Ceaseless Tidal Zoning for Straits of Malacca using Spatial Interpolation

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Key words: Tidal Modelling, Ceaseless Tidal Zoning, Spatial Interpolation, Hydrography, Offshore Navigation

ABSTRACT

Strait of Malacca is a tidally complex area with different tidal range patterns and range values. Therefore, standard co-tidal charts are inappropriate in this region. However tidal zoning can handle such complexities; but create discontinuity between the adjacent zones. Therefore, a different approach is needed such that to handle tidally complex areas effectively and providing continuous results. A new concept termed as Ceaseless Tidal Zoning was developed by adopting the tidal zoning and conventional co-tidal charts. Here, the tidal amplitude and phase fields are assumed to be obeying the two-dimensional (2D) Laplace's Equation (LE) and the interpolation is computed by numerically solving the LE on a gridded mesh. First the appropriate boundary condition coefficients were tested and determined by using simulated test basins. In addition, for realistic scenario, data from ten tidal stations were selected as the known stations and another ten stations were selected as the check stations such that to cover both sides of the Straits of Malacca. Best solution was obtained with the boundary condition factor $\boldsymbol{a}$ = 0.9 for the coastline and the optimum convergence was achieved with the relaxation coefficient $\boldsymbol{r}$ =1.62. A Matlab based computer application was developed to provide continuous tidal corrections for onboard bathymetric reduction based on the developed Ceaseless Tidal Zoning (CTZ) technique. The statistical results showed a 100% correlation with the check stations and also a very good correlation over 0.8 in offshore areas with the altimetric sea surface heights. Finally a tidal profile across the Malacca Strait was obtained with the developed CTZ application and analysed for the discontinuity between the zones. It is shown that this approach has minimized the discontinuity of the tidal values in crossing the zones.

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1. INTRODUCTION

Dynamic nature of the water and air surface adds a great uncertainty to the measurements in hydrography (Ingham & Abbott, 1993). The total water depth measured at a point during the survey is termed as raw sounding. But these raw soundings must be corrected for various effects before utilizing in the final charting. The most obvious effect is the periodic fluctuation of the instantaneous water level with respect to a standard reference level or datum, termed as tides. Tide is mainly generated due to the gravitational influence of the Moon-Sun system. In addition, the value of the actual tide in a location is modified due to the factors like water depth, bottom friction and basin oscillation, etc (Forrester, 1983; Pugh, 1996). The metrological effects and oceanographic effects like water mixing, currents, etc are also effect (Hicks, 2006). This makes the tide, a highly complicated phenomenon. Ever since humans began dealing with the ocean, this was always has being a challenge and drowns their attention. Today, with the increased maritime activities the demand for better understanding, accurate measurements and prediction of tide is on high demand than ever before.

2. BACKGROUND

Over the years, various applications have developed to obtain tides at the unknown locations. Co-tidal chart is one of the common products that provide tidal predictions to be computed in offshore (UKHO, 1969; David, 1980; Forrester, 1983). They are more suitable for offshore tidal computation than near-shore. The coverage of co-tidal charts is very few as no enough data available. It is difficult and expensive to establish and maintain tide gauges in offshore. Because of that, the results from the conventional co-tidal charts could not use for accurate applications. To fill up these gaps in offshore tides, some researches used the tides derived from the satellite altimetric mission data (Yanagi *et al*, 1997; Smith *et al*, 2000; Vella and Ses, 2001; Ardalan and Farahani, 2007). But the data is sparse and the number of tidal constituents can resolve is few due to the long repetition cycle (eg. 9.9 days in Jason 2). However, the instantaneous accuracy of the altimetry is within 3 to 4cm (Benada, 1997) and this has improved the accuracy of the existing co-tidal charts.

2.1 Tidal Zoning

Another problem in a large area tidal prediction is how to relate the tides to the standard datum. Discrete tidal zoning technique is developed to address this issue (Pawlowski *et al*, 2002). In this case, it is assumed that the water level in a particular zone having a constant magnitude and phase relationship to a measured nearby tide gauge (standard port), hence the datum separation is also spatially interpolated as well as the tidal constituents (Hess and Gill, 2003). However this is also not free of defects. The other greatest problem comes once you are crossing the border, from one zone to the other (Tronvig and Gill, 2001). There is always a discontinuity between zones.

