MODELING TIDE AND STORM SURGE IN THE EAST COAST OF PENINSULAR MALAYSIA

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MODELING TIDE AND STORM SURGE IN THE EAST COAST OF PENINSULAR MALAYSIA

by

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LIST OF SYMBOLS

Symbols	***Descriptions***	***Units***
H	instantaneous water elevation	m
h	depth	m
h_{max}	maximum depth	m
η	water elevation above the MSL	m
g	acceleration due to gravitational force (given 9.81)	ms^{-2}
x	distance in –x direction	m
y	distance in –y direction	m
t	time	s
u	velocity of x component	ms^{-1}
v	velocity of y component	ms^{-1}
n	Manning Roughness co-efficient for friction	$m^{-1/3}s$
$\eta(t)$	function of elevation respect to the time	m
N_C	total number of harmonic components	unitless
i	index number of harmonic component	unitless
a_i	amplitude of i^{th} harmonic component	m
T_i	period of i^{th} harmonic component	s
α_i	phase angle of i^{th} harmonic component	radian
π	the ratio of the circumference to the diameter of a circle (given 3.14159)	unitless
V_n	normal velocity component	ms^{-1}
V_c	velocity component along the coastline	ms^{-1}
Q	injected water	m^3s^{-1}
ω	Earth's rate of rotation (given 7.2722×10^{-5})	s^{-1}
φ	Chézy bottom friction coefficient	$m^{1/2}s^{-1}$
ρ_a	density of air, kgm^{-3} (given 1.15)	kgm^{-3}
C_D	wind drag coefficient (given 0.0015)	unitless
ρ	density of fluid (assumed 1150 for saline water)	kgm^{-3}
W_x	wind velocity in x-direction	ms^{-1}
W_y	wind velocity in y-direction	ms^{-1}
$\|W\|$	wind speed	ms^{-1}
u_0	velocity of injected water in x-direction	ms^{-1}
v_0	velocity of injected water in y-direction	ms^{-1}

k	wind shear stress parameter	unitless
f	Coriolis parameter	s^{-1}
M	total flux in x-direction	m^2s^{-1}
N	total flux in y-direction	m^2s^{-1}
υ_x	dynamic eddy viscosity constant in x-direction	m^2s^{-1}
υ_y	dynamic eddy viscosity constant in y-direction	m^2s^{-1}
ϕ	latitude	degree
p	atmospheric pressure on MSL (10^2)	hPa
$\times$	dimension of the area	unit square
M2	principle lunar (semi-diurnal tidal constituent)	
K1	luni-solar declinational (diurnal tidal constituent)	
^{o}N	degree north from equator	
^{o}E	degree east from Meridian Greenwich	
Δ	infinitesimal difference (delta)	
δ	partial derivative	
=	equal	
$\leq$	less and equal than	
$\geq$	more and equal than	
%	percentage	
$\lvert . \rvert$	absolute value	
/	division	
m	meter	
s	second	
kg	kilogram	
hPa	hectoPascal	
rad	radian	

LIST OF ABBREVIATION

Abbreviation	*Full Description*
ASCII	American Standard Code for Information Interchange
B.C.	Before Christ
CDC	Climate Diagnostic Centre
CFL	Courant–Friedrichs–Lewy
COAL	Climate and Ocean Analysis Lab in Universiti Kebangsaan Malaysia
COAMPS	Coupled-Ocean Atmosphere Mesoscale Prediction System
DHI	Danish Hydraulic Institute
FDDA	Four-Dimensional Data-Assimilation
FORTRAN	Formula Translation
FTCS	Forward Time Central Space
FTFS	Forward Time Forward Space
GCM	General Circulation Model
GrADS	Grid Analysis Display System
GUI	Graphical User Interface
HHDDMMYY	HourDayMonthYear (e.g. 05020404 for 5.00am on 2 April 2004)
HHW	Higher High Water
HLW	Higher Low Water
INOS	Institut Oseanografi in Universiti Malaysia Terengganu
JTWC	Joint Typhoon Warning Centre
JUPEM	Jabatan Ukur dan Pemetaan Malaysia
LHW	Lower High Water
LLW	Lower Low Water
KUSTEM	Kolej Universiti Sains dan Teknologi Malaysia
MATLAB	*MATrixLABoratory*
MIKE SWMM	Modeling of Waste Water and Storm Water Systems
MMD	Malaysia Meteorological Department
MM5	Fifth Generation Mesoscale Model
MPI	Message Passage Interface
MSDOS	Microsoft Disk Operation System

MSL	Mean Sea Level
NCAR	National Center for Atmospheric Research
NCEP	National Center of Environment Prediction
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NOGAPS	Navy Operational Global Atmosphere Prediction System
POM	Princeton Ocean Model
PSU	Pennsylvania State University
RAM	Random Access Memory
RBC	Radiation Boundary Condition
SCS	South China Sea
SLOSH	Sea, Lake, and Overland Surges from Hurricanes
SLP	Sea Level Pressure
SPLASH	Special Program To List Amplitudes of Surges From Hurricanes
SST	Sea Surface Temperature
SWE	Shallow Water Equations
TC	Tropical Cyclone
UKM	Universiti Kebangsaan Malaysia
USM	Universiti Sains Malaysia
UTC	Coordinated Universal Time
VCE	Vatnaskil Consulting Engineer

