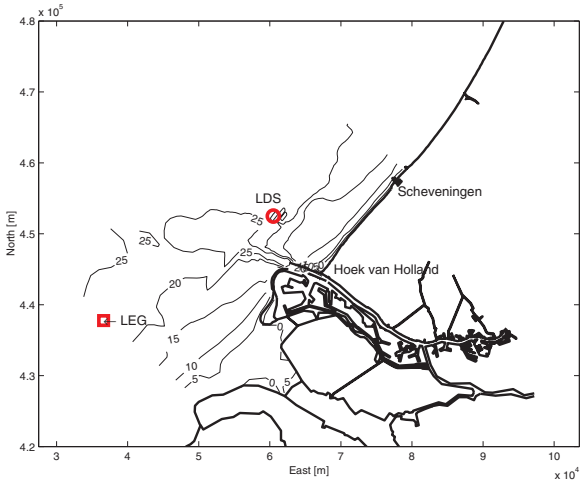


Fig. 1 Overview of pit location (LDS is pit location, LEG is offshore wave station).

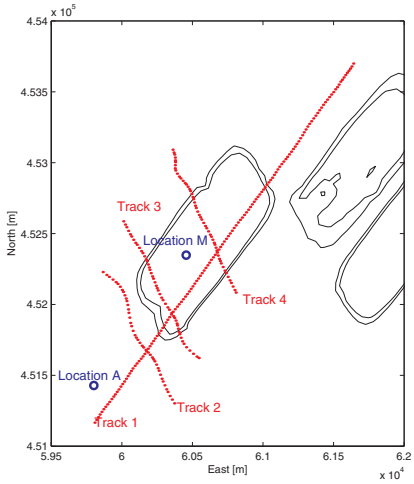


Fig. 2 Plan view of LDS with measurement locations (blue) and tracks (red).

In this paper the performance of the upgraded Delft3D model was evaluated against the PUTMOR dataset (Svašek, 2001). In this experiment, carried out by Rijkswaterstaat between October 1999 and March 2000, data on water movement, water quality and morphology were

collected in and around an offshore pit (Lowered Dump Site, referred to as LDS). The dimensions of the pit are 1300 m x 500 m x 10 m, the pit depth is relative to the seabed at an approximate water depth of 24 m, yielding a total volume of circa 6.5×10^6 m^3.

The current velocities were measured continuously through the vertical with ADCP's at the center of the pit (Location M) and 500 m south of the pit (Location A). Additionally, eight flow track measurements were carried out along four tracks at 20 March 2000 during maximum ebb and flood (see also Figures 1 and 2). Details of the presented model verification can be found in Walstra et al. (2002).

OVERVIEW OF THE DELFT3D MODEL

Delft3D fully integrates the effects of waves, currents, and sediment transport on morphological development (Nicholson et al., 1997). The module simulates the processes on the curvilinear grid system as used in the flow module, which allows a very efficient and accurate representation of complex areas. The SWAN-model is used as the wave module in Delft3D. The flow module of Delft3D is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation program which calculates non-steady flow and transport phenomena resulting from wave, tidal and meteorological forcing on a curvilinear, boundary fitted grid.

In the morphodynamic simulations the 'sediment on line' version was used. This has recently been introduced in the Flow module, so that the transport components can be calculated during the flow simulation. In this 'on-line' mode the transport rates can be computed using:

- a multi-layer model approach (3D) based on the numerical solution of the 3D advection-diffusion equation (Lesser et al., 2000);
- a one layer model approach (2DH) based on sand transport capacity formulations for bed-load and suspended load transport excluding or including the Galapatti method to account for the lag effects of the suspended load transport (van Rijn et al., 2001).

DATA SELECTION AND MODEL SCHEMATISATIONS

For the verification two representative periods were considered (see Figure 3). The first period is during neap tide with relative high waves and strong winds. The second period is during spring tide with low waves and winds. During Period 1 the wind mainly comes from the West with an average wind speed of about 12 m/s. For Period 2 the wind speed is usually less then 5 m/s (Figure 4).

The six bathymetric surveys that were carried during the PUTMOR experiment could not directly be used for comparison, as the accuracy of the individual surveys was smaller then the observed morphological development. However, based on a statistical analysis of the six bathymetric surveys RIKZ was able to construct a map of sedimentation-erosion patterns which was scaled to one year (see Figure 5, blue is erosion and red is sedimentation). An indication of the accuracy of the bottom changes is shown in Figure 6 in which the squared correlation factors between the six bathymetric surveys are shown. For large areas there is a relatively low correlation (less then 0.4) which implies that in those regions the measured bottom changes were close to, or smaller then, the accuracy of the measurements. The bottom

changes at the northeastern and southeastern pit slopes can be considered inaccurate. However the region landward of the LDS where erosion occurs has a relative high correlation.

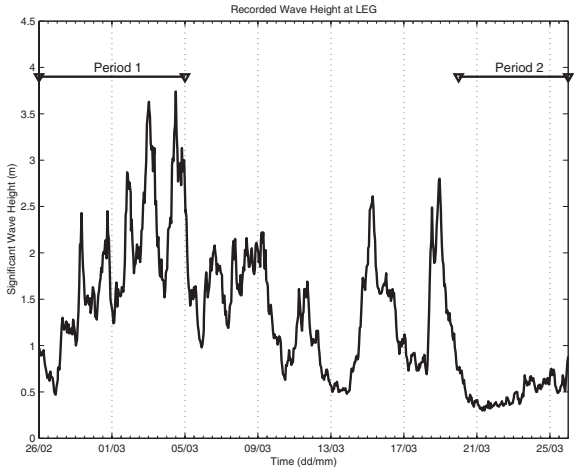


Fig. 3 Measured deep-water wave conditions at Licht Eiland Goeree (LEG).

