MATHEMATICAL MODELING FOR TSUNAMI WAVES USING LATTICE BOLTZMANN METHOD

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To my mother and father

&

My brother

AHMAD ZERGANI

For your infinite and unfading love, sacrifice, patience, encouragement and

Best wishes

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ABSTRACT

This research focuses on tsunami wave modelling. The nature of tsunami waves can be conditionally divided into three parts; generation, propagation and inundation (or run-up). General patterns and important characteristics of tsunamis can be predicted by various sets of governing equations and commonly used models which include elastic wave, nonlinear shallow water and forced Korteweg de Vries (fKdV) equations. In order to construct tsunami model, we divide this modelling into two parts; the first part contains seismic (earthquake) wave that focuses on the nonlinear elastic wave equation. The equation has been successfully applied to the tsunami generation part and is shown to give suitable complex flow simulation of elastic wave generation. The second part essentially deals with the nonlinear shallow water equations which are often used to model tsunami propagation and sometimes even the run-up part. This work specifically studies the properties of propagation of tsunamis. Shallow water equations have become the choice model of operational tsunami modelling for irrotational surface waves in the case of complex bottom elevation. The run-up part basically deals with the KdV and fKdV equations for unidirectional propagation and effects of external noise and damping terms for the studies of tsunami run-up. Several test-cases are presented to verify propagation and run-up model. The simulation algorithm of this research is based on the lattice Boltzmann method (LBM). The aim of this research is to use the LBM to solve tsunami waves modelling. Several problems for simulation of tsunami waves are generated with LBM. The appropriate equilibrium distribution function is selected and extended to solve the related three-dimensional problems and appropriate units are chosen and changed in accordance with lattice Boltzmann simulations and stability of lattice Boltzmann models. These models are solved and the solutions with different boundary conditions are analysed to produce relevant patterns and behaviours, assumptions and approximations for modelling tsunami and seismic waves. These analyses have been implemented via accurate, robust and efficient LBM for solving the tsunami sets of equations under complex geometry and irregular topography. The graphical output profiles are generated by using Matlab version 2012.

ABSTRAK

Kajian ini memberi tumpuan kepada model gelombang tsunami. Sifat gelombang tsunami boleh dibahagikan kepada tiga bahagian mengikut syarat; penjanaan, perambatan dan limpahan (atau *run-up*). Pola umum dan ciri-ciri penting tsunami boleh diramalkan dengan pelbagai set persamaan utama dan model yang biasa digunakan termasuk gelombang elastik, air cetek bukan linear dan persamaan Korteweg de Vries paksaan (fKdV). Dalam usaha membina model tsunami, pemodelan ini dibahagikan kepada dua bahagian; bahagian pertama mengandungi gelombang seismik (gempa bumi) yang memberi tumpuan kepada persamaan gelombang elastik bukan linear. Persamaan ini digunakan dengan jayanya untuk bahagian penjanaan tsunami dan terbukti memberi simulasi aliran kompleks penjanaan gelombang elastik yang sesuai. Bahagian kedua pada dasarnya adalah berkenaan persamaan air cetek bukan linear yang sering digunakan untuk memodelkan perambatan tsunami dan kadang kala juga bahagian limpahan. Kerja ini secara khususnya mengkaji sifat-sifat perambatan tsunami. Persamaan air cetek telah menjadi model pilihan dalam pemodelan operasi tsunami untuk gelombang permukaan tak berputar dalam kes dongakan kompleks bawah. Bahagian limpahan pada dasarnya berkaitan dengan persamaan fKdV untuk perambatan satu arah dan kesan bunyi luaran serta terma redaman dalam kajian limpahan tsunami. Beberapa kes ujian dibentangkan untuk mengesahkan model perambatan dan limpahan. Algoritma simulasi kajian ini adalah berdasarkan kaedah kekisi Boltzmann. Tujuan kajian ini adalah untuk menggunakan LBM dalam menyelesaikan pemodelan gelombang tsunami. Beberapa masalah untuk simulasi gelombang tsunami dijana dengan LBM. Fungsi taburan keseimbangan yang sesuai diambil dan dilanjutkan untuk menyelesaikan masalah tiga dimensi yang berkaitan dan unit yang sesuai dipilih serta diubah mengikut simulasi kekisi Boltzmann dan kestabilan model kekisi Boltzmann. Model ini diselesaikan dan penyelesaian dengan syarat sempadan yang berbeza dianalisis bagi menghasilkan corak yang relevan serta perilaku, andaian serta anggaran pemodelan gelombang tsunami. Analisis ini dilaksanakan menerusi LBM yang jitu, teguh dan berkesan bagi menyelesaikan set persamaan seismik dan tsunami di bawah geometri kompleks dan topografi yang tidak teratur. Profil hasil grafik dijana dengan menggunakan Matlab versi 2012.

