MORPHODYNAMIC UPSCALING WITH THE MORFAC APPROACH IN TIDAL CONDITIONS: THE CRITICAL MORFAC

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A hampering factor in the application of morphodynamic models is the potential excessive time needed to complete a simulation. One way to upscale a model run is the use of a morphological factor, or MORFAC. In this paper, we investigate the upper limit to the value of the MORFAC as a function of model geometry and timestep for a schematized case of tidal flow, and we suggest a way to make a conservative estimate of this value using a morphology-based CFL condition.

Keywords: morphodynamic modelling; MORFAC; Delft3D; long term coastal evolution

INTRODUCTION

The recently developed Morphological Acceleration Factor (MORFAC) approach for morphodynamic upscaling enables numerical process-based simulations of morphological evolution at decadal to millennial time scales (Roelvink, 2006). Conceptually, one starts with the reasonable assumption that during a simulation time step, the changes in hydrodynamics are magnitudes bigger than the changes in morphology. By multiplying the morphological change after a hydrodynamic timestep with a certain factor, and updating the bathymetry accordingly before the start of the next timestep, one can gain enormous reductions in simulation time. There have been some efforts to investigate the validity of the MORFAC concept for coastal applications. A number of morphological simulations using this approach, mostly with tidal forcing only, have concluded that this approach produces sufficiently realistic outcomes (Lesser et al., 2004; Roelvink, 2006). Simulations with a MORFAC as high as 1000 have been used in recent qualitative studies of the long-term evolution of tidal basins (Dissanayake et al., 2009a,b; Van der Wegen et al., 2008; Van der Wegen and Roelvink, 2008; Dastgheib et al., 2008; Dastgheib, 2012).

Ranasinghe et al. (2011) pioneered the systematic investigation of the limitations and strengths of the MORFAC concept by showing the dependencies and sensitivities of the MORFAC approach to forcing conditions and model parameters in a simple case of a sand bar subjected to a uniform unidirectional flow. They proposed a criterion to determine the critical MORFAC in such a case, based on a CFL condition for morphological change. The current study takes that investigation one step further and includes the harmonic tidal flow in the investigation.

METHODOLOGY

Under ideal circumstances, we would be able to compare the outcomes of a morphodynamic model simulation using morphological acceleration with real measured bathymetries that cover the entire period of the simulation. A nice recent example of this was presented by Dam et al. (2013) for the Western Scheldt. This also allows checking the inherent quality of morphodynamic model code, by running simulations without acceleration. In the present case (and generally) this kind of datasets is not available. As such, we turn to the next best thing, being a schematized approach.

In the current study a series of morphological simulations in 2DV mode were carried out using the Delft3D code (Lesser et al., 2004). The geometry of the model represents a flume with a length of 9000m, and a depth of 4m. A symmetrical hump with a crest height of 2 m below the mean water level and the shape of a gaussian function is situated in the middle of the flume (i.e. crest location at x=4500m). Following Ranasinghe et al. (2011), we specifically choose a bar morphology, as shoals contract the flow in the vertical, leading to higher sediment transport, thus limiting the potential critical MORFAC. Harmonic weakly reflective velocity boundaries with 1 m/s amplitude and period of 12 hours were applied at the both ends of the flume, without phase difference between the model boundaries. The Engelund and Hansen (1967) total load formulation was used for sediment transport

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calculations. The bed material consists of medium-fine sand with a grain size of 200µm. In the series of simulations, the MORFAC was varied systematically from 1 to 700.

The simulation with a MORFAC=1 is considered as the benchmark simulation. The *critical MORFAC* is then defined as highest MORFAC that results in a morphology that is similar to that predicted by the benchmark case at the same morphological time. Since a MORFAC was applied in the simulation, the morphological results are only valid and comparable in different simulations at the end of hydrodynamic tidal cycles (Roelvink, 2006, Roelvink and Reniers, 2012). Therefore, in all the discussions and demonstrations of the results, the number of tidal cycles is considered as the time unit and all outputs are presented at the end of hydrodynamic tidal cycles. The system is said to be in morphodynamic equilibrium when the change in the amplitude of the hump in one tidal cycle approached zero. In this case, the time of reaching equilibrium thus determined was 1000 tidal cycles (500 days).