MODELING TIDE AND STORM SURGE IN THE EAST COAST OF PENINSULAR MALAYSIA

ABSTRACT

The primary focus of this thesis involves the numerical simulations of the hydrodynamic flows in the coastal areas of Terengganu, which is subjected to tides and the two seasonal monsoons. For this purpose, we developed two numerical simulation models named TIDE-2D and TUNA-SU, based upon modification and enhancement of existing in-house models TIDE and TUNA-M2 respectively. Both models are governed by the two-dimensional depth-integrated shallow water equations (SWE), which are widely used to simulate similar hydrodynamic regimes. These equations are solved by means of the explicit finite difference method with a staggered grid system, which are restricted in the time step by the Courant-Friedrichs-Lewy (CLF) criterion to ensure numerical stability. The validation of TIDE-2D and TUNA-SU are performed by comparing the model simulation results with known analytical solutions and solutions derived from previously tested software AQUASEA. The tidal dynamics in the coastal areas of Terengganu is satisfactorily simulated by means of TIDE-2D. Similarly TUNA-SU performs satisfactorily to simulate interesting current patterns in South China Sea, which agree with observations during the northeast and southwest monsoons. Finally, two storm surge cases that occurred in Peninsular Malaysia's coastal areas are simulated by means of TUNA-SU. These two storm surges are induced by the Tropical Cyclone Vamei of 2001 and the Extreme Northeast Monsoons of 2004. Atmospheric inputs for these two storm events, which are required to model storm surges, are derived from simulations by the 5th Generation PSU/NCAR mesoscale model (MM5). Simulations reveal that the extreme northeast monsoon produced sea level rise of 50 to 60 cm while the observed sea level rise is 50 cm.

PEMODALAN PASANG SURUT DAN LURUAN RIBUT DI PANTAI TIMUR SEMENANJUNG MALAYSIA

ABSTRAK

Fokus utama dalam tesis ini adalah melibatkan simulasi berangka bagi aliran hidrodinamik di kawasan luar pesisiran Terengganu yang berkait dengan pasang surut dan dua monsun bermusim. Bagi tujuan ini, kita membina dua model simulasi berangka bernama TIDE-2D dan TUNA-SU berdasarkan pengubahsuaian dan peneguhan model dalaman yang sedia ada iaitu TIDE dan TUNA-M2 masing-masing. Model-model ini diperhalkan oleh persamaan air cetek berintegrasi-kedalaman dua-dimensi yang digunakan secara meluas untuk mensimulasi rejim hidrodinamik yang serupa. Persamaan-persamaan ini diselesaikan melalui kaedah beza terhingga tak tersirat dengan sistem grid bertindih-silang yang dihadkan sela masanya oleh criteria Courant-Friedrichs-Lewy (CFL) untuk memenuhi kestabilan berangka. Penentusahan TIDE-2D dan TUNA-SU dijalankan dengan membandingkan keputusan model yang disimulasi dengan penyelesaian analitis yang diketahui dan penyelesaian yang diterbitkan daripada perisian AQUASEA yang telah diuji sebelum ini. Dinamik pasang surut di kawasan luar pesisiran Terengganu disimulasi dengan baiknya dengan menggunakan TIDE-2D. Dengan cara yang serupa, TUNA-SU berprestasi memuaskan untuk mensimulasi corak arus yang menarik di Laut China Selatan, yang telah diperakui dengan pemantauan semasa monsun Timur Laut dan Barat Daya. Akhirnya, dua kes luruan ribut yang berlaku di kawasan persisiran Semenanjung Malaysia disimulasi dengan TUNA-SU. Dua luruan ribut ini diaruh oleh Siklon Tropika Vamei 2001 dan Monsun Timur Laut Ekstrim 2004. Input atmosferik bagi dua kejadian ribut yang diperlukan untuk memodel luruan ribut diterbitkan melalui simulasi dengan Generasi Kelima PSU/NCAR model mesoskala (MM5). Simulasi menunjukkan bahawa monsun timur laut ekstrim

menghasilkan kenaikan paras laut sebanyak 50 hingga 60 cm manakala kenaikan paras laut dipantau adalah 50 cm.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Lately, much attention has been given to the development of numerical ocean models aiming to simulate physical processes in the coastal areas. These models encompass a number of modules that simulate wave, tide and tsunami propagation, sea circulation as well as storm surge. Since the past few decades, ocean models were used to study the ocean processes because this methodology is considerably inexpensive, versatile and flexible. During the old days, these experiments were actually conducted by laboratory experiments, which involved high cost and bulky instruments. However, the numerical modeling systems used currently only need computers and compiler software to run these simulations.

This study focuses on numerical ocean modeling of flow problem induced by tide and storm surge. To resolve the flow problem efficiently, we need to incorporate realistic data to the solution field. These data include coastline, depth, dynamical properties of sea water, astronomical tide and meteorological interaction. In hydrodynamics, the above characteristics are very important in determining the flow in the ocean. Much of the work has been done using numerical models featuring two-dimensional depth averaged flow model, namely shallow water equations (SWE). This model governs flow problem that is associated with long wave propagation theory. According to this theory, the wave propagation in ocean is assumed to be laminar flow in which the wave amplitude is much smaller than the depth of ocean and this depth is much smaller than the wavelength.