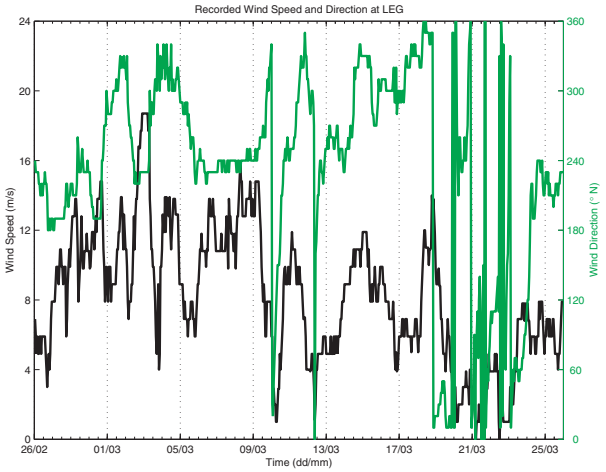


Fig. 4 Measured wind speed and direction at Licht Eiland Goeree (LEG).

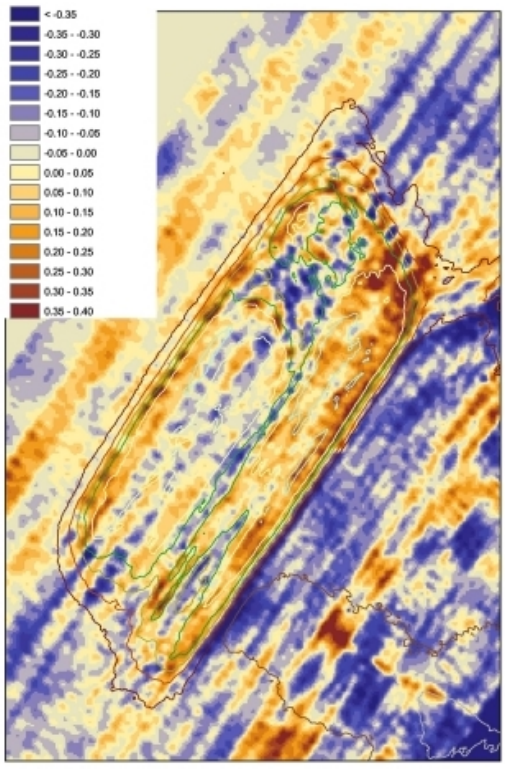


Fig. 5 Sedimentation-erosion patterns scaled to one year.

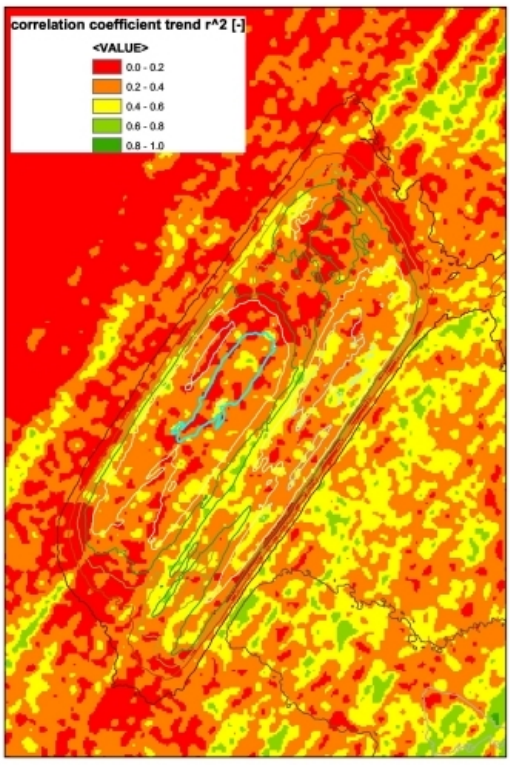


Fig. 6 Map of squared correlation factor of the six bathymetric surveys.

The hydrodynamic evaluation is performed as a hindcast in which all (measured) forcing conditions are imposed on the model as accurately possible. In the simulations measured waves, wind and river discharges were used, while the tidal forcing was obtained from the HCZ-model, (Roelvink et al., 2001) covering a large part of the Dutch coastal zone (Figure 8). The horizontal computational grid of the local model has a horizontal resolution varying from 40 m in the pit to 1500 m at the model boundaries (Figure 7). The associated bathymetry was obtained from the PUTMOR survey after construction of the pit. The remaining bathymetry was obtained from the HCZ model bathymetry. Both lateral boundaries were velocity boundaries whereas the coast parallel seaward boundary was largely a water level boundary. For both periods depth-averaged (2DH) and 3-dimensional (3D) simulations were carried out. For the hydrodynamic verification of the 3D model a vertical grid with 10 equidistant layers was used. In the 3D morphodynamic simulations the flow-model uses a non-equidistant vertical grid of 10 layers, as a relative high resolution is required near the bed. The layer distribution was set to (in % of the water depth from surface to bottom): 10.00, 10.00, 15.00, 22.50, 15.75, 10.50, 6.75, 4.50, 3.00, and 2.00. In In Table 1 an overview is given of the simulations that were carried out.

Table 1 Overview of Delft3D Simulations.