2.2 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)* and expected to behave as 2D Laplace's Equation (LE). In 2D LE, the solution between three data points is considered as a flat plane and this is the simplest way to interpolate between the points. Function T is equal to the values where data is available (equation 02). This is where the tidal stations are located and T_i's are the tidal values.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0 \qquad 01$$

$$\mathrm{T}(\mathrm{x}_i, \mathrm{y}_i) = \mathrm{T}_i \qquad 02$$

The numerical solution of LE can be determined on a square gridded mesh defined by lattices or distance. The coastline and the location of each observation station must be defined. Once the gridding has being done, the coastline boundary has to be determined by considering cells that contains the coastline. Then, all the water cells were tagged as water cells. The remaining cells are land cells. The most important thing in gridding is the cell size should be appropriate so that it can still retain the important features like narrow straights, etc (Hess & Gill, 2003 & Hess *et al*, 2004).

2.2.1 Boundary Conditions

The boundary conditions are needed for *T* (Tidal) function at each tide gauge stations as well as coastline and open water boundaries. At each tide gauge stations where the observations available, the boundary conditions are given by the corresponding equation 03. The open water boundary condition for *T* has a zero slope in normal direction (η), where, η is the direction normal to the boundary.

$$\frac{\partial T}{\partial \eta} = 0 \qquad 03$$

However at the coastline boundary, the above boundary condition is irrelevant. Especially near the corners, it courses the packing of the contours around the data point. Therefore another boundary condition was developed by Hess *et al* (2004). This was based on the concept that the variation of the tide (*T)* near shore is determined by the variation of the water level at a small distance away from the shore. Here, the boundary slope is set to be proportional to the mean interior slope (equation 04). The 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 one value for ***a*** which will describe the natural distribution of the field. It has to be settled with trial and error, area by area approach.

$$\frac{\partial T}{\partial \eta} = a\overline{\frac{\partial T}{\partial \eta}} \qquad 04$$

2.2.2 Finite Differences for LE

The solution for LE is found for *T* on each grid corner iteratively. Finite solution at i , j for iteration k can be expressed as follows;

$$T^k_{i+1,j} + T^k_{i-1,j} + T^k_{i,j+1} + T^k_{i,j-1} - 4T^k_{i,j} = 0 \qquad 05$$

Then, an estimated value $T^*_{i,j}$ can be obtained by solving the equation 05 as follows;

$$T^{*}_{i,j} = \frac{1}{4}\left[T^{k}_{i+1,j} + T^{k}_{i-1,j} + T^{k}_{i,j+1} + T^{k}_{i,j-1}\right] \qquad 06$$

This T^{*} is an intermediated solution. In this way, the large numbers of equations are solved simultaneously. Since, there are many equations to be solved with lesser number of knowns; an iterative solution approach was used. The greatest advantage of this approach is, there is no need of large matrices for storing intermediate computations. In this process, the relative error is computed at each iteration and checked against a user defined tolerance (e). The array T is iterated until the following convergence criterion is met in accordance with the equation 07. Hess (2002) has obtained good results for $e = 5\times10^{-5}$. This final numerical solution and convergence are sensitive to the boundary conditions (Hess & Gill, 2003).

$$\max\left|T^{k+1}_{i,j} - T^{k}_{i,j}\right| \leq e \qquad 07$$

Usually, the iterative computation processes take long time to converge. Therefore, successive relaxation (SR) technique was used to accelerate the convergence (equation 08). 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 simulation with test basins by comparing the number of iterations taken with different values of ***r***.

$$T^{k+1}_{i,j} = \mathrm{r}T^{*}_{i,j} + (1-r)T^{k}_{i,j} \qquad 08$$

2.3 Satellite Altimetric Sea Surface Heights

Satellite altimeter is a space observing technique to measure the height between the satellite and the earth or sea surface. It is achieved via two-way travel time of a radar wave transmitted from the altimeter antenna and the reflected by the surface. These data being used in geodesy and geophysics in determination of the Earth's size and shape, Earth's gravity field analysis, bathymetric studies, tectonic plate movements, etc (Fu and Cazenave, 2001). One of the main application of the altimetry is the oceanography. Ocean surface effects like tides, currents, ocean circulation, sea level rise, etc were studied and modelled over the years.

The exact position of the altimeter is measured or monitored relative to the references ellipsoid (WGS84). In addition to that, any interference that occurred during the signal path must be known and corrected. Water vapour, ionized particles in the atmosphere and sea state are some of the main factors that effect the signal interference. Nevertheless, most of the influences can be corrected during the data processing. Hence, altimetric data processing requires a lot of information before being able to use the data for applications (Scharroo 2011; Fu and Cazenave, 2001).

