9th International Conference on Hydroinformatics
HIC 2009, Tianjin, CHINA

CALIBRATING THE REGIONAL TIDAL PREDICTION OF THE SINGAPORE REGIONAL MODEL USING OPENDA

ALAMSYAH KURNIAWAN, OOI SENG KEAT
Singapore-Delft Water Alliance, National University of Singapore, EW1-02-05,
2 Engineering Drive 2, Singapore 117577, email: sk.ooi@nus.edu.sg
HERMAN GERRITSEN, DANIEL TWIGT
Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands

Calibrating a hydrodynamic model for tide is typically an engaged and difficult process. This process is complicated further in the vicinity of the Singapore and Malacca Straits by the tidal flow interactions between the Indian and Pacific Oceans, the presence of numerous islands and small channels and the lack of a matching network of reliable tidal observation stations across the region. The Must Have Box or MHBox study of Sea Level Anomalies and Current Anomalies in the Singapore region uses the Singapore Regional Model. The present paper focuses on calibrating the Andaman Sea tidal forcing of the SRM through the use of a portable interface for enabling flexible data assimilation and calibration (OpenDA). Attention is given to the formulation of a well-balanced Goodness-of-Fit criterion for the parameter optimisation process, taking into account uncertainty in model and data. The DUD method is used to successfully evaluate and improve the overall response of the SRM by simultaneously varying tidal amplitudes and phases at the 5 support points along the Andaman Sea boundary. In addition OpenDA is used to evaluate and improve local and overall tidal characteristics through varying local bed friction and/or depth in a region within Malacca Strait.

1. INTRODUCTION

The MHBox study focuses on the comprehensive analysis and understanding of residual water levels and currents and their forcing mechanism for the highly complex Singapore regional waters [1]. A deterministic hydrodynamic model application named the Singapore Regional Model (SRM) is applied [2], which focuses on representing water level and current dynamics in Singapore waters including their approaches, to ensure that the large scale features are dynamically represented in the model itself. The original model objective was a balanced overall tidal representation around Singapore itself. Previous studies by Ooi et al. [3,4] have shown that it is possible to improve the overall tidal representation of the model as a whole. The use of domain decomposition [3] has shown that it is possible to use selective grid refinement to improve the tidal prediction of the original model but at much higher computational cost. Single parameter optimization of the tidal constituents on the boundaries [4] has also shown that the overall tidal representation of the SRM could be further improved. This study [4] also introduced the use of a data assimilation tool, OpenDA, to possibly evaluate and improve the overall tidal response of the SRM by simultaneously varying the amplitudes and phases in the tidal forcing at the boundaries and to evaluate and improve tidal characteristics at particular stations i.e. through varying local bed friction or depth. The present paper discusses the tidal calibration of SRM using OpenDA by optimising the tidal forcing at the Andaman Sea (AS) and the effect of varying the depth and bed friction in one particular region of interest.

2. SINGAPORE REGIONAL MODEL

The Singapore Regional Model (SRM) covers a domain stretching from northern Sumatra to the eastern coast of Borneo. SRM has open water boundaries on the Andaman Sea, Java Sea and the South China Sea at which tidal constituents are input for tidal forcing of the model. It features a boundary-fitted curvilinear-spherical orthogonal grid which consists of around 38,500 horizontal grid cells, and the sizes of the grid cells vary from approximately 200 m to 300 m around Singapore Island to approximately 15 km at the open sea boundaries (Figure 1). To accurately account for the tidal predictions, eight main tidal components Q1, O1, P1, K1, N2, M2, S2 and K2 are prescribed at the three open sea boundaries. The Admiralty charts based model depths range from maximum about 2000 m in the AS to approximately 40-50 m depth in the Singapore Strait. Calibration of any model for tide requires an accurate bathymetry and coastal geometry representation, for which purpose the SRM has been updated with the latest available coastline geometry of 2004. Another requirement for proper calibration is accurate observation data. To properly assess the station selection and observation data it was decided to subdivide the model domain into 8 distinct regions as shown in Figure 1 and rank the stations within each region with regards to their quality and reliability. The number of stations was reduced from 155 observation locations originally based on the International Hydrographic Observation (IHO) database to a total of 80 observation stations that include a mix of IHO, Maritime and Port Authority of Singapore (MPA) and University of Hawaii Sea Level Center (UHSLC) observations, plus satellite based tidal constants derived by tidal analysis of level-2 altimeter along-track data sets from the RADS database [5].