The resulting morphology of the benchmark case after 1000 tidal cycles was then compared with the predicted morphology of the simulations with a higher MORFAC at the exact same morphological time (500 days) using the Brier Skill Score (BSS, Van Rijn et al., 2003):

$$BSS = 1 - \frac{< (z_b - z_{b,mf=1})^2 >}{< (z_{b,t=t0} - z_{b,mf=1})^2 >} \qquad (1)$$

where z_b is the resulting bathymetry from evaluated simulation, $z_{b,MF=1}$ is the observation simulation with MF=1 (benchmark case), and $z_{b,t=t0}$ is a baseline (initial bathymetry). A BSS of 1 denotes perfect correspondence between the modeled bathymetry with a higher MORFAC, and the benchmark case with a MORFAC equal to 1. Note that the end point in time of the simulations with higher MORFACs should coincide with the end of a hydrodynamic tidal cycle in those simulations (Roelvink, 2006). Therefore by choosing 1000 tidal cycles as the time of reaching morphological equilibrium in the benchmark simulations, the comparison can be done only with the simulations with a MORFAC of 1, 2, 5, 10, 20, 50, 100, 200, 500 and 1000.

Although in complicated situations, simulations with a BSS of 0.5 are considered to be sufficiently accurate (Van Rijn et al., 2003), in this idealized case a BSS of 0.99 is adopted as cut-off for the lowest MORFAC value at which model results started to depart from the benchmark case (Ranasinghe et al., 2011).

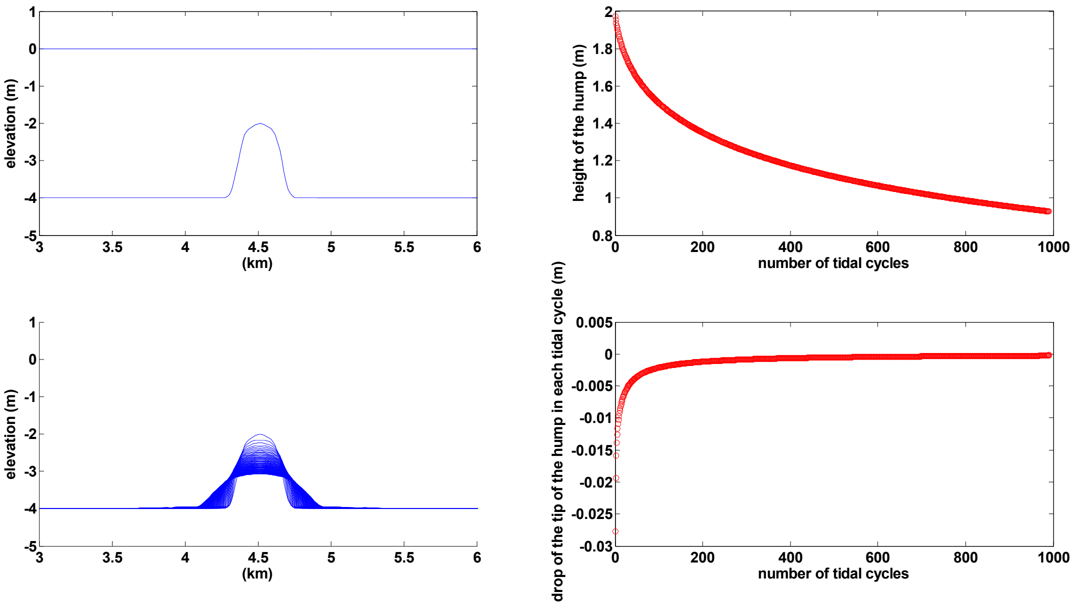

Figure 1: Example of a reference simulation (Ū=1 m/s, dt =3 s, dx= 15 m, MF=1). The change in the crest height is insignificant after about 1000 tidal cycles.

As in Ranasinghe et al. (2011), the flow velocity, grid size, hydrodynamic time step, and the MORFAC were varied systematically to investigate the dependencies and sensitivities of model predictions to these variables. Simulations were performed for Ū =0.5, 0.75, 1.0, 1.25 and 1.5 m/s; dx = 7.5, 15 and 30 m; dt = 0.75, 1.5, 3, 6 and 12s; *MORFAC* = 1, 5, 10, 20, 50, 100, 200, 500 and 1000. This resulted in 600 runs.