Many researchers around the world have developed similar tide and storm surge models. Too often, these models are only applicable for specific modeling studies. These models are known as 'closed form models'. In this thesis, two numerical hydrodynamic models namely TIDE (Koh, 2004) and TUNA-M2 (Koh et al., 2005a) are modified and enhanced to model tide and storm surge in the east coast of Peninsular Malaysia. While model enhancement will introduce complexity in the ocean processes and a lengthier computer code, this research has attempted to retain the modeling algorithms to function as simple as possible. Although model enhancement provides better modeling capability, increased functions and complexity can also increase the possibility of errors. In order to avoid logical errors and improper numerical formulations, these enhanced models are validated with a similar and more established hydrodynamic model known as AQUASEA. Some observed data available in the study area are also used to further assist model validation.

One of the problems faced in numerical tide and storm surge modeling is the reconciliation of model results with data. In numerical modeling, many problems arise when we need to close the problem mathematically with proper initial and boundary conditions. Typically, the initial and boundary data is seriously insufficient at the solution field. At the open boundary, the case is worse. Besides the problem of unavailability of these data, the form of the boundary condition is also uncertain. Hence, the calibrations of these models are difficult to be realized. To overcome these problems, this study will suggest some best solutions to define these numerical tide and storm surge models by illustrating several interesting case studies.

1.2 Tide

Tide is defined as the alternate rise or fall of local sea level which results from the combination of gravitational pull from the moon and the sun exerting centrifugal forces when the earth rotates. As observed, the tidal levels vary from area to area. This variation is influenced by the coastal topography, ocean bathymetry and other factors, which will be discussed briefly.

The initial studies of tidal behavior had been conducted by Eudoxas as early as 356 B.C. Tide phenomenon was not fully explained until the late sixteenth century. Only in year 1687, Sir Isaac Newton explained the celestial motions and forces in his famous *Principia*. In 1886, the existing theory was further strengthened by George Darwin (Darwin, 1886). He had proposed the 'Equilibrium Theory of Tides' which is also sometimes called the theory of static tide (Refer to Appendix A). He described tides as a fluctuation of water height which is apparent when traveling across the same latitude line through the static and disfigured water layer. Actually, this generated fluctuation should have a typical range of only half a meter which is not observed in reality. This is why the Equilibrium Theory of Tide fails to explain why some bays and coastal areas experience tidal ranges from 3 m up to 15 m. The Bay of Fundy at Nova Scotia for example, has the tidal amplitude of 15 m, which is one of the world's greatest tidal amplitudes (Pugh, 2004).

There is another theory which is known as the 'Dynamic Theory'. This theory can explain the exceptional high variations of tide. These tidal variations are induced by non-astronomical factors which include the configuration of coastline, meteorological and hydrodynamic processes as well as the resonance generated at bays and tidal inlets.

The ocean bathymetry and Coriolis force also exert many effects on the idealized equilibrium of tides.

1.3 Storm Surge

Storm surge is induced by the great magnitude of wind stress probably from a hurricane, typhoon, tropical cyclone and even seasonal monsoons that are present at the open sea. Hurricanes are categorized according to their centre pressure, wind speed and their height. They are usually measured by using the Saffir-Simpson scale of one to five (Stern, 2005). The inverse barometric effect and the on-shore wind stress from a hurricane or cyclone can pile up the water above the normal sea level and emerge to the coastal land when they make a landfall which we call storm surge (Liu, 1997). This storm surge becomes more severe if it coincides with higher mean water during a spring tide.

Storm surge often has implications on coastal flood and strong wave currents. It usually causes colossal damage to coastal structures, loss of human lives and properties almost every year (Jakobsen, 2004). Example of the coastal regions which are vulnerable to hurricanes and storm surges are Bay of Bengal, east coast of United States of America, Turkey situated along the Mediterranean Sea, some European coasts along the Adriatic Sea, Aegean Sea and North Sea, the Great Australia Bight, Hong Kong and some bays along the East China Sea.

1.4 Objectives of Thesis

The objectives of the thesis are as follows:

1. To enhance one-dimensional numerical tide model TIDE (Koh, 2004) to two-dimensional numerical tide model TIDE-2D. This model is then validated by conducting model intercomparison with AQUASEA (De Vries et al., 1994). TIDE-2D is applied to simulate tidal dynamics at the coastal areas of Terengganu.
2. To enhance the numerical tsunami propagation model TUNA-M2 to numerical storm surge model TUNA-SU. TUNA-SU is validated by conducting model intercomparison with AQUASEA and an analytical formula. TUNA-SU will be used to study current circulations at the coastal waters of South China Sea during the northeast and southwest monsoons.
3. To model two storm surge cases in Malaysia which are induced by the Tropical Cyclone Vamei of December 2001 and an Extreme Northeast Monsoon of December 2004.
4. To introduce an atmospheric model which is employed to provide the atmospheric inputs for the storm surge modeling as above (3).

1.5 Scope of Thesis

The thesis encompasses model enhancements: firstly, the enhancement of one-dimensional tide model to two-dimensional tide model and secondly, the enhancement of a tsunami propagation model to a storm surge model. Some theoretical aspects of tide and storm surge will be discussed to impart basic knowledge of the subjects to the readers. Lastly, simulations on tide and storm surge will be conducted in the east coast of Peninsular Malaysia and South China Sea to illustrate the application of these in-house models. For the purpose of presentation flow, this thesis is systematically organized into six chapters.

Chapter 1 provides an overview of the thesis which includes the objective, scope and chapter organizations. Chapter 2 will discuss the most recent studies conducted in tide and storm surge modeling by other researchers. Literature relevant to this research will be reviewed. The software which has been used in this thesis together with other related models for the purpose of tide and storm surge modeling will also be introduced.