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LIST OF ABBREVIATIONS

BGK	-	Bhatnagar-Gross-Krook approximation of the collision operator (collision operator)
CFD	-	Computational fluid dynamics
D2Q9	-	two-dimensional LB model with nine velocities
D3Q19	-	three-dimensional LB model with nineteen velocities
DF	-	distribution function (usually denoted fi)
EVM	-	Finite Volume Method
fKdV	-	forced Korteweg-de Vries
KDV	-	Korteweg-de-Vries equation
LB	-	lattice Boltzmann
LBM	-	lattice Boltzmann method
LES	-	large eddy simulation
LG	-	lattice-gas
MRT	-	multi relaxation time model
NS	-	Navier-Stokes
NSE	-	Navier-Stokes equations
PDE	-	Partial differential equations
SWE	-	Shallow water equations
SWS	-	shallow water simulation
TRT	-	two-relaxation-time
VOF	-	volume of fluid free surface simulation model

LIST OF SYMBOLS

ρ	-	Density
e_i	-	Lattice vectors
c	-	Lattice velocity
w_i	-	weighting factors
f	-	Distribution functions
Ω_i	-	Collision operator
τ	-	Relaxation parameter
ν	-	Kinematic viscosity
p	-	Pressure
f^{eq}	-	Equilibrium distribution function
u	-	Velocity
H	-	Width of the channel
μ	-	Dynamic viscosity
Re	-	Reynolds number
f_i	-	Particle distribution function along an arbitrary velocity vector
f_i^{eq}	-	Equilibrium distribution function
Δt	-	Lattice time step
Δx	-	Lattice cell size
g	-	Gravity acceleration vector
Kn	-	Knudsen number (ratio of mean free path and char. scale)
h_i	-	amending functions
$\nabla \times$	-	Curl
$\nabla.$	-	Divergence
l_x, l_y, l_z	–	Vector
u_p	-	Vector p wave

u_s	-	Vector S wave
ψ	-	Scalar wave
λ	-	Rayleigh factor
α	-	P wave velocity
β	-	S wave velocity
c_α	-	phase velocity for P wave
η_α	-	Diffraction quantity for p wave
k	-	Wavenumbers
τ_{ij}	-	Shear stress

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Natural disasters have had and will always have a major impact on human society. Earthquakes can ravage large areas and bring suffering and grief to many people living in such regions. The question remains why and how do earthquakes occur and which physical laws govern their behaviour? Although we know a lot more today than only a hundred years ago, still there are many unanswered questions and more work will be needed to better understand these phenomena.

From old times, tsunamis have caused tremendous damages to human race. In 2004, Indonesia and other countries surrounding Indian Ocean were damaged by Sumatra tsunami. Tsunami is generally caused by the earthquakes generated by the fault movement along the ocean trenches. Countries bordering oceans with such trenches like Japan have high possibility to be attacked by the ocean earthquake tsunami. Tsunamis exhibit a wide variety of diverse fluid dynamical features. General patterns and significant characteristics of tsunamis can be forecasted by different sets of governing equations. Firstly, the shallow water equation has been one important and commonly used. Main characteristics of tsunamis can be predicted by shallow water equations which depict the irrotational motion of an incompressible inviscid fluid in the long wave limit. The shallow water equation describes propagation of waves in weakly nonlinear and weakly dispersive media. Peregrine (1967) is derive the some type shallow water equations for water of various depth, which can easily define the nonlinear transformation of irregular, multidirectional waves in shallow water. The depth-integrated equations for the conservation of mass and momentum for an incompressible and inviscid fluid are characterized by shallow water. The vertical velocity is assumed to vary linearly over the depth to reduce the 3D problem to a 2D one. Secondly, Korteweg-de Vries (KdV) equation can predict the characteristic of tsunamis. Tsunami propagation is often modelled by the (KdV) equation and forced Korteweg-de Vries (fKdV) equation, a non-linear evolution Partial Differential Equation (PDE). The most important characteristic of the KdV equation is a special class of solutions called solitary waves or solitons, in which a large number of physical applications are particularly significant for stable localized waves. A simple example of a soliton is a tsunami wave. Although the solitary wave is now well understood the theory behind it is still very active.

