Ceaseless Tidal Zoning for Straits of Malacca using Spatial Interpolation

by:
M.D.E.K. Gunathilaka
Mohd Razali Mahmud

ADVANCED HYDROGRAPHY AND OCEANOGRAPHY RESEARCH UNIT PLS
FACULTY OF GEOINFORMATION AND REAL ESTATE
UNIVERSITI TEKNOLOGI MALAYSIA
81310 UTM JOHOR BAHRU

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OUTLINE

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- Conclusions

INTRODUCTION

- Raw sounding data need various corrections before final charting. Most obvious effect is the tides - a periodic fluctuation of the instantaneous water level; mainly generated due to the gravitational influence of the Moon-Sun system and the rotation of the earth.

- Tides are influenced by: gravity, meteorological and oceanography factors

- Due to Increased maritime activities, and better understanding of marine environment;
- Accurate measurements and prediction of tides are important.

CO-TIDAL CHARTS

- Co-tidal chart is a common product that shows different variations in heights of tides, particularly with reference to periods of either high or low tides;
- Conventionally determined by tide gauge data; It provide tidal prediction data offshore.
- The computations involved are more suitable for offshore tidal information than near-shore.
- The coverage of co-tidal charts is very few; due to insufficient data coverage.
- Offshore tide gauges are difficult and expensive to be established and maintained. Because of that, the results from the conventional co-tidal charts could not be use for accurate offshore applications.
- To fill up these gaps for offshore tides, some researches used the tides derived from satellite altimetry mission data to improve the accuracy of the existing co-tidal charts.

TIDAL ZONING

- Another problem: how to relate the tides to the standard datum in large areas.
- Discrete tidal zoning technique is developed to address this issue.
  - The water level in a particular zone is assumed to be having a constant magnitude and phase relationship to a measured nearby tide gauge, hence the datum separation is also spatially interpolated as well as the tidal constituents.
- However this is also not free of defects. Thus, the greatest problem of all, arises when there are crossings around the border / edges of the areas of interest, i.e. from one zone to the other.
  - There is always a discontinuity between the zones.

Spatial Interpolation by Numerical Solution of Laplace's Equation

- Here, the tidal field is modelled as a two-dimensional (2D) vector field *T(x,y)*, [Eq. 1] and expected to behave as 2D Laplace's Equation (LE). In 2D, the solution between three data points is considered as a flat plane and this is the simplest way of interpolation between the points.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \qquad \textbf{[Eq. 1]}$$

- Function *T* is equal to the values where data is available [Eq. 2]. This is where the tidal stations are located and T_i's are the tidal values.

$$\mathrm{T}(\mathrm{x_i}, \mathrm{y_i}) = \mathrm{T_i} \qquad \textbf{[Eq. 2]}$$

Spatial Interpolation by Numerical Solution of Laplace's Equation (cont…)

- Numerical solution of LE can be determined on a square gridded mesh.
- The coastline and the location of each observation station must be defined.
- Once the gridding is done, the coastline boundary has to be determined by considering cells that contains the coastline.
- Then, all the cells that fall within the water areas are tagged as 'water cells', otherwise, they are land cells.
- The cell size should be appropriate so that it can still retain the important features like narrow straights, etc .

Spatial Interpolation by Numerical Solution of Laplace's Equation (cont…)

Boundary Conditions

- At each known tide gauge stations, the boundary conditions are given by the Eq. 3.

$$\frac{\partial T}{\partial \eta} = 0 \qquad \text{[Eq. 3]}$$

- For open water, boundary condition for *T* is a zero slope in normal direction (η), where, η is in normal direction to the boundary.
- Another boundary condition is based on the concept that the variation of the tide (*T*) near the shoreline is determined by the variation of the water level at a small distance away from the shore. Here, the slope boundary is set to be proportional to the mean of the interior slope [Eq. 4].

$$\frac{\partial T}{\partial \eta} = a\overline{\frac{\partial T}{\partial \eta}} \qquad \text{[Eq. 4]}$$

Spatial Interpolation by Numerical Solution of Laplace's Equation (cont…)

Boundary Conditions

- In the Eq. 4, spatial average of the derivatives over the few cells is represented by the over-bar component and the proportionality constant '***a***' is selected between zero and one.
- It is difficult to fix a value for ***a*** that describes the natural distribution of the field.
- This can be achieved by trial and error; area by area approach.