	Simulations for Period 1			Simulations for Period 2			
Parameter	2DH-1.1	2DH-1.2	2DH-1.3	3D-1	2DH-2.1	2DH-2.2	3D-2
Waves	+	-	-	+	-	-	-
Salinity	+	+	+	+	+	-	+
Wind	+	+	-	+	+	+	+

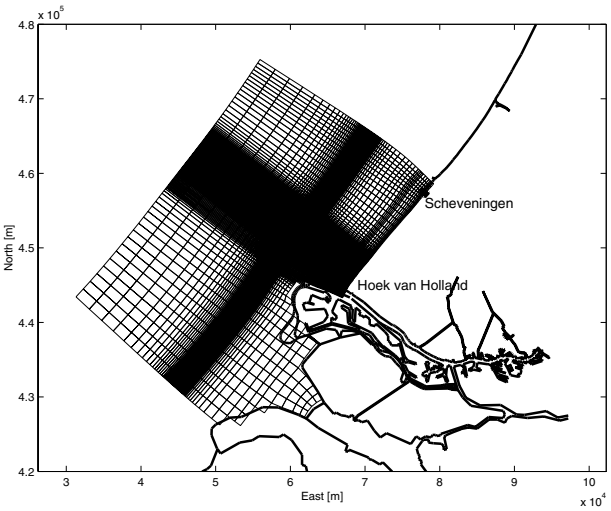


Fig. 7 Local model grid.

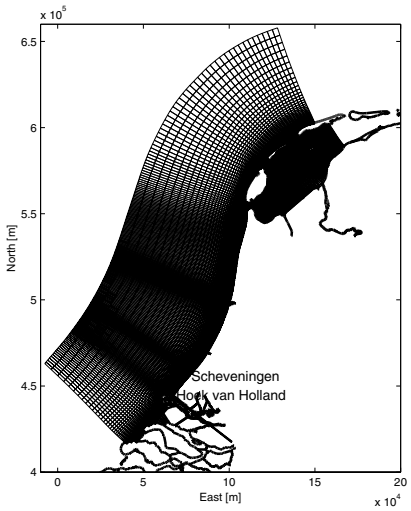


Fig. 8 HCZ-model grid

OVERVIEW OF STATISTICAL PARAMETERS

For an objective evaluation of the model performance the following statistical parameters are used: the linear correlation coefficient (r), the best-fit slope forced through the origin (m), the root mean square error ε_{rms}, and the Relative Error Vector (REV) is used (see Eq. 1).

$$REV = \frac{\left\langle \sqrt{\left(u_{meas} - u_{calc}\right)^2 + \left(v_{meas} - v_{calc}\right)^2} \right\rangle}{\left\langle \sqrt{\left(u_{meas} + v_{meas}\right)^2} \right\rangle} \quad (1)$$

The *REV* is used to evaluate the velocity vectors and was developed in the Coast3D project (Van Rijn et al., 2002). Because experience with the parameter is limited only a preliminary indication was given of the interpretation of this statistic, which is summarized in Table 2. In the statistical analysis the error ranges in the measurements were not included eventhough these may have a considerable positive effect on the outcome of the statistical parameters.

Table 2 Qualification of the Relative Error Vector (*REV*).

Qualification	*REV*
Excellent	<0.2
Good	0.2-0.4
Reasonable/Fair	0.4 - 0.7
Poor	0.7 - 1.0
Bad	>1.0

VERIFICATION OF DELFT3D

The hydrodynamic verification is primarily based on the statistical parameters described above. However, to give an indication of the model performance first a limited number of time series and vertical velocity profiles will be compared with measurements. The visual comparison is made for a selection from Period 1 in which the 2DH and 3D results are shown in which all effects (wind, waves and salinity) were included.

Comparison of Model Results with Field Data

In Figure 9, where the predicted and measured water levels are compared, occasionally relative large errors are present which are probably caused by moving pressure fields or other meteorological effects not taken into account in the model. The difference in water levels for the 2DH and 3D simulations was negligible. In Figure 10, the depth-averaged longshore and cross-shore velocities are compared for the 2DH and 3D simulations. Both in 2DH and 3D the model performs reasonably well, but in 3D the model shows an improved agreement in both the longshore and cross-shore direction. Notice that the large deviations in the water level predictions on 27/02 are not reflected in the velocity predictions. The relative large phase error between 29/02 12:00 to 1/03 00:00 in water level predictions does result in deviating velocity predictions. In Figure 11 predicted and measured velocities at the lowest and highest available vertical measuring positions are shown for Locations A and M. The agreement at the upper level is reasonable for the longshore component whereas the cross-shore component has a large amount of scatter which occasionally results in relative large deviations. Near the bed there is a remarkable agreement during most of the period in both longshore and cross-shore direction. The deviations on 29/02 are again caused by the phase error mentioned earlier.

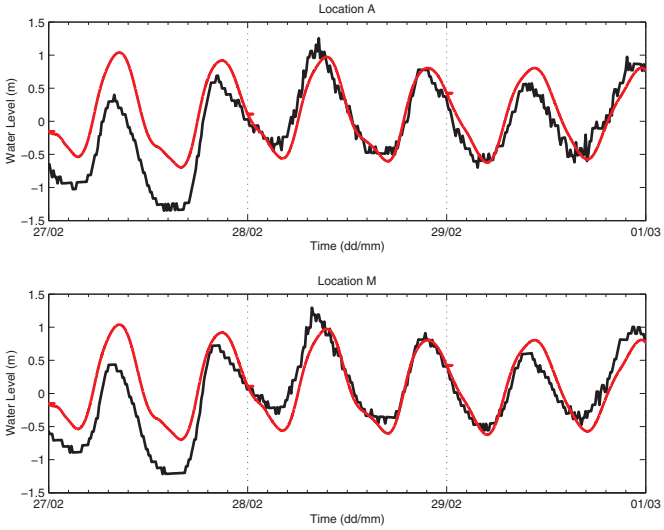


Fig. 9 Comparison of water levels at Locations A and M (red: Delft3D, black: measurements).