RESULTS

Figure 2 exemplifies how the BSS changes when we change the morphological acceleration in three different simulations, featuring a change in grid cell size, time step and velocity at the boundary. Steadily increasing the morphological acceleration , and applying the criterion that a BSS smaller than 0.99 invalidates the simulation results, results in critical MORFAC values that differ by a factor of more than 2, i.e. about 60 (green), 90 (blue), and 130 (red).

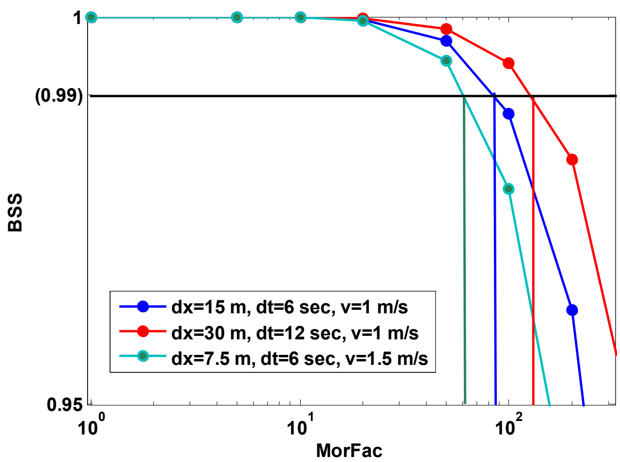

Figure 2: Determination of the critical morphological factor using a Brier Skill Score of 0.99 as cut-off value

From Figure 2 however, it is not clear whether the determining factor for the establishment of the critical MORFAC is the grid cell size, the time step or the incoming velocity. To investigate the dependency and sensitivity of the critical MORFAC to each of these variables, we present these separate relationships in the next sections.

The influence of the incoming velocity is studied by using the ambient Froude number $Fr = \bar{U}/\sqrt{gh}$ (Figure 3), calculated at the boundary of the domain, where the bathymetric changes are negligible (h constant, not shown), and the velocity signal $\bar{U}$ is undisturbed by the bed protrusion. As in the unidirectional flow case presented by Ranasinghe et al. (2011), there exists an inverse proportionality relationship between the critical MORFAC and Fr. However, the value of the allowable critical morphological acceleration is more than an order of magnitude smaller than in the case of unidirectional flow, e.g. 4000 for Fr=0.11 in the unidirectional case (Ranasinghe et al. 2011, their Figure 5), but less than 200 in the case of reversing currents (Figure 3). This can be explained by the higher potential for velocity and transport gradients in space and time, and thus morphological changes, in reversing flows.

The hydrodynamic Courant number $Cr = \bar{U}dt/dx$ (dt is the hydrodynamic timestep, dx the grid cell size) can be used to explicitly link the critical morphological acceleration factor to the stability of the hydrodynamic simulation, although Delft3D uses the implicit ADI scheme (Stelling and Leendertse, 1991), which is unconditionally stable, and gives reliable results for Cr values up to 10 (Deltares, 2013). From the simulations, there appears to be no direct link between the critical MORFAC and Cr (Figure 4), and moreover, the critical MORFAC can change with a factor of 7 for the same Cr value (e.g. Cr=0.2, Figure 4).

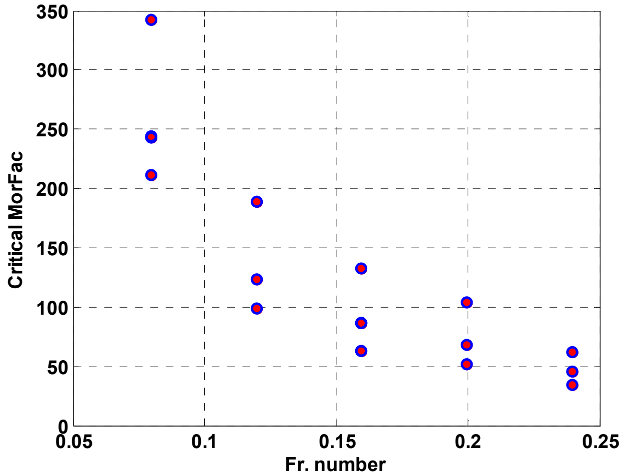

Figure 3: Critical MORFAC in function of the ambient Froude number $Fr = \bar{U}/\sqrt{gh}$