2.1 Development and Performance of a Coarser Grid Version of SRM

A one year simulation with SRM requires 12 hours total CPU time, and simple “twin tests” [4] using OpenDA had required 4-5 iterations to obtain a solution. This implies at least 60 hours total computational time if the twin tests had been carried out with the SRM. It was decided to create a 3x3 coarser grid version of the SRM to reduce the computational time. The minimum simulation period of 1 year was retained as it permits tidal analysis to be carried out without coupling tidal constituents. The 3x3 ratio increases the grid sizes around Singapore Island to approximately 1000 m, but decreases the total number of grid cells of the model from 38,500 to 4,200 cells. The computation time then reduces to 45 minutes. The coarsening was carefully carried out to ensure that the locations of the open sea boundaries are the same and that the volume difference between the original and the coarse domain is small enough to be deemed acceptable.

To have a better understanding of any reduction in accuracy due to the coarser grid resolution, a model performance comparison analysis has been carried out between the original and coarse grid models. Figure 2 shows the root mean square error (RMSE) obtained by taking the difference in water levels between the fine and coarse grid results at different stations calculated over a 1-year simulation. Over the whole model domain the average RMSE<0.1m. It was decided to exclude stations with RMSE>0.2m in the analysis of the coarse model simulations, thus reducing the number of observation stations in the coarse model to 77. The equivalence between the sensitivity behaviour of the coarse version and original SRM makes it possible to conduct efficient calibration on the coarse version, which is then input for a limited number of final calibration runs with the full model.

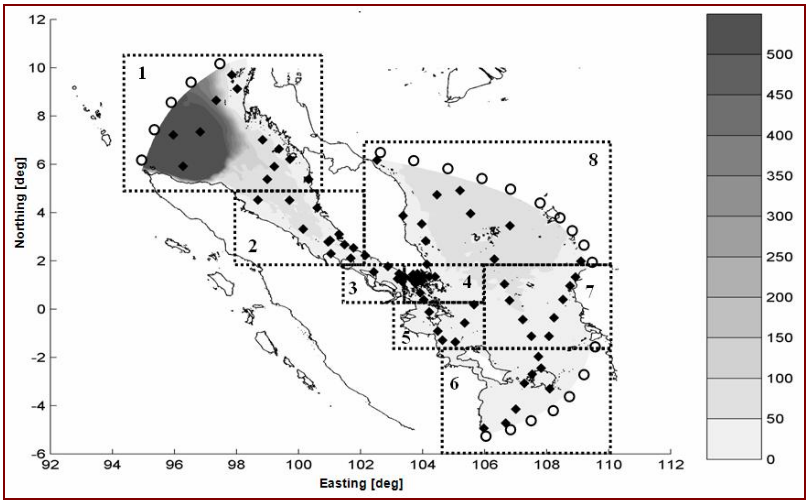


Figure 1: Singapore Regional Model showing boundary support points (big open circles; where tidal and mean level forcing are prescribed and adjusted) and the eight distinct regions with observation locations (*diamond*'s) used for calibrating the model.