Chapter 3 begins with a brief introduction of TIDE which is a numerical tide model governed by one-dimensional SWE. The main focus in this chapter will be the enhancement of TIDE to TIDE-2D. TIDE-2D is governed by two-dimensional SWE which incorporates the nonlinear advection term and friction term. This chapter will also demonstrate how the shallow water model is solved by using the finite difference method with a staggered grid system. TIDE-2D is validated by comparing the simulated tidal elevations and current velocities of TIDE-2D with AQUASEA by running identical tide experiments. The validated TIDE-2D will be then be used to study the tidal dynamics in the coastal areas of Terengganu, which is situated in the east coast of Peninsular Malaysia. Realistic data such as coastal and island boundaries as well as bathymetry are incorporated in the model. Characteristics in the model setting such as grid resolutions and the effect of island on the tide will also be studied.

Chapter 4 begins with a brief introduction of a tsunami propagation model TUNA-M2, which is also governed by the two-dimensional SWE (Teh et al., 2005).

The main focus in this chapter is the enhancement of TUNA-M2 to a storm surge model TUNA-SU. Atmospheric forcing terms such as wind stress and Sea Level Pressure (SLP) gradient which are critical in modeling storm surge are added to TUNA-M2. These two terms are usually not considered in the modeling of tsunami propagation because their contributions to the amplitude of tsunami waves are not significant. Wind stress and SLP gradient become more important in the modeling of sea circulations and storm surge. Other physical terms which are also incorporated in TUNA-SU are Coriolis force and horizontal eddy viscosity. The presence of these terms is required to represent the physics of storm surge more realistically. At the open sea, we introduce radiation boundary conditions in TUNA-SU to represent the open sea of a restricted calculation field. In addition, TUNA-SU will be validated by model intercomparison with AQUASEA and an analytical formula by illustrating a wind setup experiment. This chapter also reviews some conceptual study on storm surge such as integrating the model with different coastline shapes and bathymetry. Finally, TUNA-SU is applied to model current circulations in the South China Sea during the occurrence of northeast and southwest monsoons.

Chapter 5 discusses an atmospheric model which is known as mesoscale model (MM5). MM5 has been utilized to downscale any crude atmospheric data generated by global models before these data can be used as atmospheric forcing in TUNA-SU. Next, we will describe the synoptic history of two storm cases which occurred at the coastal regions of Peninsular Malaysia. They are Tropical Cyclone Vamei of December 2001 and Extreme Northeast Monsoon of December 2004. By incorporating the atmospheric data which has been downscaled by the MM5 earlier, TUNA-SU will simulate these two storm surge cases. We will also present the simulation results such as surge elevations and current velocities. These results are displayed in time series of surge elevations, contours of distributed elevations and vector plot of the current velocities.

Lastly, Chapter 6 will conclude and summarize important findings of Chapters 3, 4 and 5. Future studies will be recommended for those who wish to further advance and improve the research conducted in this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This research focuses on model enhancement for solving tide and storm surge problem, specifically on the study of tide and storm surge at the coastal areas of Peninsular Malaysia. The coastal areas which are a part of South China Sea have many of the sea's characteristics such as the climate change, sea circulations and seasonal monsoons throughout the year. Similar models have been developed by other coastal modelers around the world, thus this chapter will review relevant studies which have provided recommendations, motivations and ideas for the researcher to conduct this study.

2.2 Tide Modeling

To achieve the understanding of tide modeling, a comprehensive knowledge on tide and tidal dynamics is compulsory. Following are some recommended literature on tide which is found most useful for this research (Ippen, 1966; Duxbury, 1971; Bishop, 1984; Pugh, 2004). Till this present day, the shallow water equations (SWE) are still conventionally used to model the tidal flow.

The SWE governing the fluid flow problem are actually derived from Navier-Stokes Equations. A local university textbook by Koh (2004) presented one-dimensional shallow water model and how this model can be solved by employing finite difference with staggered grid system. The knowledge of handling one-dimensional model is important when we proceed to two- and three-dimensional shallow water models. This shallow water model can also be solved by finite element method (Koh, 1988). Tide modeling using one-dimensional numerical model, TIDE-1D and two-dimensional hydrodynamic software, AQUASEA had been conducted in Malaysia. These model studies had been implemented in the Western Channel of Penang (Koh and Lee, 1991), Southern Channel of Penang (Ng, 2002) and the Straits of Johore (Syamsidik, 2003). All these work has motivated this research to explore the development of two-dimensional flow model named as TIDE-2D.

Some examples of tide modeling which employed two-dimensional, vertically integrated finite difference scheme can be found in Crean et al. (1988) and Baumeister and Manson (2002). More advanced numerical simulations had been studied by Chau (1996) by using two-dimensional model with boundary-fitted orthogonal curvilinear grid system. This simulation had been conducted to study tidal flow in Tolo Harbour, Hong Kong. Much attention has also been given to develop three-dimensional tide model because powerful computers are more affordable nowadays.

Three-dimensional tide model has been used to study tidal flow at Singapore's coastal waters and the results provided some useful information on the tidal features in our coastal region (Zhang and Gin, 2000). However, three-dimensional tidal model is not developed in this thesis for two reasons: first, the data and computing resources are limited; secondly, two-dimensional model is adequate to model tide and storm surge. Without losing generality, this study does not include the vertical flow component in our study domain specifically in South China Sea.