Spatial Interpolation by Numerical Solution of Laplace's Equation (cont…)

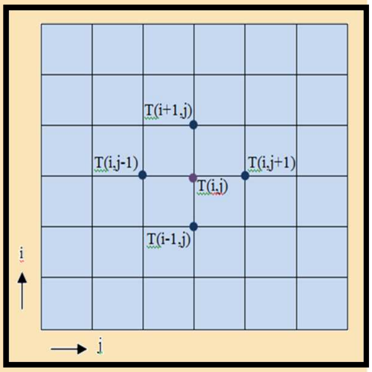
Finite Differences for LE

- The finite solution of *T* at each location *i, j* for iteration *k* is as follows,

$$T_{i+1,j}^{k} + T_{i-1,j}^{k} + T_{i,j+1}^{k} + T_{i,j-1}^{k} - 4T_{i,j}^{k} = 0 \qquad \textbf{[Eq. 5]}$$

- An estimated intermediate value is obtained by solving the following equation

$$T_{i,j}^{*} = \frac{1}{4}\left[T_{i+1,j}^{k} + T_{i-1,j}^{k} + T_{i,j+1}^{k} + T_{i,j-1}^{k}\right] \quad \textbf{[Eq. 6]}$$



- The array TN is iterated until the absolute error

$e = 5 \times 10^{-5}$

$$\max \left| T_{i,j}^{k+1} - T_{i,j}^{k} \right| \leq e \qquad \textbf{[Eq. 7]}$$

Spatial Interpolation by Numerical Solution of Laplace's Equation (cont…)

Finite Differences for LE

- Usually, the iterative computation processes take long time to converge. Therefore, successive relaxation (SR) technique was used to accelerate the convergence [Eq. 8].

$$T_{i,j}^{k+1} = \mathrm{r}T_{i,j}^{*} + (1-r)T_{i,j}^{k} \qquad \textbf{[Eq. 8]}$$

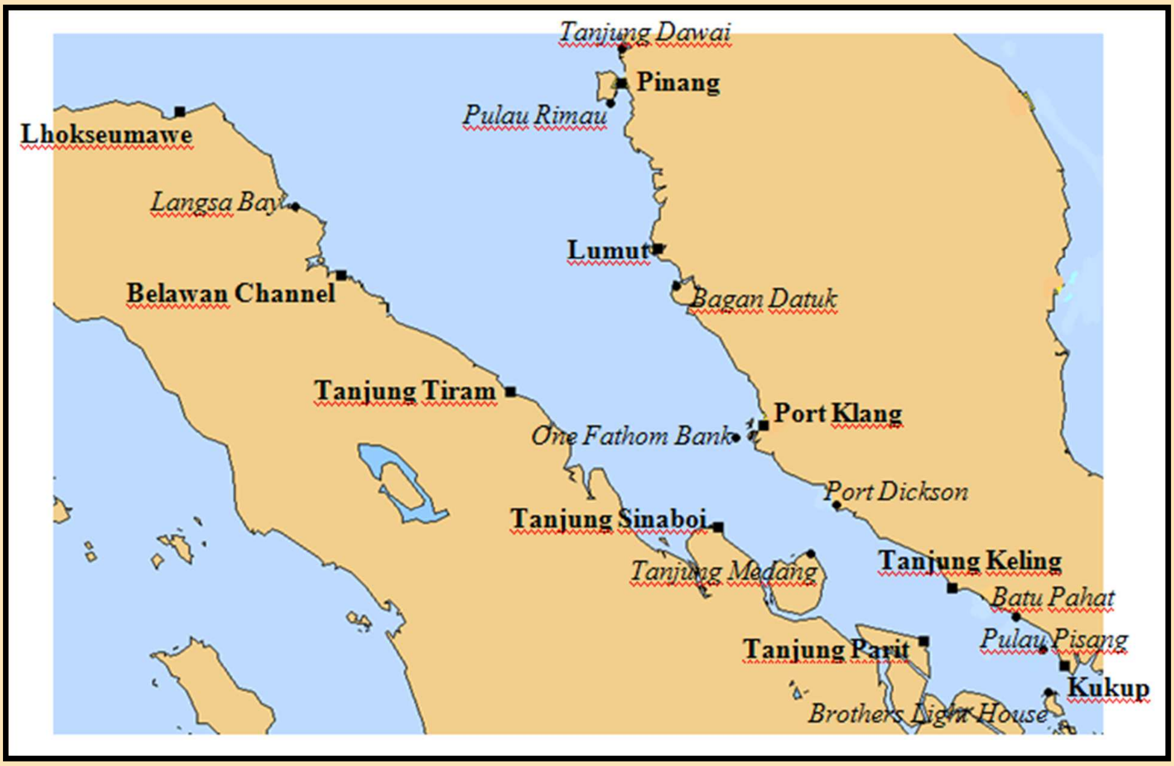
In SR, intermediate solution $T^{k+1}_{i,j}$ is a weighted combination of the intermediate iteration $T^{*}_{i,j}$ and the previous value $T^{k}_{i,j}$, where ***'r'*** is chosen between 1 and 2 after doing simulations.