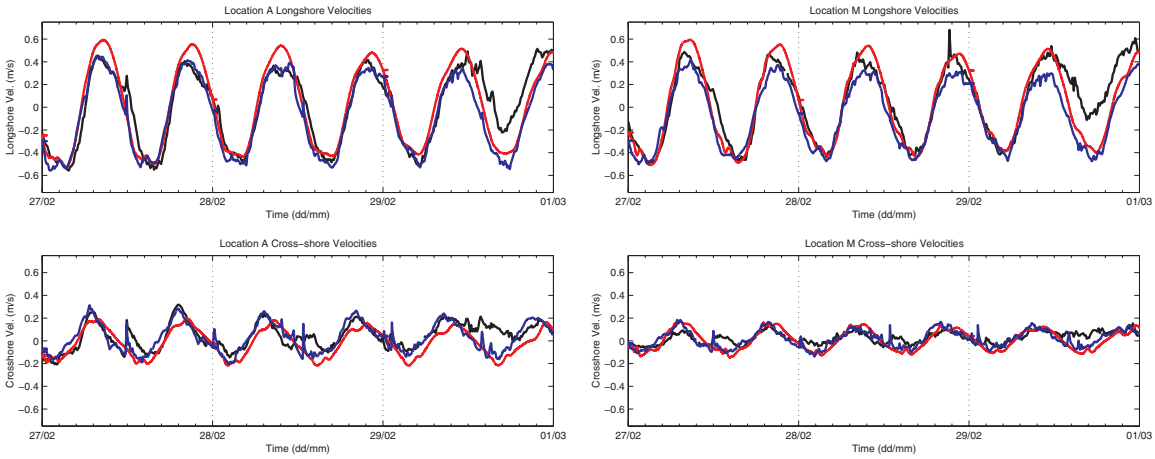


Fig. 10 Comparison of depth-averaged longshore and cross-shore velocities at Locations A and M (red: 2DH, blue: 3D, black: measurements).

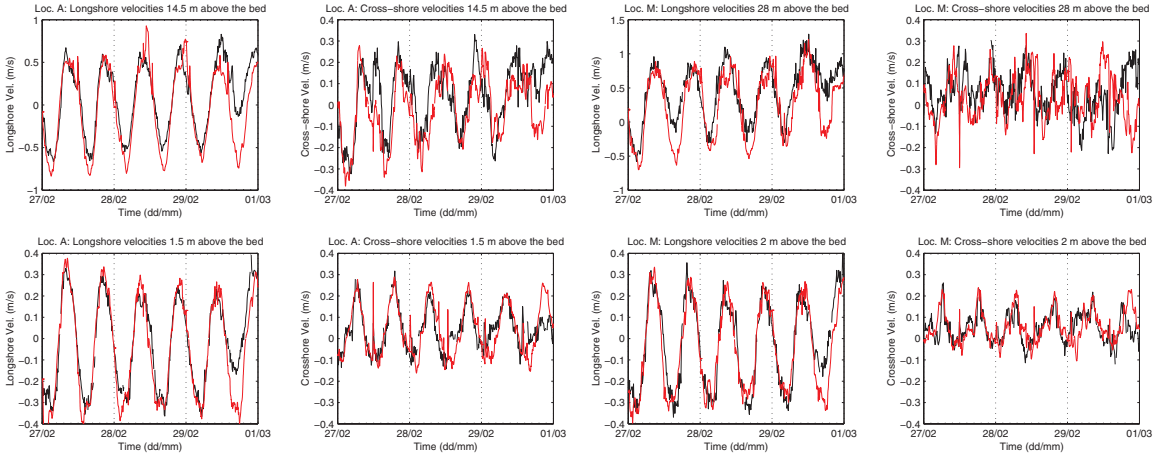


Fig. 11 Comparison of longshore and cross-shore velocities at Locations A amd M (red: Delft3D, black: measurements).

In Figure 12 the depth-averaged velocities along Track 1 (approximately 35°N, directed parallel to the main tidal direction, see Figure 2) are compared during maximum flood and ebb. The pit causes a deceleration in the longshore velocities, which is also predicted by the model. The pit approximately has the same effect on the cross-shore velocities but to a smaller extent. The accuracy with which the cross-shore velocities are reproduced in both 2DH and 3D is remarkable. It is somewhat disappointing to see that the longshore flood velocities are somewhat over-estimated by the 3D simulations. This is investigated further by examining the vertical velocity profiles in Figure 13.

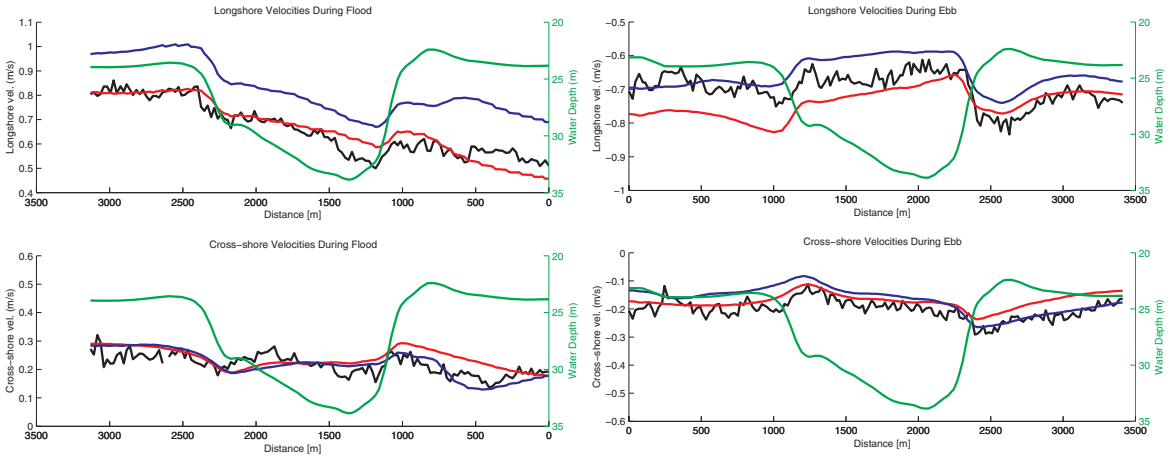


Fig. 12 Comparison of depth-averaged longshore and cross-shore velocities along Track 1during maximum flood (red: 2DH, blue: 3D, black: measurements).