3. AIM

The greatest defect in tidal zoning is the discontinuity of the computed tides between the zones (Tronvig and Gill, 2001). Therefore the aim of this paper was to develop an application to provide ceaseless tidal zoning (CTZ) technique that can provide smooth continuous tidal predictions throughout the entire region.

4. CEASELESS TIDAL ZONING (CTZ)

4.1 Spatial Interpolation

The boundary condition factor '***a***' and relaxation coefficient '***r***' must be settled in order to solve the LE appropriately. First of all, ***a*** value was determined by simulating different test basins with different boundary configurations by adopting different values for ***a***. It was slowly increased in 0.1 steps between 0 and 1 and the resulted field contours were examined and the corresponding ***a*** value was chosen accordingly. The first block was a simple 20x25 grid with two known stations at the diagonal having values 20 and 100 at the top left and bottom right corners. This same block was simulated for different boundary configurations. Next block was also a square shaped block with a larger grid (30x40) having three known stations. The third block is a 'L' shaped 30x40 grid which is also having the same station configurations. Final block was also a 30x40 grid having an irregular land grid with same three stations. This was designed to simulate the irregular coastal features as it is in the real coastal region. Then, a real data test was carried out for Straits of Malacca using the Lowest Astronomical Tide (LAT) datum levels to validate the results by comparing the computed vs. known datum levels at the check tide gauge stations.

The relaxation coefficient ***r*** decides the number of iterations taken to converge the final results. The convergence factor (***e***) 10^{-5} was used in all the cases. The ***r*** value was slowly increased by 0.1 steps between 1 and 2 for each test block as in the above and the total number of iterations was compared in each configuration. Finally, a value was chosen corresponding to the least number of iterations for the ***r***.

4.2 CTZ development

Numerical girding of the area was created using a digital chart as the base map. Cell size of 0.1^0 was chosen in order to retain the original coastal features in the area. Thereafter, all the cells were separated in to land, water and coastline boundary cells. Then, all the land cells were given null values in order to reject them from further computation since tide is irrelevant on land. The coastline boundary cells were separately used in application of the appropriate boundary conditions. Total of 53x74 gridded mesh was generated to cover the Straits of Malacca region. All together 20 tidal stations (historical & currently running) were chosen along the both edges of the strait. The data was obtained with the collaboration of Department of Surveying and Mapping Malaysia (JUPEM), Royal Malaysian Navy (RMN) and the National Coordinating Agency for Surveys and Mapping Indonesia (Bakosurtanal) for the year 2009. Pinang, Lumut, Port Klang, Tanjung Keling, Kukup, Lhokseumawe, Belawan Channel, Tanjung Tiram, Tanjung Sinaboi and Tanjung Parit were used as known stations. Tanjung Dawai, Pulau Rimau, Bagan Datuk, One Fathom Bank, Port Dickson, Batu Pahat, Pulau Pisang, Brothers Light House, Tanjung Medang and Langsa Bay were chosen as the check stations (Figure 01) to validate the near shore results.

Figure 01 Selected Tidal Stations at the Strait of Malacca (Known stations shown by a black square and check stations by black dot)

4.3 Computation of Satellite Altimetric SSH with Tidal Signature

The satellite altimetric data was derived for the range of between 1° N ≤ Latitude ≥ 6°N and 96° E ≤ Longitude ≥ 104°E covering the Malacca Straits region from the Jason-2 satellite for the year 2009. The sea surface height (SSH) data have been corrected for orbital altitude, altimeter range corrected for instrument, sea state bias, ionospheric delay, dry and wet tropospheric corrections, electromagnetic bias and inverse barometer corrections. These corrections were done by applying specific models for each correction in RADS. However, in this study, the tidal signiture must be preserved in the altimetric data in order to compare with the computed tidal values from the modelling in offshore areas. Therefore, the altimetric data was processed with out selecting any models for ocean and load tide.

When the altimetric satellite passes over the track, a series of SSH measurements are taken in a single footprint. However, a single value is needed in the final comparison with the modelled tide, corresponding to the cell size in the tidal modelling application. Because of that, a similar type of cell layer structure was generated using Sounding Grid Utility (SGU) tool in QINSy hydrographic software.