Aim

- Since the greatest defect in tidal zoning is the discontinuity of the computed tides between the zones.
- Therefore, the aim of this study is to develop an application that can provide smooth continuous tidal predictions throughout the entire region, termed as 'Ceaseless Tidal Zoning' (CTZ) technique.

DEVELOPMENT OF CTZ

- Grid 0.1^0 of the area was created using a digital chart as the base map. The cells were separated into land, water and coastline boundary cells.
- The coastline boundary cells were separated using boundary conditions. Total of 53x74 gridded mesh was generated to cover the Straits of Malacca region.
- Some 20 tidal stations (historical & currently running) were used – (**Pulau Pinang, Lumut, Port Klang, Tanjung Keling, Kukup, Lhokseumawe, Belawan Channel, Tanjung Tiram, Tanjung Sinaboi and Tanjung Parit**).
- The data was obtained with the collaboration of Department of Survey and Mapping Malaysia (JUPEM), Royal Malaysian Navy (RMN) and the National Coordinating Agency for Surveys and Mapping Indonesia (Bakosurtanal).
- Also, check stations chosen for validation of the near shore results (Tanjung Dawai, Pulau Rimau, Bagan Datuk, One Fathom Bank, Port Dickson, Batu Pahat, Pulau Pisang, Brothers Light House, Tanjung Medang and Langsa Bay).



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DEVELOPMENT OF CTZ (cont…)

Computation of Satellite Altimetric SSH with Tidal Signature

- The satellite altimetric data was derived for the Malacca Straits region between 1° N ≤ Latitude ≥ 6° N and 96° E ≤ Longitude ≥ 104° E covering the Malacca Straits region frofrom the Jason-2 satellite for the year 2009.
- The sea surface height (SSH) data have been corrected for: orbital altitude and altimeter range correction for instrument, sea state bias, ionospheric delay, dry and wet tropospheric corrections, electromagnetic bias and inverse barometer corrections by applying specific models in RADS.
- However, in this study, the tidal signature is preserved in the altimetric data by not selecting any models for ocean and tide load.
- A single value for SSH is estimated at each cell area for the final comparison with the modelled tide by exporting all the SSH to a similar type of cell layer structure and is generated by using Sounding Grid Utility (SGU) tool in QINSy software.