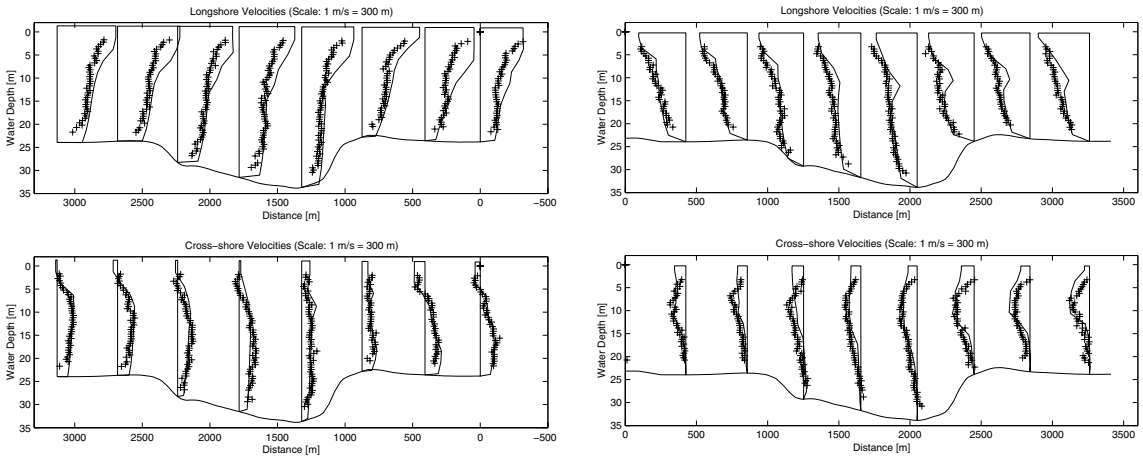


Fig. 13 Comparison of measured (crosses) and calculated (solid) velocity profiles (top: longshore; bottom: cross-shore) for Track 1 during maximum flood (left) and maximum ebb (right).

From Figure 13 it is clear that the over-predictions during flood are mainly caused by an over-estimation of the velocities in the upper part of the water column. However, in the lower part of the water column the model gives an accurate prediction of the longshore velocities. During ebb the longshore velocities are well predicted throughout the water column. The vertical distribution of both the measured and computed longshore velocities has a

logarithmic-shape in the lower half of the water column. However, the longshore velocities near the water surface increase significantly especially during flood. This feature is over-estimated, but qualitatively reproduced well by the model. The increase is primarily ascribed to the fresh water plume from the outflow of the Nieuwe Waterweg as wind and waves were low during the time period considered (H_s < 0.5 m and wind < 5 m/s). The cross-shore velocities have a complex vertical distribution in which reversal of the flow direction is occasionally present. This phenomenon is reproduced well by the model.

Statistical Evaluation of Model Performance

In Table 3 the statistical results based on an evaluation of the time series at Locations A and M are summarized. The 3D statistics were determined by averaging the statistics calculated at each available vertical measurement. The vertical distribution of the 3D statistics is discussed in the next paragraph.

Table 3 Statistics for Waterlevels and Depth-Averaged Velocities at Locations A and M.

Loc. A	*Water Levels*			*Longshore Velocity*			*Cross-Shore Velocity*			*Vector*
Run-ID	*r*	*M*	ε_{rms}	*r*	*m*	ε_{rms}	*r*	*m*	ε_{rms}	*REV*
2DH-1.1	0.76	0.67	0.42	0.89	0.99	0.18	0.73	0.66	0.09	0.51
2DH-1.2	0.76	0.68	0.44	0.89	1.01	0.18	0.75	0.70	0.09	0.50
2DH-1.3	0.75	0.67	0.45	0.88	0.98	0.19	0.74	0.71	0.09	0.50
3DH-1	0.76	0.67	0.42	0.86	0.93	0.21	0.71	0.75	0.11	0.54
2DH-2.1	0.97	0.99	0.28	0.98	1.15	0.13	0.90	0.79	0.07	0.32
2DH-2.2	0.97	1.01	0.25	0.98	1.15	0.13	0.91	0.73	0.07	0.31
3DH-2	0.97	0.99	0.28	0.97	1.02	0.12	0.83	0.83	0.11	0.31
Loc. M	*Water Levels*			*Longshore Velocity*			*Cross-Shore Velocity*			*Vector*
Run-ID	*r*	*m*	ε_{rms}	*r*	*m*	ε_{rms}	*r*	*m*	ε_{rms}	*REV*
2DH-1.1	0.77	0.73	0.39	0.91	1.01	0.16	0.71	1.06	0.06	0.46
2DH-1.2	0.78	0.71	0.41	0.91	1.01	0.15	0.73	1.07	0.06	0.44
2DH-1.3	0.77	0.70	0.42	0.91	0.99	0.16	0.73	1.08	0.06	0.45
3DH-1	0.77	0.73	0.39	0.88	0.88	0.19	0.63	0.78	0.09	0.50
2DH-2.1	0.97	0.96	0.31	0.98	1.12	0.11	0.89	1.15	0.06	0.26
2DH-2.2	0.97	0.98	0.29	0.99	1.14	0.11	0.89	1.08	0.05	0.24
3DH-2	0.97	0.96	0.31	0.98	0.96	0.12	0.84	0.86	0.09	0.28

The error statistics show that the trends in water level predictions are reasonable with correlation coefficients of 0.76 and 0.97 for Periods 1 and 2, respectively. The velocities are reproduced well with correlation coefficients generally exceeding 0.9, whereas the root mean square error for the velocities lies between 0.11 and 0.21 m/s for the longshore velocities and between 0.06 and 0.11 m/s for the cross-shore velocities. The effects of wind, waves and salinity on the 2DH results are limited. The error statistics of the depth-averaged velocities from the 3D simulations are comparable to the results of the 2DH-simulations. As was the case for the 2DH-simulations, the 3D cross-shore velocities had lower correlations and *m*-values compared to the statistics of the longshore velocities. The *REV* indicates a 'reasonable' prediction for Period 1 and a 'reasonable to good' prediction for Period 2, according to the definition given in Table 2.