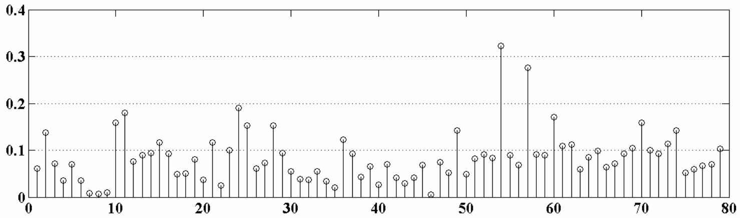


Figure 2 Comparison of performance between coarse and fine grid model based on RMSE differences in metres (y-axis) at various observation stations (x-axis) throughout the model domain. Stations with RMSE<0.2 m. implies comparable tidal behaviour.

3. DATA ASSIMILATION AND CALIBRATION

Calibration of a complex and generically applicable tidal model such as SRM, even with the advantage of a reasonably accurate coarse grid version can be a time-consuming task. This is due to the need for a large number of model runs and related post-processing tasks. Fortunately, many steps in a calibration process can be largely automated. This reduces the human workload significantly. The efficient and flexible data assimilation tool OpenDA (Open Data Assimilation) is therefore used as a calibration instrument (C-I) to improve the tidal prediction of the SRM. OpenDA's semi-automated parameter estimation method Doesn't Use Derivatives (DUD) can be applied with or without user-defined constraints on parameters for structured variation of the parameters. It evaluates and optimises by minimizing a Goodness-of-Fit (GoF) criterion. The parameter values that correspond to the minimum value of the GoF are considered the optimum parameter values for the given calibration experiment. In the present application of the C-I for tidal calibration of the SRM, the GoF can be represented by:

$$GoF = \frac{1}{2}\sum_{r=1}^{r=R\max}\sum_{s=1}^{s=S\max}\sum_{n=1}^{n=N\max} w_{r,s}\left(H_{r,s,n}^{sim}(t)-H_{r,s,n}^{obs}(t)\right)^2 \Big/ \left(\sigma_{Hobs}\right)^2 \qquad (1)$$

in which H is the water level measured at time t, *sim* refers to results obtained from model simulations, *obs* are observed values, *Nmax* is the number of timesteps in the time series, *Smax* is the number of stations in region *r*, *Rmax* indicates the regions for which observations are included while σ_{Hobs} denotes the uncertainties assigned to the observations (here: tidal prediction values). σ_{Hobs} is set at 0.05m. The weight $w_{r,s}$ is set uniformly equal to 1.

3.1 Calibration Parameters

Tidal amplitudes and phases (H,G) at boundary locations, roughness and depth are likely model parameters for calibration of any tidal model. The focus of the present calibration will be on uniform variation of amplitudes and phases of dominant semi-diurnal constituents M2 and S2 along the Andaman Sea boundary. Region 3 is a region with strong resonance features and was chosen as the region within the model where the depth and roughness will be calibrated. The application of OpenDA is by no means restricted to the set-up of this study. The GoF and list of calibration parameters is easily extended (or reduced).

4. RESULTS AND DISCUSSION

The results of the calibration will be discussed in terms of the improvement in the GoF and the improvement in tidal amplitudes and phases (H, G) in the stations of the selected observer regions and those in the whole model domain. The reason for the two measures will be discussed in Section 4.1. For the analysis of the results of the tidal forcing changes and the depth and bathymetry changes the simulated tidal constants (H,G) at the observation stations were obtained using TRIANA [6]. A practical error measure for tidal constituent k is the summed vector difference (SVD) over selected regions or for the entire model

$$SVD_k = \sum_{r=1}^{r=R\max} \sum_{s=1}^{s=S\max} VD_{k,r,s} \tag{2}$$

where

$$VD_{k,r,s} = \sqrt{\left[\left(H_{c,k} \cos G_{c,k} - H_{o,k} \cos G_{o,k} \right)^2 + \left(H_{c,k} \sin G_{c,k} - H_{o,k} \sin G_{o,k} \right)^2 \right]} \tag{3}$$

and $H_{c,k}$, $H_{o,k}$, $G_{c,k}$, $G_{o,k}$ are the computed and observed astronomical amplitudes and phases of a given tidal constituent k.