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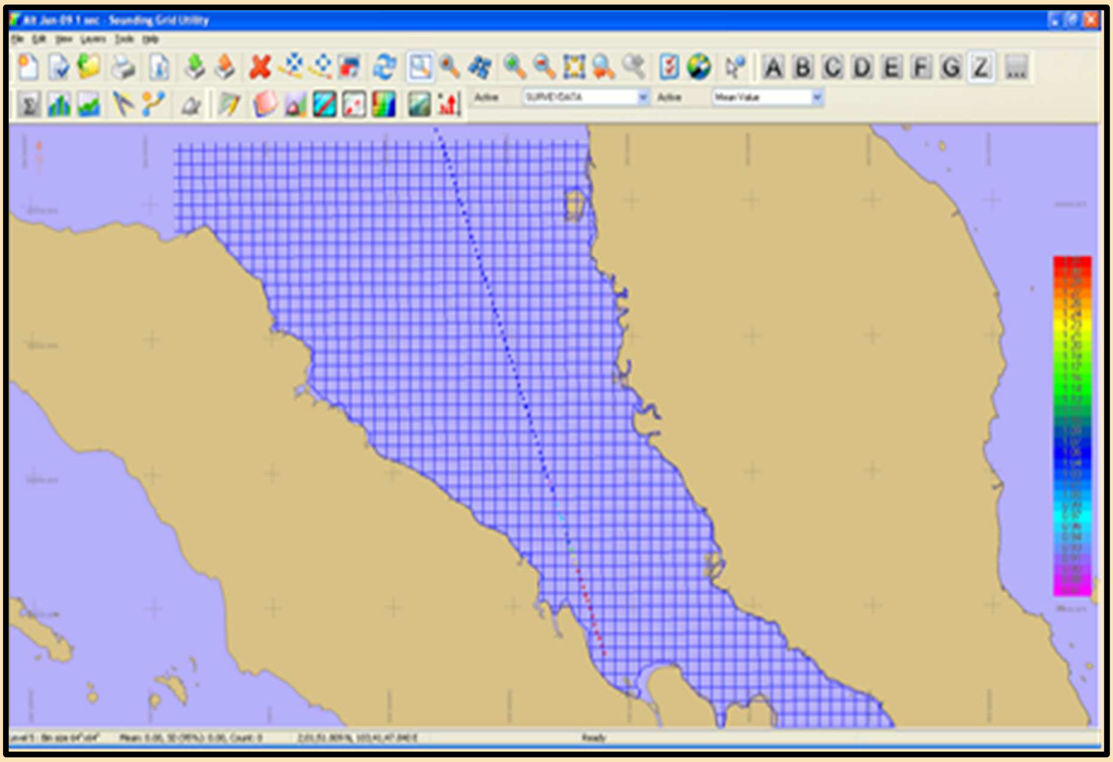

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EVALUATION OF THE CTZ

Boundary Condition Test

- As the value of ‘***a***’ gradually increased, the LAT datum difference between the published (known) and the computed with spatial interpolation is decreasing and after passing the value of 0.9, the difference is increasing again.
- Therefore value 0.9 is chosen for boundary condition factor (***a***) for coastline, as it gave the least datum differences at the check station.
- Similarly, at the simulated test basins, the contours became straightened, evenly distributed and do not make packing of contours near the stations as the value ***a*** reaches 0.9. This is similar to the realistic tidal hydrodynamic.

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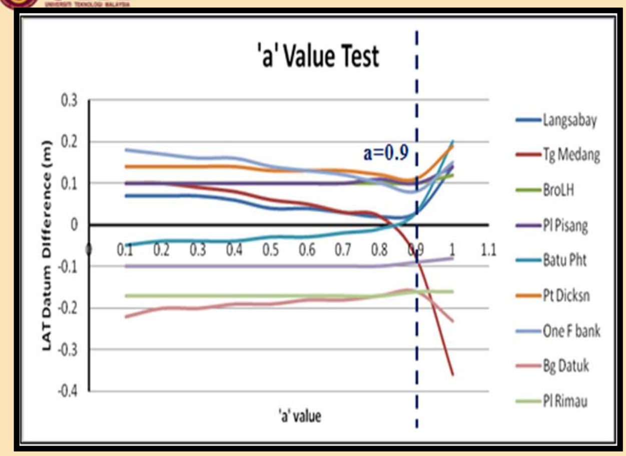
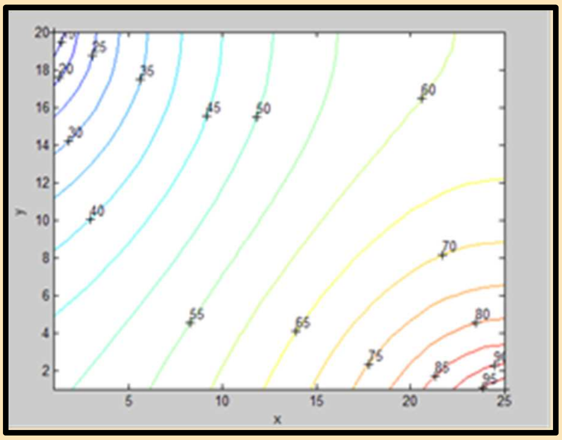
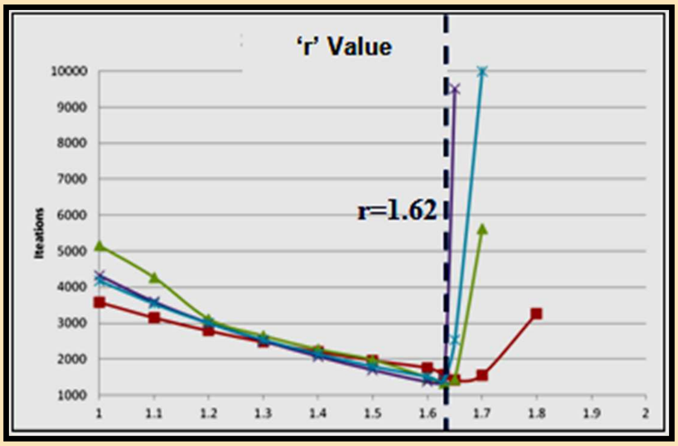