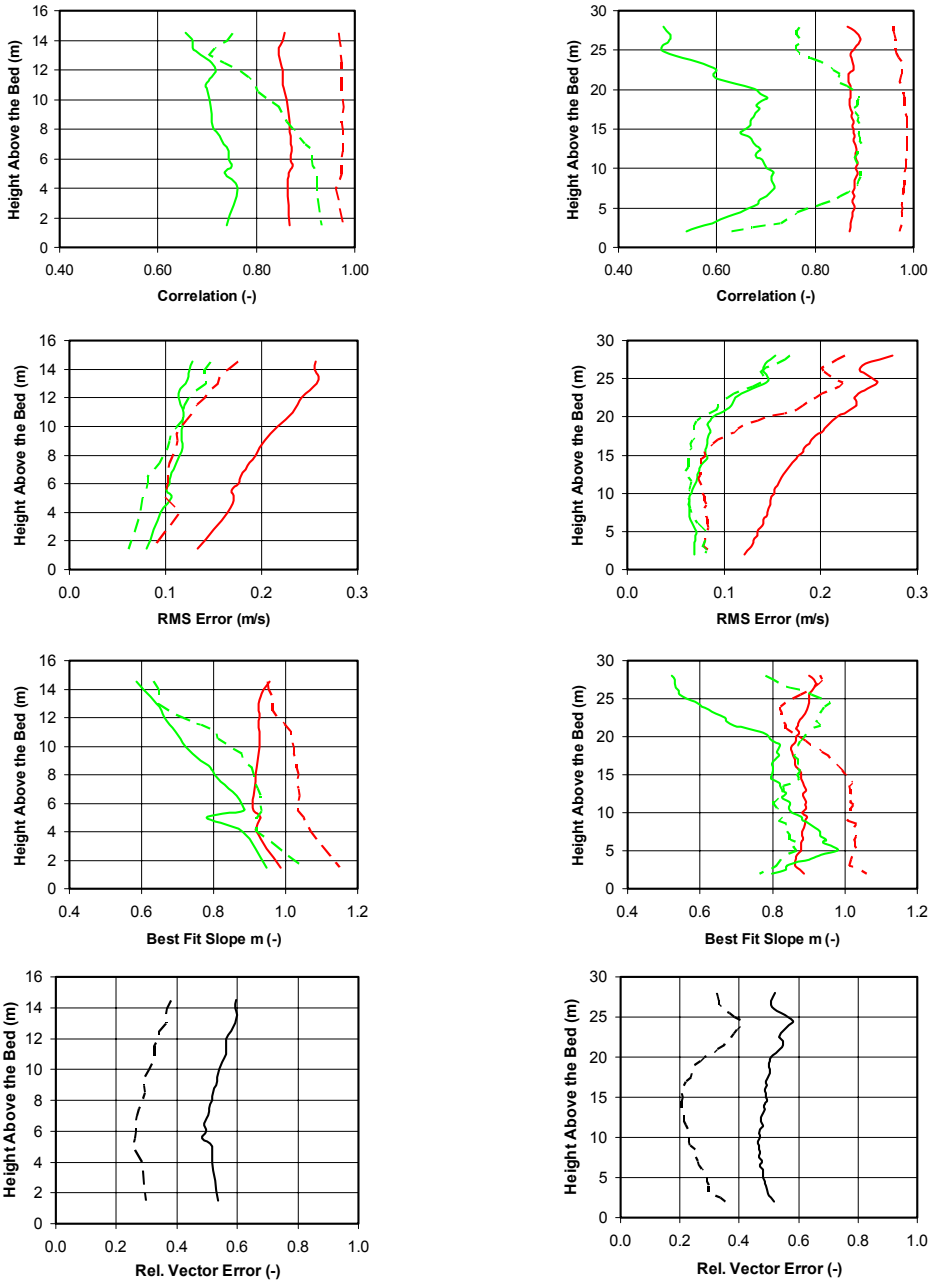


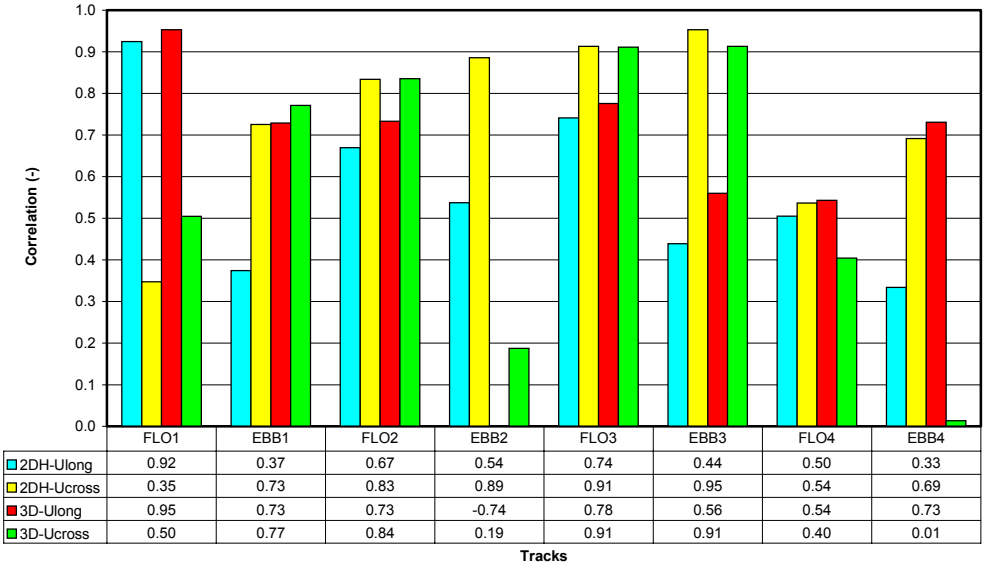
Fig. 14 Statistic results for Period 1 (solid lines) and Period 2 (dashed lines) at Locations A (left column) and M (right column), colors indicate longshore (red) and cross-shore components (green).