2.3 Oceanography Research in South China Sea

Marine investigations of the South China Sea (SCS) and Gulf of Thailand were conducted from 1959 to 1961 by a German oceanographer, Klaus Wrytki (Wrytki, 1961). He had documented most of his discoveries in a volume of Naga Reports about SCS which was claimed to be one of the most complicated seas in the world. This investigation has been carried out by means of sea explorations and data collections by modern measuring instruments back at that time. His first documentation on SCS received high recognition and many consulted his report for data which they found most useful. Many have reviewed the works of Wrytki and provided further discussion about the characteristics of SCS (Yanagi et al., 2001; Jilan, 2004). The most recent documentation of SCS which is published by Morton and Blackmore (2001) had related marine biota, ecology, coastal erosions and marine pollutions of SCS to the seasonal monsoons and the current circulations.

Some of the published journals show study had already been focused on numerical modeling on SCS by means of Princeton Ocean Model (POM). POM is a free program which solves flow problem by using three-dimensional primitive equations and ocean model. This program is employed to simulate most of SCS's characteristics such as sea circulations, thermohaline and baroclinic structures during the seasonal monsoons (Chu et al., 1999). In 1993, a mooring observation has been employed at Terengganu's coastal waters to study tides, tidal currents, sea temperatures and sea level rise due to strong wind of northeast monsoons (Taira et al., 1996). This study suggested that the sea level rise of 50 cm can be observed at Terengganu coastal regions during the northeast monsoon which has been qualitatively reproduced in this thesis as well.

2.4 Atmospheric Research in South China Sea

Some of the research has been conducted to study the synoptic disturbances during December 2004 which had occurred in South China Sea and the east coast of Peninsular Malaysia (Liew et al., 2006). Hindcast simulations of Tropical Cyclone Vamei of December 2001 and Extreme Northeast Monsoon of December 2004 have been successfully integrated at the Climate and Ocean Analysis Lab (COAL) in Universiti Kebangsaan Malaysia by using mesoscale model (MM5) (Liew and Tangang, 2005; Liew, 2006). Their simulation results of MM5 in these experiments are fairly matched with the observed data. Based on this reason, this thesis utilizes the MM5 simulated results for the atmospheric inputs for storm surge modeling. Besides, these data also came with smaller resolutions as required for these modeling purposes.

Koh (2006) had conducted similar effort by running a hindcast model of Tropical Cyclone Vamei by using Coupled-Ocean Atmosphere Mesoscale Prediction System (COAMPS). COAMPS is an advanced oceanic-atmospheric model which is developed by the United States Naval Research Laboratory. The atmospheric diagnostics by Chang (2006) suggested some synoptic event such as Borneo vortex and cold wind surge from Siberian high are responsible in forming these two synoptic disturbances; Tropical Cyclone Vamei which had formed near-equatorial region and Extreme Northeast Monsoon over the South China Sea.

2.5 Storm Surge Modeling

For the past few decades, much effort has been focused at the storm surge modeling induced by extreme localized atmospheric systems such as tropical cyclones and midlatitute depression. One of the oldest frameworks of storm surge modeling had been initialized by Jelenianski (1965). He suggested that the hurricane storm surge prediction problem should be solved by numerical means instead of statistical analysis. The first numerical method used at that time is the linear shallow water model without bottom friction and solved by explicit finite difference scheme.

Lately, staggered grid system with explicit or implicit finite difference scheme has been recognized to solve many numerical problems which are associated with shallow water model (IOC, 1997). Storm surge modeling has been conducted at many parts of the world to provide routine flood warnings in several countries. A number of surge models already exist for Bay of Bengal, a region which is highly vulnerable to the natural disaster. Most of these studies were led by Das (1972), who also employed the linear shallow water model to study the peak surge elevations resulting from basic cyclone setup. To date, we can see many research on storm surge modeling by using two-dimensional depth-integrated shallow water equations being carried out consistently (Salisbury and Hagen, 2006).

Storm surge model with curvilinear grids had been idealized by Johns et al. (1981) which allowed stretching to improve refinement of the computational grid near shore. In 1972, a storm surge model known as SPLASH had been successfully developed (Jelesnianski, 1972). It was an operational model used by NOAA to forecast hurricanes surges along the east coast of United States. In 1992, operational use of SPLASH had been replaced by a more established model known as SLOSH. This model was capable of simulating the storm surge at the sea and the resulted inundation in the land (Jelesnianski et al., 1992; Houston and Powell, 1993; Murillo and Seider, 1998). Some research also focused on several numerical developments such as improving radiation boundary conditions (RBC) which is difficult to implement but yet necessary for all storm surge model (Tang and Grimshaw, 1996; Tang and Grimshaw, 1999; Palma and Matano, 2001; Jones and Davies, 2004).

From the literature reviewed, two-dimensional nonlinear depth-averaged model with finite difference scheme is still used for storm surge modeling until today (De Vries et al., 1994; Zhang and Li, 1995; Caviglia and Dragani, 1996; Tang et al., 1996; Wakelin and Proctor, 2002). Some of these storm surge models had been improved to incorporate additional features such as geographical coordinate (Flather, 1993) and coastal inundations (Hubbert and McInnes, 1999; Peng et al., 2003). A study conducted by De Vries et al. (1995) concluded that all storm surge models governed by shallow water model developed generically by many institutes should converge to one common approach.