5. EVALUATION OF THE CTZ

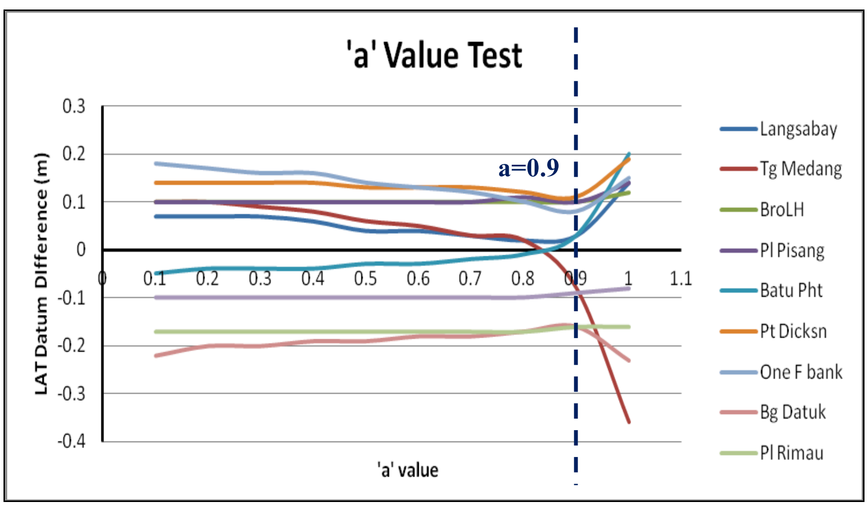

Figure 02. ‘***a***’ value test results

As the '***a***' value gradually increased, the LAT datum difference between the published (known) and the computed with spatial interpolation is decreasing and after passing the value 0.9, the difference is increasing again (Figure 02). Therefore value 0.9 is chosen for boundary condition factor (***a***) for coastline, as it gave the least datum differences at the check station. In addition to that, this value has given the least number of iterations as well. Where as in the simulated test basins, contours became straighter evenly distributed and do not make packing of contours near the stations as the value ***a*** reaches 0.9 (Figure 03). This is similar to the realistic tidal hydrodynamic. Therefore, value 0.9 is chosen as the most realistic value for all the coastal boundaries.

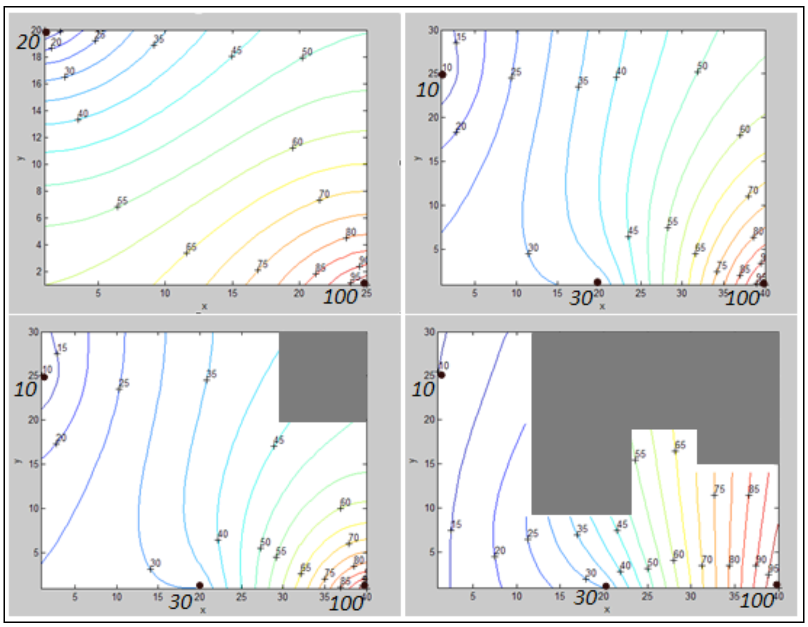

Figure 03 Simulation results with different test blocks having '***a***'=0.9

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 (Figure 04). Hence, 1.62 is chosen as the optimal value for ***r***.