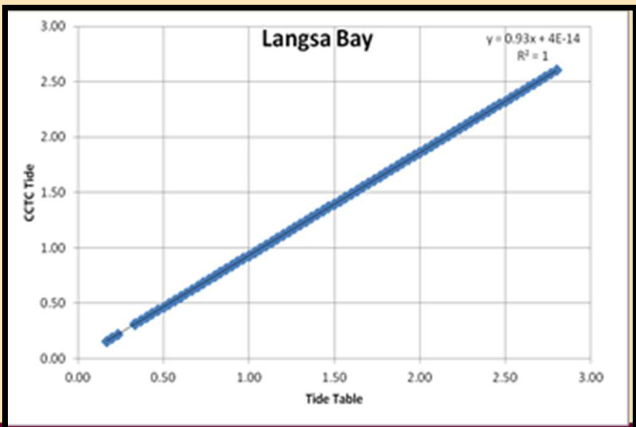
EVALUATION OF THE CTZ (cont…)

- During the relaxation parameter (***r***) test case, it was noted that the overall contour pattern is not effected by the relaxation parameter.
- However, the total number of iterations rapidly decreased with the increasing ***r*** and again begins to jump up after passing the value around 1.6. Hence, 1.62 is chosen as the optimal value for ***r***.



EVALUATION OF THE CTZ (cont…)

- The hourly CTZ results at the check stations were compared with the corresponding values from the tide tables for the month of January 2009.
- Then, to quantify the results, correlation coefficient and standard deviations were computed for each tidal station. All the standard deviations are around 0.1m and the correlation coefficients (R^2) equal one at all the stations.

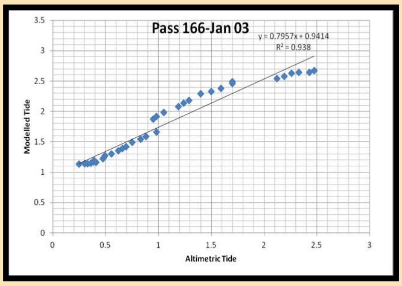


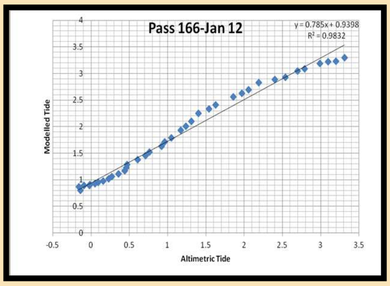
CTZ vs. Tide Table

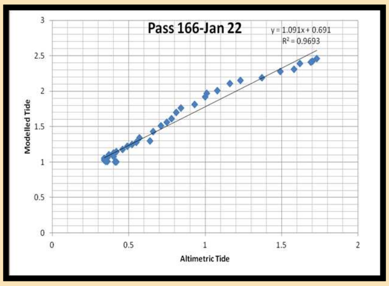
Station	Correlation (R^2)	Std (m)
Lhokseumawe	1	0.15
Langsa Bay	1	0.10
Pulau Rimau	1	0.09
Tanjung Dawai	1	0.09
Lumut	1	0.14
Bagan Datuk	1	0.13
One Fathom Bank	1	0.10
Belawan Channel	1	0.14
Tanjung Tiram	1	0.15
Tanjung Senaboi	1	0.13
Tanjung Medang	1	0.12
Tanjung Parit	1	0.13
Port Dickson	1	0.16
Brothers Light house	1	0.09
Batu Pahat	1	0.15
Pulau Pisang	1	0.10