Three-dimensional surge models were also applicable for storm surge but these models are rather complicated, require more numerical 'crunching' and huge computing resources (Li and Zhang, 1996). One of the most popular is the Princeton Ocean Model (POM) which is governed by three-dimensional primitive ocean model (Mellor, 1996). This model is also applicable for storm surge modeling. More advanced storm surge modeling has been conducted by Ozer et al. (2000) and Choi et al. (2003) who worked on the coupling of tides, surges and wave in a set of model. Their work was motivated by Heaps (1983), who suggested the need for wave model to improve the specification of wind stress in surge models. Storm surge prediction can also be conducted by using neural network which is a non-numerical approach (Lee, 2006).

2.6 Software Review

A hydrodynamic software known as AQUASEA version 7.2 is used to verify the in-house model of TIDE-2D and TUNA-SU. AQUASEA solves the depth averaged shallow water model by means of Galerkin Finite Element method (VCE, 1998). There are other hydrodynamic packages which can be downloaded for free or purchased commercially. One of the free hydrodynamic software is a one-dimensional model, DYNHYD (Version 5.0), which runs under MSDOS platform (Ambrose et al., 1993). MIKE SWMM which also solves two-dimensional flow is Windows™-based and more user-friendly (DHI, 2000). AQUASEA and MIKE SWMM can be purchased at moderate cost for academic purposes.

To display the simulations results, MATLAB version 6.5 and Grid Analysis Display System (GrADS) are used in this thesis. MATLAB is a commercialized software while GrADS is an open source software which is available for free. In this research, MATLAB is used to manipulate the output file generated from the simulations of TIDE-2D and TUNA-SU. This is done by converting the output file of ASCII format to the machine language or binary format which is required and readable by the GrADS (Nakamura, 2001).

GrADS provides many plotting functions with fairly good presentations such as contour plot and vector plot with actual sea-land boundary also incorporating the latitude/longitude coordinate system. GrADS is also capable of displaying simple line plot which allows us to display the time series in certain observation points directly without using any spreadsheets. GrADS is a command prompt application that can run on both Windows™ and Linux operating systems. Since GrADS is an open source program, it is built without user’s interface. However, it is not difficult to operate (Doty, 1995).

CHAPTER 3

TIDE MODELING

3.1 TIDE

To model tides, a mathematical formula which can solve the flow problem is introduced. This model which is written in partial differential form governs the continuity and motion of fluids. TIDE is a model used to simulate tide propagation in one-dimensional flow (Koh, 2004). TIDE is governed by one dimensional SWE without friction which consists of one continuity equation (3.1) and one momentum equation (3.2). The formulation is written as follows:

$$\frac{\partial \eta}{\partial t} = -H\frac{\partial u}{\partial x} \qquad (3.1) \qquad\qquad \frac{\partial u}{\partial t} = -g\frac{\partial \eta}{\partial x} \qquad (3.2)$$

where

H = h+η = instantaneous water elevation [m];

η = water elevation above the MSL [m];

u = velocity of x component [ms^{-1}];

g = acceleration due to gravitational force (given 9.81 ms^{-2});

x = distance in –x direction [m];

t = time [s].

3.2 TIDE-2D

Numerical model TIDE-2D is the enhancement of TIDE which supports two-dimensional flows defined in x- and y- directions. This model is governed by two-dimensional depth averaged integrated shallow water model (Moe et al., 2002). This model consists of a continuity equation (Equation 3.3) which can be derived from the

Mass Conservation Law. There are also two momentum equations which govern the flows in x-direction (Equation 3.4) and y-direction (Equation 3.5). These momentum equations are derived from Newton's Second Law of Motion (Pond and Pickard, 1978). These three equations can be expressed as:

$$\frac{\partial \eta}{\partial t}+\frac{\partial (uH)}{\partial x}+\frac{\partial (vH)}{\partial y}=0 \tag{3.3}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x}-\frac{gn^2}{H^{4/3}}u\left(u^2+v^2\right)^{1/2} \tag{3.4}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial y}-\frac{gn^2}{H^{4/3}}v\left(u^2+v^2\right)^{1/2} \tag{3.5}$$

where

h = depth [m];

η = water elevation above the MSL [m];

H = h+η = instantaneous water elevation [m];

g = acceleration due to gravitational force (given 9.81 ms^{-2});

x = distance in –x direction [m];

y = distance in –y direction [m];

t = time [s];

u = velocity of x component [ms^{-1}];

v = velocity of y component [ms^{-1}];

n = Manning Roughness co-efficient for friction [$m^{-1/3}s$].

Cartesian coordinate is used for the model, x-axis for eastward and westward while y-axis for northward and southward. While applying the shallow water model, we need to make some general assumptions, that is the flows in our model are laminar which are only in x- and y- directions and the two velocity components, u and v are depth averaged velocities.

3.3 Numerical Implementations

TIDE-2D modeling system is developed by using a software compiler named FORTRAN. The manual and syntax of this compiler are available from Etter (1993) and Nyhoff and Leestma (1999). To build TIDE-2D, some detailed understandings on numerical algorithms are needed.

3.3.1 Finite Difference Scheme

The shallow water model must be solved in order to obtain η, u and v for any $t > 0$ (Equation 3.3 to 3.5). Due to the nonlinearity of the advection and bottom friction terms, it is difficult to derive an analytical solution for our shallow water model. TIDE-2D is developed to solve this difficulty by means of numerical approximations. It is based upon the finite difference method with a staggered grid system (Koh, 2004).