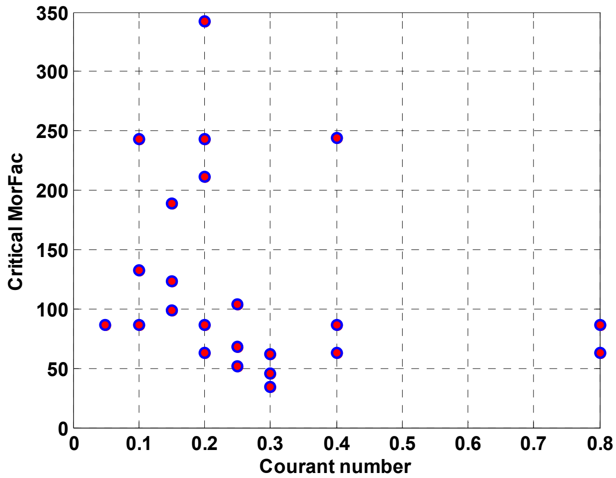

Figure 4: Critical MORFAC in function of Courant number $Cr = \bar{U}dt/dx$

The individual contributions of hydrodynamic timestep *dt* and grid cell size *dx* to the change in the critical MORFAC were analyzed in two ways: (1) by keeping the Cr value a constant, so changing dt and dx simultaneously, and (2) by changing dx or dt, allowing Cr to vary. The values of *dt* were set to 1.5, 3 and 6 seconds, and the values of *dx* to 7.5, 15 and 30m. The results are presented in Figure 5-Figure 7. An increase in the grid cell size *dx* results in an increase of the critical MORFAC in a near-linear fashion (Figure 5, Figure 6), irrespective of Cr being constant or not. This is intuitively correct, as this larger grid cells result in smaller morphological courant number (see below, Discussion). There is of course a limit to the maximum grid cell size, in order not to lose relevant morphological detail in the simulation, e.g. the transition between a channel and a shoal.

In the case of keeping *Cr* constant, i.e. letting *dx* vary with a change in *dt*, the critical MORFAC increases with an increase in *dt*. When we let *Cr* vary with *dt*, keeping *dx* constant, there is no clear relationship between *dt* and the maximum allowable morphological acceleration (Figure 6). In line with the findings of Ranasinghe et al. (2011), the influence of *dx* on the critical MORFAC appears to overwhelm any effect of *dt*.

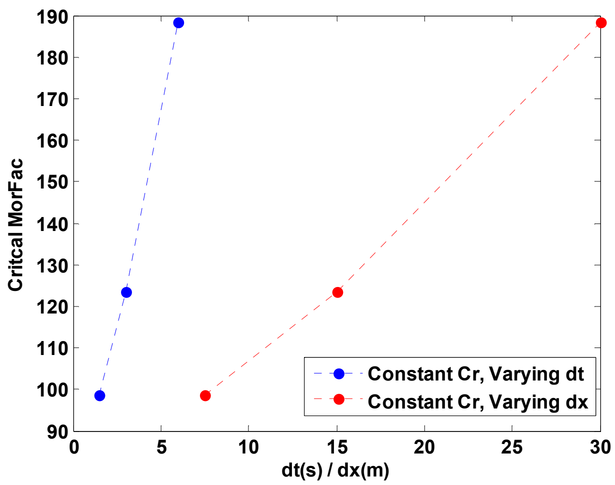

Figure 5: Changes of the critical MORFAC for a constant Courant number $Cr = \bar{U}dt/dx$, but varying dt (1.5s; 3s; 5s) and dx (7.5m; 15m; 30m)