In Figure 14 the statistics from the 3D simulations are shown with respect to the vertical coordinate for Periods 1 (solid) and 2 (dashed), red indicates the longshore component and green the cross-shore component. The correlation (top row of plots) for the longshore velocities is almost constant along the vertical. However, the cross-shore velocities show a decreasing correlation higher in the water column which is most pronounced for Location M.

The model has a higher correlation for the longshore velocities than the cross-shore velocities at both locations.

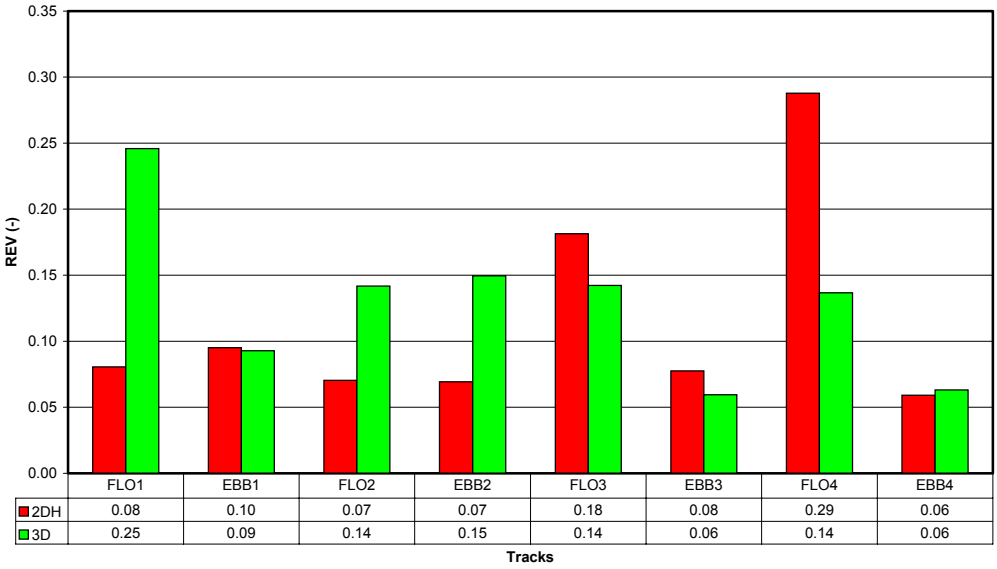
It is interesting to see that for both periods the cross-shore velocity correlation has a similar vertical distribution at Location M with relatively low correlations (0.55 and 0.65 for Period 1 and 2) near the bed. The lower correlation of the cross-shore velocities compared to the longshore correlation is mainly due to the significantly lower cross-shore velocities. This is confirmed by the ε_{rms} (second row of plots) which is significantly lower for the cross-shore velocities. The ε_{rms} values for both locations are comparable and show a gradual increase higher in the water column. The best-fit slope, m, decreases significantly, higher in the water column for the cross-shore velocities. This seems to give a somewhat negative impression of the cross-shore velocity predictions, which is not confirmed by the time series comparisons. The decreased m-values are probably caused by outliers, which have a large effect on the resulting best-fit slope. The *REV* is also approximately constant across the vertical with values in the range of 0.5 to 0.6 for Period 1 and 0.2 to 0.4 for Period 2 which results in a 'reasonable to fair' and 'good' qualifications for Period 1 and 2, respectively.

The vertical distribution of most statistics is approximately similar for both periods, which illustrates the capability of the model to give accurate predictions under different conditions over most of the water column.



	FLO1	EBB1	FLO2	EBB2	FLO3	EBB3	FLO4	EBB4
2DH-Ulong	0.92	0.37	0.67	0.54	0.74	0.44	0.50	0.33
2DH-Ucross	0.35	0.73	0.83	0.89	0.91	0.95	0.54	0.69
3D-Ulong	0.95	0.73	0.73	-0.74	0.78	0.56	0.54	0.73
3D-Ucross	0.50	0.77	0.84	0.19	0.91	0.91	0.40	0.01

Fig. 15 Correlations of depth-averaged velocities derived from the 2DH and 3D simulations along the four tracks.



	FLO1	EBB1	FLO2	EBB2	FLO3	EBB3	FLO4	EBB4
2DH	0.08	0.10	0.07	0.07	0.18	0.08	0.29	0.06
3D	0.25	0.09	0.14	0.15	0.14	0.06	0.14	0.06

Fig. 16 Relative Error Vectors of depth-averaged velocities derived from the 2DH and 3D simulations along the four tracks.