In the staggered grid system, η (elevation), u (velocity in x-direction) and v (velocity in y-direction) nodes are evaluated with different time and space. The evaluation of η, u and v nodes is illustrated in Figure 3.1. As we can see, η, u and v have different number of nodes in the x- and y-directions. For the time step, η nodes have an initial time level of $T = 0$. The subsequent iterations where the η nodes are updated are at $T = \Delta t$, $2\Delta t$, $3\Delta t$ and so on. However, the velocity nodes, u and v have an initial time level of $T = 0.5\Delta t$ and the subsequent iterations where the u and v are updated are at $T = 1.5\Delta t$, $2.5\Delta t$, $3.5\Delta t$ and so on. In short, time layers which accommodate η and time layers which accommodate u and v are laying alternately on each other by time interval of 0.5Δt. For visualization, this staggered scheme actually forms a three dimensional cube, in which the horizontal layers determine the space (x- and y- direction) and vertical layers determine the time (Refer also Figure 3.1).

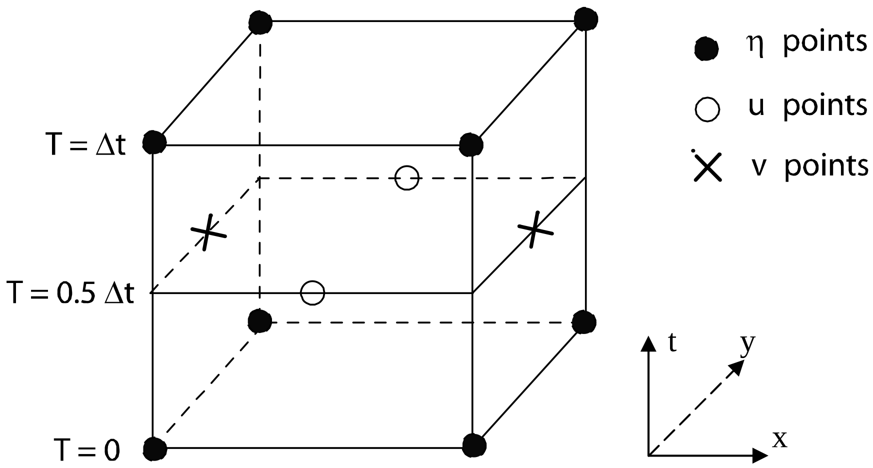

Figure 3.1: A staggered grid system in computational domain

Every term in Equations 3.3 to 3.5 except the nonlinear advection terms are approximated by using the forward time and forward space (FTFS) scheme as in Equation 3.6 (Koh et al., 2005a) respectively. The notation i and j denote the location of η, u and v nodes in Cartesian coordinate while k refers to the time step which are well-defined in the staggered grid system.

$$\left(\frac{\partial \eta}{\partial t}\right)_{i,j}^{k+\frac{1}{2}} = \frac{\left(\eta_{i,j}^{k+1} - \eta_{i,j}^{k}\right)}{\Delta t} \quad ; \quad \left(\frac{\partial \eta}{\partial x}\right)_{i+\frac{1}{2},j}^{k} = \frac{\left(\eta_{i+1,j}^{k} - \eta_{i,j}^{k}\right)}{\Delta x}; \quad \left(\frac{\partial \eta}{\partial y}\right)_{i,j+\frac{1}{2}}^{k} = \frac{\left(\eta_{i,j+1}^{k} - \eta_{i,j}^{k}\right)}{\Delta y};$$

$$\left(\frac{\partial u}{\partial t}\right)_{i+\frac{1}{2},j}^{k} = \frac{\left(u_{i+\frac{1}{2},j}^{k+\frac{1}{2}} - u_{i+\frac{1}{2},j}^{k-\frac{1}{2}}\right)}{\Delta t} \; ; \; \left(\frac{\partial v}{\partial t}\right)_{i,j+\frac{1}{2}}^{k} = \frac{\left(v_{i,j+\frac{1}{2}}^{k+\frac{1}{2}} - v_{i,j+\frac{1}{2}}^{k-\frac{1}{2}}\right)}{\Delta t} \qquad (3.6)$$

To treat the nonlinear advection terms which have higher sensitivity to the numerical instability, forward time and central space (FTCS) scheme is employed (Equation 3.7). This scheme provides the needed improved stability. However, for the bottom friction term which is also nonlinear, FTFS is sufficient. It is important to note that advections are not evaluated at the boundary nodes due to the implementation of central space scheme.

$$\left(\frac{\partial u}{\partial x}\right)_{i,j}^{k+\frac{1}{2}} = \frac{\left(u_{i+1,j}^{k+\frac{1}{2}} - u_{i-1,j}^{k+\frac{1}{2}}\right)}{2\Delta x} \quad ; \quad \left(\frac{\partial u}{\partial y}\right)_{i,j}^{k+\frac{1}{2}} = \frac{\left(u_{i,j+1}^{k+\frac{1}{2}} - u_{i,j-1}^{k+\frac{1}{2}}\right)}{2\Delta y}$$

$$\left(\frac{\partial v}{\partial y}\right)_{i,j}^{k+\frac{1}{2}} = \frac{\left(v_{i,j+1}^{k+\frac{1}{2}} - v_{i,j-1}^{k+\frac{1}{2}}\right)}{2\Delta y} \quad ; \quad \left(\frac{\partial v}{\partial x}\right)_{i,j}^{k+\frac{1}{2}} = \frac{\left(v_{i+1,j}^{k+\frac{1}{2}} - v_{i-1,j}^{k+\frac{1}{2}}\right)}{2\Delta x} \qquad (3.7)$$

For numerical stability, time step Δt is restricted by the Courant–Friedrichs–Lewy (CFL) criterion as given by the following equation (Moe et al., 2002).

$$\Delta t \le \frac{\Delta x}{\sqrt{2gh_{\max}}} \qquad (3.8)$$

where h_{max} is maximum depth in the solution field.