For both the SVD and the GoF the percentage of improvement (*%IMP*) was defined as

$$\%IMP = (InitialValue_M - FinalValue_M) / InitialValue_M \times 100\% \tag{4}$$

where M can either be the SVD or the GoF.

4.1 Tidal Boundary Condition Calibration

For the tidal boundary condition calibration six different parameter and observer settings were tested. They are listed in Table 1 as tests 1 to 6. Table 1 also shows the number of jointly varied parameters, the number of iterations required to calculate the optimum parameter settings and the *%IMP* in the GoF. Initially, regions 1 and 2 were selected as observers as they were expected to be the regions most directly affected by the AS boundary. The first test was calibrating the phases of M2 and S2. This results in an improvement of the GoF of 12.09%, in addition this improves the overall model SVD for M2 and S2 by 11% and 2.07%, respectively. The *%IMP* for the GoF and the model SVD for M2 and S2 is higher in test 2 compared to test 1,. This result suggests that compared to phase, the amplitude may be more significant in these observer regions. Tests 3 to 6 combine both the phases and amplitudes of M2 and S2 as parameters to evaluate the effect of the amplitude in conjunction with the phase. Test 3 with regions 1 and 2 as observers for the C-I shows an improvement in the GoF of 36.3%. From Table 2 it is observed that this also results in an improvement of 15.02% in the SVD of the overall model for S2 and 22.1% improvement in the SVD for M2 over the whole domain.

Additional tests were carried out to test the sensitivity of the optimisation result to the choice of observer stations. Test 4 only has region 1 as an observer and shows the improvement of GoF of 33.71%. Although the SVD of S2 in region 1 shows the largest improvement of Gof (42.31%) among the 6 tidal calibration tests, the SVD of S2 shows smallest improvement of GoF (0.46%) in the overall model. Regions 1 and 2 have to be included together as observers as those stations are most indicative for changes in AS tidal forcing. The result also illustrates the need to assess the overall performance of the C-I with a measure that covers the overall model and not just the GoF, which is based only on the observer sets. The other two calibration tests for the boundary calibration explore the sensitivity of the calibration to including the effect of the resonance region either directly (test 5) or indirectly (test 6) as observers. Both tests 5 and 6 show that by including the resonance region there is an improvement to the overall model SVD of M2 (25%) as compared to test 3 (22.1%). However Figure 3 shows that the result of this overall improvement is due to the improvements in the SVD in regions 3 and 4 and not at the regions near the boundary (regions 1, 2) where it was expected that the improvements in SVD would come from. The results of tests 3 to 6 show that tidal constituent M2 is more sensitive to the choice of observer sets than S2. The results from test 1 to 6 indicate that for calibrating the tidal forcing constants (H,G) at the AS boundary, the best feasible solution is test 3 where the phases and amplitudes are varied simultaneously.

Table 1. Summary of OpenDA tests showing parameters that were varied, the observer regions selected, number of parameters *P* and the %IMP in GoF reported by OpenDA.

Test	Parameter *(p)* varied	Observer Regions used	*P*	Iter.	GoF		Remarks
					Initial	*%IMP*	
1	Phase of M2 & S2	1,2	2	5	9.63E+05	12.09	
2	Amp. Of M2 & S2		2	6		29.10	
3	Phase & Amp. Of M2, S2		4	5		36.30	
4	Phase & Amp. Of M2, S2	1	4	5	2.36E+05	33.71	
5	Phase & Amp. Of M2, S2	1,2,3	4	11	1.85E+06	41.26	
6	Phase & Amp. Of M2, S2	1,2,4	4	11	2.34E+06	37.72	
7	Depth in Region 3	3	1	4	5.48E+05	57.50	Starting point was the optimum result in Test 3
8	Friction in Region 3	3	2	18		3.19	
9	Depth, Friction (Region 3)	3	3	17		58.65	