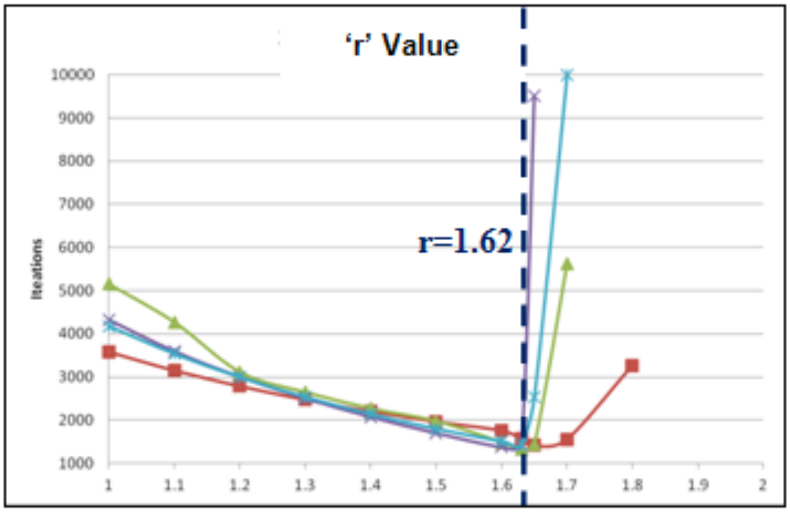

Figure 04 '*r*' value test results

The hourly CTZ results at the check stations were compared against the corresponding values from the tide tables for the month of January 2009. Then, to quantify the results, correlation coefficient and standard deviations were compared at each tidal station (Table 01). All the standard deviations were around 0.1m and the correlation coefficients (R^2) were one (Table 01) at all the stations. An example correlation graph for the station Langsabay is shown in Figure 05.

Table 01: 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

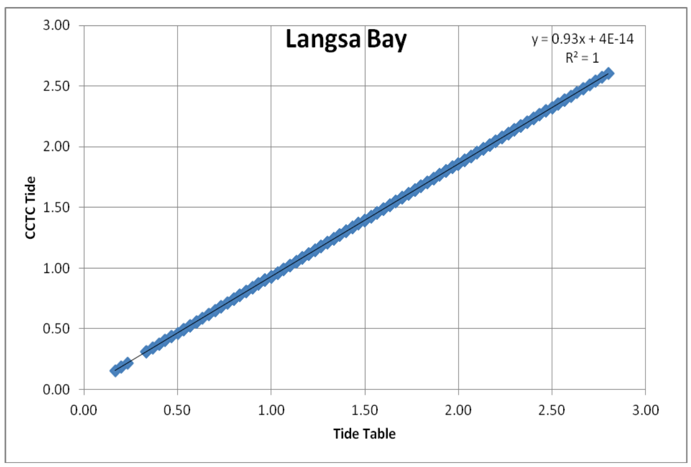

Figure 05 Corelation between CTZ vs. Tidal Table data – Langsabay

To examine the accuracy of the CTZ in the offshore, a correlation test was carried out along the Jason-2 altimetric measurement tracks for the month of January 2009 at the Straits of Malacca (Figures 06). The data sets are highly correlated as the correlation coefficients are over 0.8.