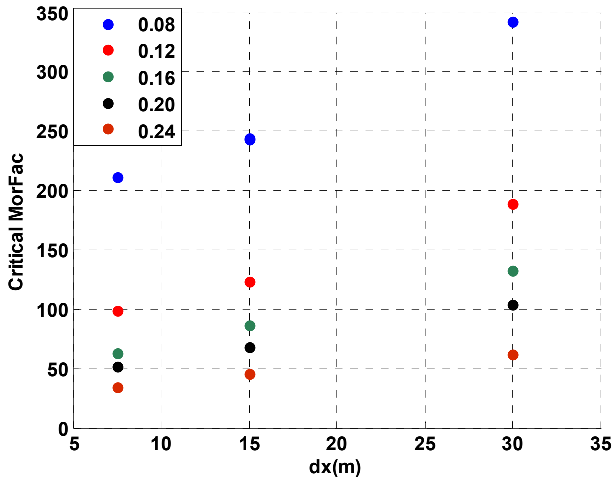

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Figure 6: Dependency of the critical MORFAC on grid cell size *dx*. The changes in color of the data points relate to differing Froude numbers

DISCUSSION

Taking the above results into consideration, we can ask whether it is possible to determine an *a priori* maximum morphological factor applicable for a given modeling assignment. Morpodynamic update discretizations in numerical models are usually implemented using an explicit scheme. As such, the bedform propagation at the scale of interest should not exceed 1 grid cell within one morphological timestep. To formalize this concept, we use a morphological Courant condition Cr_{mor}:

$$Cr_{mor} = C_{bed} * dt * MF / dx \tag{2}$$

where C_{bed} is the propagation speed of the bedform, dt is the hydrodynamic timestep, MF is the morphological scale factor and dx is the grid cell size. The product dt*MF represents the morphological timestep. The bedform propagation speed can be calculated as follows (e.g. Roelvink and Reniers, 2012):

$$C_{bed} = \frac{b|\vec{S}|}{(1-\varepsilon)h} \tag{3}$$

where b is the assumed power of the velocity-transport relation, $\vec{S}$ is the sediment transport vector, ε is the sediment porosity, and h is the water depth. To define the critical morphological factor for a given grid geometry and hydrodynamic timestep, we have to find a maximum value for C_{bed}, in such a way that $Cr_{mor} < 1$. One possible way to do this is by running an ISE (initial sedimentation-erosion) model, for a period of for example a spring-neap cycle, and determining the maximum value of the sediment transport S. This will give an indication of the most conservative value for Cr_{mor} and the critical MORFAC.

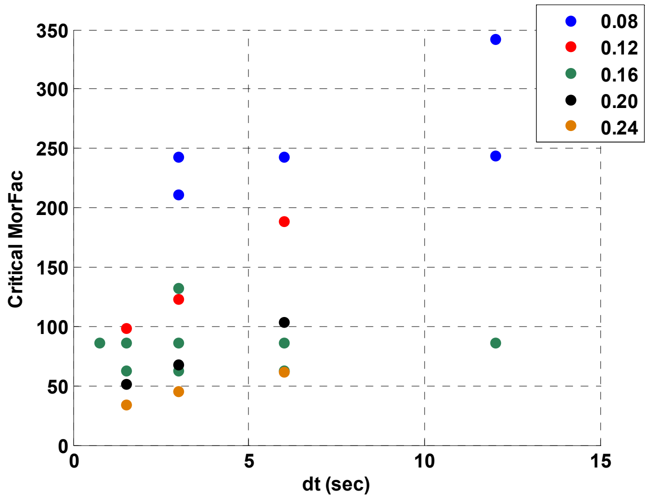

Figure 7: Dependency of the critical MORFAC on grid cell size *dt*. The changes in color of the data points relate to differing Froude numbers

Of course, the caveats listed by Ranasinghe et al. (2011) apply in the case of tidal flow as well. By using an ISE approach, the C_{bed} is determined using results from the initial phase of the simulation only, not taking into account bed updates at later stages that might influence the maximum water depth and the shape of the bed. Moreover, assumptions made about the derivation of Equation 3, such as the value for b, may not hold in reality. The use of different numerical schemes might yield different results for the same input. So in general, it is very hard to develop a generally applicable, physics based criterion for the a priori determination of a critical MORFAC, but a short sediment transport simulation can *assist* in choosing the initial conservative value.