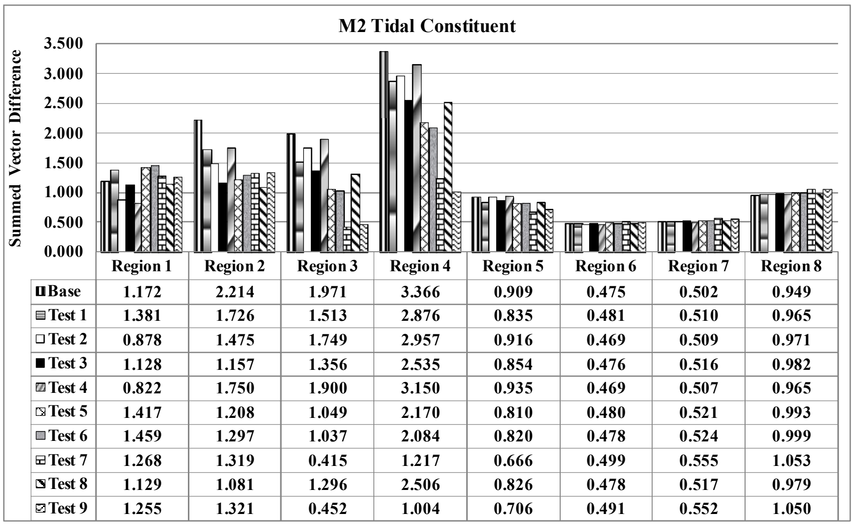
4.2 Bed Friction and Depth

The starting point for the calibration of a uniform multiplicative factor to depth and/or a uniform additive change to bed friction in part of Region 3 is the optimum result from test 3. Table 1 shows that the *%IMP* in GoF is significantly larger when depth is calibrated (test 7, 57.5%) as compared to when just bed friction is calibrated (test 8, 3.19%). This improvement is also reflected in the M2 and S2 components as shown in Table 2 where the overall SVD for the M2 and S2 components each show an improvement of approximately 22-27%. Varying depth and bed friction simultaneously (test 9) results only in a small additional *%IMP* to test 7 in GoF, and in the M2 and S2 components. This result suggests that depth is more important than bed friction in this region.

The importance to the overall model representation by calibrating depth and friction in this region is shown by the 22-24% improvement in the overall model SVD for M2 and 25-27% improvement in the overall model SVD for S2 when compared to test 3. This is illustrated further when it is considered that the 66 – 69% *%IMP* in the observer SVD for M2 and S2 only accounts for approximately 2-10% of the overall model *%IMP* in SVD for M2 and S2. Over 60% of the actual improvement in SVD for the model occurs in regions 2, 4 and 5, most significantly in region 3, see Figure 3

Table 2. %IMP in SVD for M2 and S2 for the overall model and the observer region.

Test	M2				S2			
	Overall Model		Observer only		Overall		Observer only	
	Initial SVD (m)	*%IMP*	Initial SVD (m)	*%IMP*	Initial SVD (m)	*%IMP*	Initial SVD (m)	*%IMP*
1	11.56	11.00	3.39	8.24	5.61	2.07	1.87	0.75
2		14.14		30.51		15.27		26.00
3		22.10		32.52		15.02		27.88
4		9.17	1.17	29.86		0.46	0.81	42.31
5		25.18	5.36	31.42		17.63	2.64	24.71
6		24.74	6.75	28.32		17.85	3.34	22.54
7	9.00	22.35	1.97	69.40	4.77	25.17	0.77	66.35
8		2.13		4.42		2.91		5.66
9		24.13		66.67		26.95		67.61