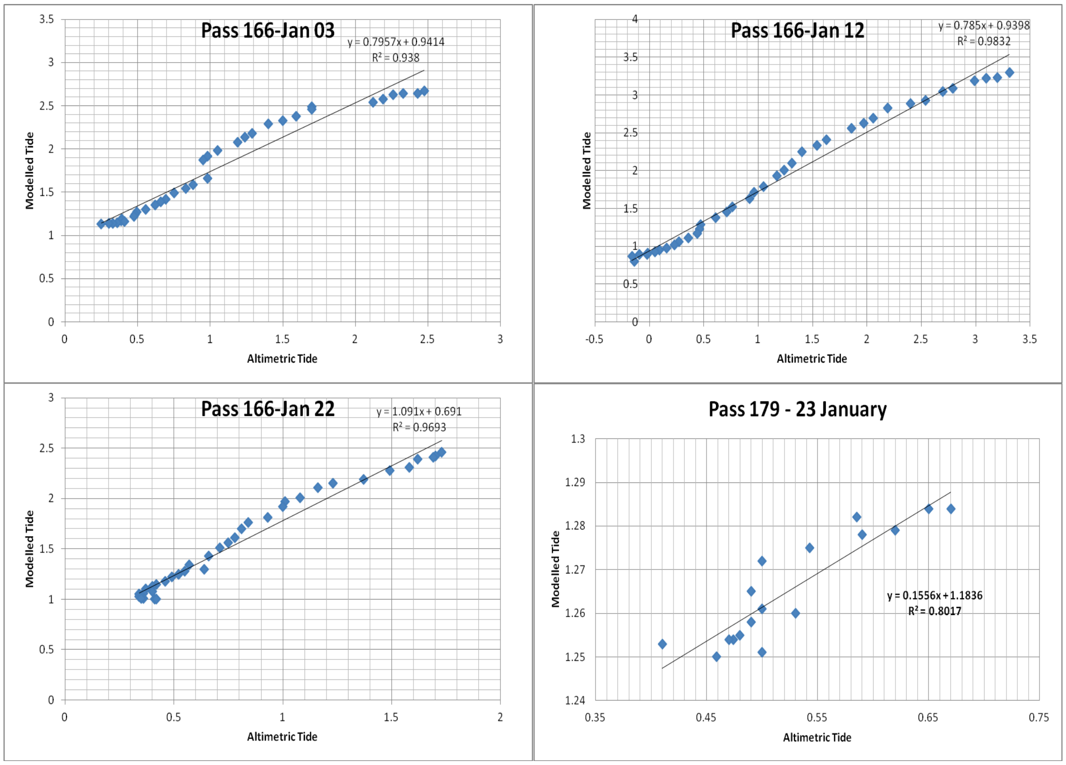

Figure 06 Correlation comparisons with CTZ vs. altimetric tides for Jason2 - January 2009

Finally, a tidal profile was generated using the CTZ across the entire Straits and shown in the Figure 07. 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 all across the region.

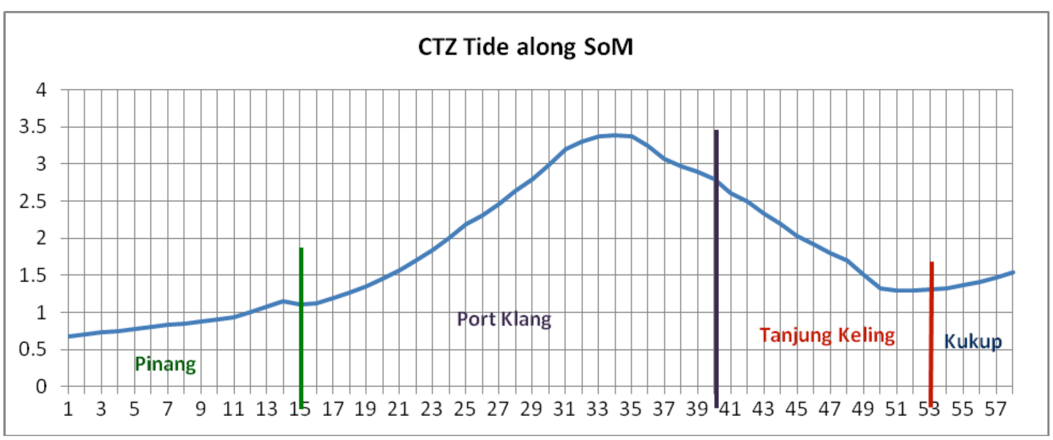

Figure 07 CTZ tide cross-section across the SoM - 1st of January 2009 at 10 AM

6. CONCLUSION

The greatest challenge was to find the boundary condition factor at the coast line such that to regenerate the natural tidal interaction at the coast. With the simulated test blocks and real data modelling, value 0.9 is determined as the most appropriate value for the coastline boundary. Here, the generated contours are much straighter, parallel and they meet the shore perpendicularly. This was further proved during the real data test results. The computed datum values and the published values at the check tidal stations are matching well when a=0.9. Usually, the iterative convergence processes taking longer time to produce results. Therefore, successive relaxation technique was applied to accelerate the convergence process. This will skip some intermediate iterations as the weighted solution is greater than the previous iteration. The weighting was done with the help of a relaxation coefficient (r) and the optimum value for r is obtained as 1.62 during the simulating process.

Ceaseless Tidal Zoning (CTZ) concept was developed by combining the conventional co-tidal charts and tidal zoning. Co-tidal chart has the disadvantage of using in the complex tidal regimes where the tidal pattern is irregular. Nevertheless, the tidal zoning can successfully address the complexity of the tides, there is always a discontinuity when crossings from one zone to the other. The CTZ has the advantage of addressing both these issues much 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. In the offshore areas, the comparison with the altimetry data has shown over 0.8 correlation along the satellite path. Finally, this approach provides spatially smooth results in the entire region.

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