CONCLUSIONS

In this paper, we investigated the influence of model geometry, timestep and flow boundary conditions on the maximum allowable morphological acceleration factor for morphodynamic simulations. We found that, as in the case of unidirectional flow, the critical MORFAC is dependent on the Froude number, the timestep and the grid cell size. The critical MORFAC decreases exponentially with increasing Froude numbers, it is quasi-linearly related to the grid cell size, and it is related to the timestep, although this relationship is secondary to the dependence on the cell size. It appears not to depend directly on the hydrodynamic Courant conditions. The critical MORFAC in tidal conditions is at least an order of magnitude lower compared to unidirectional flow conditions for the case presented in this paper.

We could not develop a generally applicable, physics based criterion for the a priori determination of the critical MORFAC, but we propose to use a short sediment transport simulation that can help choosing the initial conservative upper limit for morphological accelaration in a morphodynamic model.

As a next step, we propose to study the applicability of the morphological Courant criterion for a number of schematized cases. Until now, we only considered models featuring forcing by currents. In the near future, we intend to add waves to the boundary conditions of the present simple 1D model. The logical continuation of this is then to study schematized 2DH cases, like a 2D hump. A third improvement to the current approach would then be to try and differentiate between errors introduced by the numerical scheme and the use of a MORFAC.

REFERENCES

Dam, G., Van der Wegen, M., Roelvink, D. (2013). Long-term performance of process-based models in estuaries. *Proceedings Coastal Dynamics Conference 2013*, Bordeaux, France, 409-420.

Dastgheib, A. (2012). *Long-term process-based morphological modeling of large tidal basins*. PhD thesis UNESCO-IHE/DUT. CRC Press/Balkema.

Dastgheib, A., Roelvink, J. A., & Wang, Z. B. (2008). Long-term process-based morphological modeling of the Marsdiep Tidal Basin. *Marine Geology*, *256*(1), 90-100.

Deltares (2013). *Delft3D FLOW Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments - User Manual Hydro-Morphodynamics*. 710pp.

Dissanayake, D. M. P. K., Roelvink, J. A., & Van der Wegen, M. (2009a). Modelled channel patterns in a schematized tidal inlet. *Coastal Engineering*, *56*(11), 1069-1083.

Dissanayake, D. M. P. K., Ranasinghe, R., & Roelvink, J. A. (2009b). Effect of Sea Level Rise in Tidal Inlet Evolution: A Numerical Modelling Approach. *Journal of Coastal Research*, SI56, 942-946.

Engelund, F., & Hansen, E. (1967). *A Monograph on Sediment Transport in Alluvial Streams* . Teknisk Forlag , Copenhagen, 63pp.

Lesser, G. R., Roelvink, J. A., Van Kester, J. A. T. M., & Stelling, G. S. (2004). Development and validation of a three-dimensional morphological model. *Coastal engineering*, *51*(8), 883-915.

Ranasinghe, R., Swinkels, C., Luijendijk, A., Roelvink, D., Bosboom, J., Stive, M., & Walstra, D. (2011). Morphodynamic upscaling with the MORFAC approach: Dependencies and sensitivities. *Coastal Engineering*, *58*(8), 806-811

Roelvink, J. A. (2006). Coastal morphodynamic evolution techniques. *Coastal Engineering*, *53*(2), 277-287.

Roelvink, J. A. & Reniers A.J.H.M. (2011). *A Guide to Modeling Coastal Morphology* . Advances in Coastal and Ocean engineering - Volume 12. World Scientific, Singapore, 250 pp.

Stelling, G., Leendertse, J., 1991. Approximation of convective processes by cyclic ADI methods. Proceedings of 2nd ASCE conference on estuarine and coastal modeling, Tampa. ASCE, New York, pp. 771–782

Van der Wegen, M., & Roelvink, J. A. (2008). Long-term morphodynamic evolution of a tidal embayment using a two-dimensional, process-based model. *Journal of Geophysical Research: Oceans*, 113(C3).

Van der Wegen, M., Wang, Z. B., Savenije, H. H. G., & Roelvink, J. A. (2008). Long-term morphodynamic evolution and energy dissipation in a coastal plain, tidal embayment. *Journal of Geophysical Research: Earth Surface*, 113(F3).

Van Rijn, L. C., Walstra, D. J. R., Grasmeijer, B., Sutherland, J., Pan, S., & Sierra, J. P. (2003). The predictability of cross-shore bed evolution of sandy beaches at the time scale of storms and seasons using process-based profile models. *Coastal Engineering*, *47*(3), 295-327.