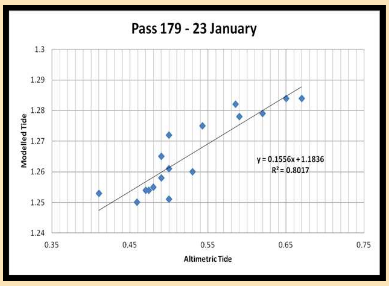
EVALUATION OF THE CTZ (cont…)

- To examine the accuracy of the CTZ at the offshore, a correlation test was carried out along the Jason-2 altimetric measurement tracks at the Straits of Malacca. The data sets are highly correlated as the correlation coefficients were over 0.8.



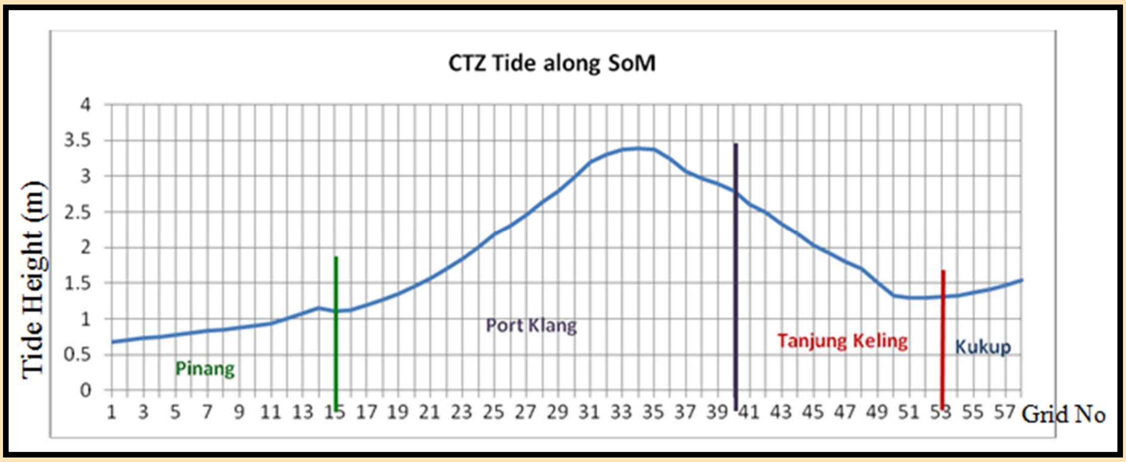






EVALUATION OF THE CTZ (cont…)

- Finally, a tidal profile was generated using the CTZ across the entire Straits. The limits of the four tidal zones are also marked along with the tidal profile. The shifts of the values are minimum and provide smooth results across the region.



CONCLUSIONS

- Ceaseless Tidal Zoning (CTZ) concept was developed by combining the conventional co-tidal charts and tidal zoning.
- Co-tidal chart is disadvantageous for complex tidal regimes where the tidal pattern is irregular.
- Nevertheless, the tidal zoning can successfully address these complexities in tides, but there is always discontinuity when crossings from one zone to the other.
- The CTZ has the advantage of addressing both issues effectively because it is a cell-based approach than area-based.
- The CTZ results showed 1 to 1 correlation (R^2=1) with the predicted tide at all the tidal stations and the standard deviations were around 0.1m at most of these stations.

CONCLUSIONS (cont…)

- In offshore areas, the comparison with the altimetry data showed over 0.8 correlation along the satellite path.
- Finally, this approach provides spatially smooth results in the entire region.
- The greatest challenge was to find the boundary condition factor at the coastline such that to regenerate the natural tidal interaction at the coast.
- In addition, successive relaxation technique was applied to ccelerate the convergence process.
- The most appropriate value for the coastline boundary was was determined to be 0.9; while, he optimum relaxation coefficient obtained was 1.62 during the simulation and sample data processing.