3.3.2 Boundary conditions

There are two types of boundary conditions used to define the model domain. One is tidal forcing which will be imposed at the open boundary. These boundary conditions reflect the realistic astronomical tide in the coastal sea. For the implementation, a harmonic series shown in Equation 3.9 is used (Bishop, 1984).

$$\eta(t) = \sum_{i=1}^{N_C} a_i \sin\left(\frac{2\pi t}{T_i} + \alpha_i\right) \tag{3.9}$$

where η is tidal elevation [m]; t is time [s]; N_C is the total number of harmonic components; a_i is amplitude of i^{th} harmonic component [m]; T_i is period of i^{th} harmonic component [s] and finally α_i is phase angle of i^{th} harmonic component [rad].

For simplicity, a single component of wave is used. Equation 3.9 can be simplified to a single harmonic equation as below (Ippen, 1966).

$$\eta = a \sin\left(\frac{2\pi t}{T} - \alpha\right) \tag{3.10}$$

Another type of boundary condition is known as solid boundary or non-slip boundary which will be imposed at the coastal and island boundaries. By using these boundary conditions, the water is not allowed to penetrate the land masses. We assume the velocity component which is normal to the coast is zero. Hence, we have

$$V_n = 0 \tag{3.11}$$

$$\frac{\partial V_c}{\partial n} = 0 \qquad (3.12)$$

where n is the coordinate in the normal direction to the coast, V_n is the normal velocity component and V_c is the velocity component along the coastline which separates the land and water (Chau et al.,1996; Karim and Tingsanchali, 2005). At the land area, both normal and tangential velocities to the coast are zero. The water, coastal boundary, tidal boundary and land areas are recognized in the model by using a 'flag' matrix where '1' indicates water, '2' for coastal boundary, '3' for radiation boundary conditions (RBC) which will be discussed further in Chapter 5, '4' for tide boundary and '0' for land.

3.3.3 Initial Conditions

In this study, we assumed $u = v = \eta = 0$ when $t = 0$ (Moe et al., 2002). To avoid artificial initial conditions, the simulation has to be conducted for a longer period of time until a dynamic steady state is achieved. The tide readings in the study area can be used as initial conditions but field work has to be conducted to measure the water elevations and current speeds at particular time. However, this method is time and cost consuming.

3.3.4 Output Control

To obtain the output for the elevation, η nodes are directly evaluated. However, we have problems to calculate the flow velocities due to the segregation of u and v nodes in the staggered grid system. Hence, we assume u node and v node to be located at the same position of η as shown in Figure 3.2. This assumption applies to all u and v nodes throughout the grid system. The impreciseness of the flow velocities caused by this assumption can be improved if small grid size is chosen in the simulation. Another option of approximation is by averaging the adjacent u and v value along the x- and y- axes for each η position. Although this option improves the computational accuracy, evaluating u and v at the irregular stair-step boundaries might be complicated.

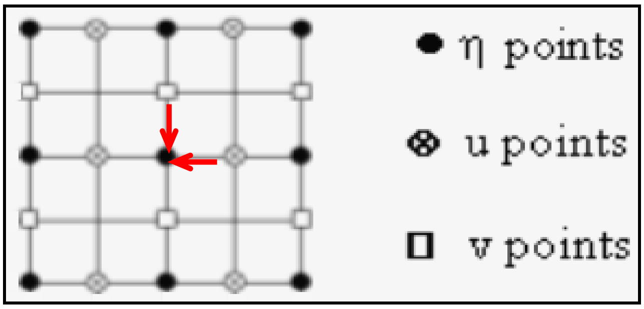

Figure 3.2: The calculation of flow velocity by assuming that u and v points are located at the same position of η (showed in two arrows)

3.4 AQUASEA

AQUASEA is a hydrodynamic software developed by Vatnaskil Consulting Engineers (VCE, 1998). The software can be used to simulate the tidal flow in estuaries and coastal areas, lake circulations as well as transport modeling. The governing equations in both AQUASEA and TIDE-2D are quite similar, which also employ the SWE. The shallow water model in AQUASEA has some additional features which are not available in TIDE-2D. These features include the Coriolis force, wind forcing and water input. These features however, are not considered for tide modeling. In AQUASEA, the continuity equation (Equation 3.13) and the momentum equations in x- (Equation 3.14) and y- directions (Equation 3.15) are written as follows.

$$\frac{\partial}{\partial x}(uH)+\frac{\partial}{\partial y}(vH)+\frac{\partial \eta}{\partial t}=Q \qquad (3.13)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{dy}=-g\frac{\partial \eta}{\partial x}+fv-\frac{g}{HC^2}\left(u^2+v^2\right)^{\frac{1}{2}}u+\frac{k}{H}W_x\left|W\right|-\frac{Q}{H}\left(u-u_0\right)=0 \qquad (3.14)$$