	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	Region 8
▥ Base	1.172	2.214	1.971	3.366	0.909	0.475	0.502	0.949
▤ Test 1	1.381	1.726	1.513	2.876	0.835	0.481	0.510	0.965
□ Test 2	0.878	1.475	1.749	2.957	0.916	0.469	0.509	0.971
■ Test 3	1.128	1.157	1.356	2.535	0.854	0.476	0.516	0.982
▨ Test 4	0.822	1.750	1.900	3.150	0.935	0.469	0.507	0.965
▩ Test 5	1.417	1.208	1.049	2.170	0.810	0.480	0.521	0.993
▦ Test 6	1.459	1.297	1.037	2.084	0.820	0.478	0.524	0.999
⊞ Test 7	1.268	1.319	0.415	1.217	0.666	0.499	0.555	1.053
◪ Test 8	1.129	1.081	1.296	2.506	0.826	0.478	0.517	0.979
▧ Test 9	1.255	1.321	0.452	1.004	0.706	0.491	0.552	1.050

Figure 3. SVD of M2 tidal constituent in the different model regions for tests 1 to 9.

5. CONCLUSIONS

The results of the OpenDA calibration tests using the coarser grid version of the SRM shows that it is possible to calibrate a complex tidal model efficiently and effectively. This paper also demonstrates that a properly designed coarse grid can be used to replace a finer grid for initial calibration purposes. The results demonstrate the practical benefits of using a tool such as OpenDA for simultaneous parameter variation when it is used in combination with physical insight and understanding of the problem at hand.

The semi-automated DUD procedure embedded in OpenDA is shown to be effective in reducing the repetitive tasks involved in calibrating such a model. For the joint calibration of the tidal constants (H,G) along the boundary, observation stations should be selected for calibration that are most sensitive to such variations (Region 1+2). The results of the depth and bed friction variation in region 3 suggests that substantial improvement can be obtained in regions where accurate bathymetry information is not readily available. Additionally, if the region chosen is an important mixing region for tides with different tidal signals this calibration process can substantially improve the model as a whole.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the support and contributions of the Singapore-Delft Water Alliance (SDWA). The research presented in this work was carried out as part of the SDWA's "Must-Have Box" research program (R-264-001-003-272). They are grateful to Charles Calkoen of BMT Argoss for providing the processed altimeter data for use in this study. They also thank MPA and UHSLC for providing maritime data for analysis.

REFERENCES

[1] Gerritsen, H., Twigt, D., Mynett, A., Calkoen, C., and Babovic, V. (2009). "MHBox- Analysis and prediction of sea level anomalies and associated currents in Singapore and Malacca Straits." *Proc. 8th Int. Conf. on Hydroinformatics, Chile, Jan. 2009, paper 188a163, 10 pages.*

[2] Zijl F. and Kernkamp H.W.J., "Further hydraulic model studies for Pulau Ubin & Pulau Tekong reclamation scheme", *Delft Hydraulics Report Z3437 for Housing and Development Board (HDB)*, (2004).

[3] Ooi, S.K., Zemskyy, P., Sisomphon, P., Gerritsen, H., and Twigt, D.J. (2009). "The effect of grid resolution and weather forcing on hydrodynamic modelling of South East Asian waters", *Proc. XXXIII IAHR Congress, Vancouver, 9-14 August 2009.*

[4] Ooi S.K., Gerritsen, H., Kurniawan, A., and Twigt, D.J., "Parameter optimization and data assimilation to improve the tidal prediction of the Singapore Regional Model" *Proc. 17th IAHR-APD Congress 2010, Auckland, New Zealand,* (2010), Session 5.

[5] Naeije M., Schrama E., Doornbos E., and Scharroo R., "The Role of Rads in Building The 15-Year Altimeter Record", ESA Workshop, Venice, Italy, (2006), 6 pages. *(http://earth.esa.int/workshops/venice06/participants/669/paper_669_naeije.pdf)*

[6] Deltares, (2006). Delft3D-TRIANA, "Tidal analysis of FLOW time-series and comparison with observed constants", User Manual, Deltares, the Netherlands.