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Thank You…

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Terima Kasih…

REFERENCES

- Ardalan, A. A., and Farahani, H. H. (2007). *A harmonic approach to global ocean tide analysis based on TOPEX/Poseidon satellite*. Journal of Marine Geophysical Researches, Springer Netherlands. Vol 28, pp235-255, September 2007.
- Benada, J. R. (1997. *TOPEX/Poseidon MGDR Generation B User's handbook (D-11007)*. Version 2, Jet Propulsion Laboratory, July 1997.
- David, P. (1980). *Co-Tidal Charts for the Southern North Sea*. Journal of Ocean Dynamics, SpringerLink, Vol 33, Issue 2, pp.68-81, March 1980.
- Forrester, W. D. (1983). *Canadian Tidal Manual*. Department of Fisheries and Oceans, Ottawa Canada, 1983.
- Fu L.L. and Cazenave A., (2001). *Satellite altimetry and Earth Sciences: A Handbook of Techniques and Applications*, International Geophysics Series, Vol 69, Academic Press, San diago, California. 463
- Hess, K. W. (2002). *Spatial interpolation of tidal data in irregularly-shaped coastal regions by numerical solution of Laplace's equation*. Estuarine, Coastal and Shelf Science, Vol 54, Issue 2, 175-192.
- Hess, K. W. and Gill, S. K. (2003). Puget Sound Tidal Datums by Spatial Interpolation. Proceedings, *5th Conference on Coastal Atmospheric and Ocean Prediction and Process.* American Metrological Society, Seattle. August 6-8, 2003.
- Hess, K. W., Schmalz, R., Zervas, C. and Collier, W. (2004). *Tidal Constituent and Residual Interpolation (TCARI): A new method for the tidal correction of bathymetric data*. NOAA Technical Report - NOS CS 4, USA. June 2004.
- Hicks, S. D. (2006). *Understanding Tides*. U.S. Department of Commerce, NOAA, National Ocean Service. December 2006.

REFERENCES cont…

- Ingham, A. E. and Abbott, V. J. (1993). *Hydrography for the Surveyor and Engineer*. 3rd Sub Edn, Wiley and Back-well. January 1993.
- Pawlowski, R., Brooks, P. D. and Oswald, J. L. (2002). Emerging Survey Technologies for Alaska's Coastal Zone. *Proceedings, 11th Conference of American Society of Civil Engineers,* 2002.
- Pugh, D. T. (1996). *Tides, Surges and Mean Sea level*. John Wiley and Son Ltd, New York, USA 1996.
- Scharroo, R., (2011). *RADS User Manual and Format Specification*, Delft Institute of Earth-Oriented Space Research and NOAA, Version 3.1. 10th December 2011.
- Smith, A. J. E., Ambrosious, B. A. C. and Wakker, K. F. (2000). *Ocean tides from T/P, ERS-1 and GEOSAT altimetry*. Journal of Geodesy, Springer Berlin, Vol 74, 399-413, 2000.
- Tronvig, K. A. and Gill, S. K. (2001). Complexities of Tidal Zoning for Key West, FL. *Proceedings: U.S. Hydrographic Conference,* The Hydrographic Society of America, Norfolk, VA. 2001.
- UKHO (1969). *Admiralty Manual of Hydrographic Surveying Vol-2*. The Hydrographer of the navy, Taunton, Somerset. 1969.
- Vella, P. J. N. M. and Ses, S. (2001). Preliminary Ocean tide model inferred by satellite altimetry for a test section of the ASEAN region. *Proceedings: 22nd Asian Conference on Remote Sensing,* Singapore, 5-9 November 2001.
- Yanagi, T., Morimoto, A. and Ichikawa, K. (1997). *Co-tidal and Co-range Charts for the East China Sea and the Yellow Sea Derived from Satellite Altimetric Data*. Journal of Oceanography, Vol 53, 303-309, Springer 1997.
- Pawlowski, R., Brooks, P. D. and Oswald, J. L. (2002). *Emerging Survey Technologies for Alaska's Coastal Zone*. Proceedings, 11th Conference of American Society of Civil Engineers, 2002.

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