The performance of the model for the measured tracks is summarized by comparing the correlation (Figure 15) and Relative Error Vector (Figure 16) along all four tracks. The relative large variation of the correlations is mainly due to the limited number of data points. The 3D-simulations have a slightly higher overall correlation for longshore as well as cross-shore velocities. Interestingly, the cross-shore velocity correlations have, on average, approximately the same value as the longshore correlation. In general the Relative Error Vector lies below 0.2 for both the 2DH and 3D simulations which is classifies these model results as 'Excellent' according to the qualifications of Table 2.

Some indicative morphodynamic simulations were made to investigate the effect of the 2DH and 3D approach on the resulting morphology. The simulations were made using the hydrodynamic conditions of Period 1 in which the morphological changes were scaled to simulate one year. In Figure 17 the predicted sediment-erosion patterns and the residual total depth-averaged transports are shown for both model runs (waves were included). Although for both simulations most changes have occurred in the direct vicinity of the pit: erosion just outside the pit and mainly sedimentation on the pit slopes, the 3D simulation has resulted in significantly larger changes in the morphology. Especially, the sedimentation at the longshore pit slopes is more pronounced in the 3D results. This is mainly caused by secondary cross-shore flows caused by the presence of the LDS. This is clearly visible if the residual transports are compared. The 2DH simulation predicts northeasterly transports parallel to the main tidal direction. As a consequence, the morphological changes are mainly present on the pit slopes perpendicular to the main tidal direction due to acceleration and deceleration of the flow. However, the 3D simulation predicts that the LDS attracts sediment from all directions, which results in southward transports at the northern part of the LDS. Although the measured morphology (Figure 5) has a very 'patchy' distribution, the sedimentation on the landward longshore slope and the erosion in the region landward of this slope is clear. This seems to be

in more accordance with the predictions made with the 3D than the 2DH results. However, it has to be stressed that no direct comparison can be made since the imposed hydrodynamic forcing conditions are not representative for longer-term morphodynamic simulations.

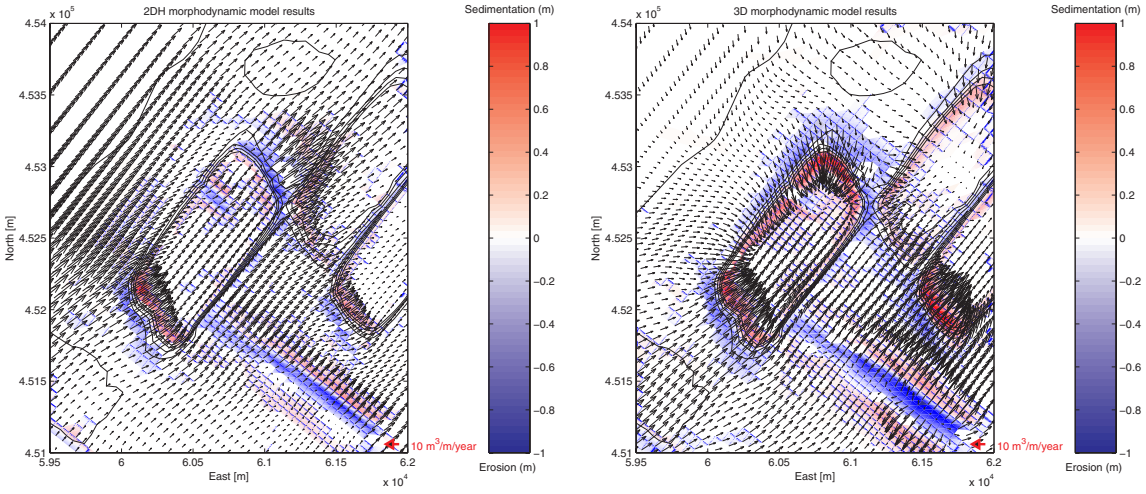


Fig. 17 Sedimentation-erosion and yearly residual transports calculated in 2DH (left) and 3D (right).

FUTURE RESEARCH

Within the framework of the SANDPIT project the model will be verified more extensively on the measured morphology. Apart from the field verification, the laboratory benchmark tests will also be considered to provide benchmark results for the anticipated implementation of improved descriptions of sand transport processes in deep water conditions.

CONCLUSIONS

This verification study has shown that the Delft3D-model is capable of reproducing the hydrodynamic measurements with reasonable to good accuracy. However, the agreement did vary in the two considered periods. In the first period, around neap tide with relatively high waves and wind, occasionally large deviations between the predictions and measurements were observed. It is thought however, that these deviations were caused by the fact that the overall HCZ-model, in which the local model was nested, was unable to accurately account for (high) wind speeds. The second period, around spring tide with low waves and wind, was reproduced accurately. In the 2DH-simulations the effect of waves, wind and salinity was limited. The tidal forcing appeared to be dominant at the investigated pit. Although no 3D sensitivity runs were made, it is thought that especially wind and salinity will have a relative large influence on the vertical velocity distributions.

The comparison with the flow track measurements showed that the model was capable of reproducing the current velocities with good accuracy. The deceleration of the flow across the long axis of the pit was represented well, especially during the ebb measurements. The 3D velocities agreed well with the measurements. Especially the representation of the complex cross-shore velocity profiles was remarkably accurate.

Although the depth-averaged velocity comparisons of the 2DH and 3D simulations resulted in comparable statistical errors, the conclusion that the former is producing reasonable results against low computational effort and that the latter only results in a limited improvement of the predictions against a high computational effort is easily made. However, it has to be stressed that the presented intercomparison has a limited validity. Especially, for morphological models the lower part of the water column is important as most sediment is transported in this region. Furthermore, the measurements revealed the complex nature of the vertical velocity profiles especially in the cross-shore direction for which logarithmic velocity profiles assumed in 2DH simulations do not hold. For accurate morphological predictions it may therefore still be necessary to make use of a 3D-model. This is confirmed by the comparison of morphological model predictions made in 2DH and 3D. It was shown that the residual transports showed large differences even with opposing transports direction.

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