The simulation algorithm of the Modelling of earthquake and tsunami in this research work shall be based on the LBM. This method has been selected due to the overall computational efficiency of the basic lattice Boltzmann algorithm, and its capability to deal with complex geometries and topologies. The LBM is a mesoscopic lattice simulation method. In the late 1980's engineers and physicists were presented the LBM. In many fields, lot of research work has been done, but the mathematical background is remaining vague. It has been applied fruitfully in many research areas. Fields of utilization of LBMs are the modelling and simulation of incompressible flows in complex geometries, for instances the flow of blood in vessels, multiphase and multi component fluids, free surface problems, moving boundaries, fluid-structure interactions, chemical reactions, flow through porous media, suspension flows, magneto-hydrodynamics, semiconductor simulations, non-Newtonian fluids, large eddy and turbulence simulations in aerodynamics to mention but a few. The limiting fluid-dynamic equations are determined by the scaling and the selection of the collision operator, where several models are possible. For this purpose, LBMs are related to a great diversity of various problems. Although LBMs are universally acclaimed for the applicability to complex geometries and interfacial dynamics, intensive difficulties become visible in the case of boundary conditions. To search expression in a comparably simple explicit algorithm on uniform grids with only local interactions is one of the advantages of lattice Boltzmann methods. The parallelization of the algorithms for the speed-up of the computations is straightforward. The improvement of differentiated quantities is a major advantage, without performing numerical differentiations.

Historically, Lattice Boltzmann (LB) was derived from the lattice-gas automata (LGA) in the 1990s, although the two methods are independent. The LGA traces particle movements on a lattice, and can recover the Navier-Stokes equations, thus simulating hydrodynamics. LGA is unconditionally stable and are very good to simulate micro-flow with large intrinsic fluctuations. However, LGA exhibits strong Galilean invariance (GI) violations, and they are limited to small Reynolds numbers. To overcome these deficiencies, LB was developed. Instead of tracing the movement of particles, LB traces the evolution of a density distribution function, which depends on position and velocity. The velocity is discretized such that, in one time step, the densities move to the neighbouring lattice sites to which their associated velocities point. This movement is called streaming. Between streaming steps, collisions occur at lattice sites and change the density distribution function. (Qian et al., 1993) introduced Bhatnagar, Gross and Krook (BGK)'s single relaxation time approximation to simplify the description of the collision. The system evolves by means of one streaming and one collision per time step. The macroscopic physical quantities mass and momentum are given by the velocity moments of the density distribution function. Because the standard BGK model describes the collision of ideal gases, the standard LB algorithm can only simulate ideal gas dynamics. To simulate non-ideal fluids, the attractive or repulsive interaction among molecules, which is referred to as the non-ideal interaction, should be included in the LB model. From the research carried out on the application of LBM, much work has not been cited using LBM for modelling of Tsunami and earthquake.

1.2 Statements of the Problem

Whenever a mathematical model is used to represent or predict the behaviour of a real physical system there are two possible sources of error that should be carefully distinguished. First, the set of equations assumed to govern the system will always oversimplify the true physical system. Secondly, given the complexity of most physical applications, the governing equations will rarely be exactly solved analytically or numerically. Computations will only be estimates of solutions to the already oversimplified system.

Tsunamis and earthquake exhibit a wide variety of diverse fluid dynamical features and no single set of governing equations approximated by a numerical method will ideally model all of the features. However, total models and significant features of tsunamis can be foretold by diverse set of governing equations: elastic wave equation, nonlinear shallow water equations and fKdV equation being important and commonly used examples.

This research specifically studies the properties of tsunami waves. In particular the study includes all these parts of the wave, generation, propagation and inundation. Some of the problems that have been identified which are related to modelling of earthquake and tsunami are listed below:

Seismic (Earthquake)

1. Nonlinearity of elastic wave equation

Tsunami (Hydrodynamics)

1. Nonlinearity of Shallow water equations
2. Korteweg-de vries (KdV) and forced Korteweg-de vries (fKdV) equation for unidirectional propagation and effects of external noise and damping term on the soliton solution of the fKdV equation.

Numerical method

1. Standard of Lattice Boltzmann method (LBM) for sets of equations in order to handle tsunami and seismic waves and the stability and accuracy of the method.
2. LBM for sophisticated geometry and irregular topography (the performance of LBM method for complex geometry and irregular topography).

1.3 Objectives of the Study

The purpose of this research is to use the Lattice Boltzmann method (LBM) to solve Seismic (Earthquake) and Tsunami waves modelling and to provide a more accurate value of actual data. This work will evaluate, using accurate, robust and efficient LBM numerical methods for solving the set of equations: elastic wave equation, nonlinear shallow water equations and KdV and fKdV equations in order to tsunami earthquake modelling.

The objectives are outlined below:

1. To solve and analyze the solutions of the governing equations with different boundary conditions via LBM when they are used for seismic (earthquake) and tsunami modeling.
2. Execute and enhance the Lattice Boltzmann Method for modelling seismic wave propagation.
3. Execute and enhance the Lattice Boltzmann Method for modelling tsunami wave propagation and inundation that are for compressible fluid flows and incompressible fluid flows (fKdV - shallow water equations).
4. To find some patterns and physical models to understand behaviour, assumptions and approximations for modelling tsunami and seismic wave propagation.

5. To compare the numerical computations of LBM output with existing methods for seismic (earthquake) and tsunami.

1.4 Scope of the Study

This study focuses on the three phases of tsunami and the numerical solutions developed for the sets of equations by the use of lattice Boltzmann method. This aims to investigate the implementation of the LBM formulation for the elastic wave, shallow water waves and fKdV equations which are based on tsunami models.

In the first phase, this covers the generation process of the diffusion and non-diffusion P-waves only. We apply LBM approach to its modelling to help understand how tsunami occurs at the initial stage. The second and third phases deal respectively with shallow water waves which are often used to model tsunami propagation, and fKdV which is used to model tsunami inundation. More precisely, we discuss the numerical discretization of the governing equations in the LBM framework on certain specified geometries, e.g. oscillatory bottom, irregular bottom, etc. Zou and He, boundaries are considered and their effects on the models are investigated. Owing to the potential of LBM which include easy coding, excellent computational efficiency for large data sets, we extend the standard of LBM for modelling of tsunami flows in three dimensions, investigate the stability and accuracy of the method and its performance in real computing environment.

1.5 Significance of the Study

Natural hazard can arise at any time in coastal areas around the world, for this purpose tsunamis are significant to study. In an effort to gain a more complete understanding of tsunamis and generate stronger warning systems, there are monitors throughout the world's oceans to measure wave height and potential underwater disturbances. The forecasting of earthquakes cannot be done, but foreseeing can be possible. Understanding behaviour, assumptions and approximations made in physical models is necessary. Forecasting of earthquakes cannot be done, but they have some patterns and designs. Sometimes foreshocks precede quakes, though they look just like ordinary quakes. But every major incident has a cluster of smaller aftershocks, which follow well-known statistics and can be predicted. The numerical simulation of physical phenomena serves as an alternative to classical solvers of partial differential equations, however, the lattice Boltzmann method is used frequently. The LBM preserves the sequence between the elaboration of a theory and the formulation of a corresponding numerical model short and considered as a precious instrument in fundamental research. Hence, LBM has been chosen to study the behaviour, assumptions of earthquakes and Tsunami. The use of LBM to model earthquake and tsunami will provide the opportunity to gain more understanding of the natural hazard and also to generate stronger warning systems. In addition, this study provides the opportunity to check the performance of LBM method for complex geometry and irregular topography.

1.6 Thesis Outline

This thesis consists of seven chapters. The introductory Chapter 1 contains discussion on the introduction, background of the problem, present work, problem statement, objectives of research, scope of the study and significance of the study.

In chapter 2, literature reviews on current researches works are shown. Gives an over view of previous work done by different researchers in the field of tsunami and seismology and geophysics to mathematical modelling and coastal engineering. In addition to that, mechanisms like the inundation, generation, and propagation of tsunamis are presented. The Lattice Boltzmann methods of solution in general and as applicable to these problems are rendered.

In chapter 3, the method of the current research LBM algorithms is stated.

In chapter 4, presents the mathematical derivation for elastic wave for the generation of earthquake. The simulation algorithm for elastic wave equation for tsunami wave modelling is the lattice Boltzmann and several test cases are presented to verify generation model. The characteristics and LBM model of the wave are discussed thoroughly.

In chapter 5, illustrates the mathematical derivation of shallow water wave for the prorogation of tsunami. The simulation algorithm for shallow water wave equation is the lattice Boltzmann and several test cases are presented to verify propagation model. The characteristics and LBM model of the wave are discussed thoroughly.

In chapter 6, shows the mathematical derivation of KdV and fKdV for the inundation of tsunami. The simulation algorithm for KdV and fKdV equations are the lattice Boltzmann and several test cases are presented to verify inundation model. The characteristics and LBM model of the wave are discussed thoroughly.

Finally, Chapter 7 presents the general conclusions of this research work and recommendations for future works. It also highlights the problems considered and a summary of the method used in solving the problem.

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