NUMERICAL MODELING FOR WAVE PROPAGATION BY SOLVING THE SHALLOW WATER EQUATIONS USING FINITE DIFFERENCE METHOD

THESIS

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Tanggal: 10 Februari 2022

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ABSTRACT

The shallow water theory has been widely used to model the wave propagation. In this thesis, the 1D wave propagation is modeled using the shallow water equations and the Preissmann implicit scheme is used to discretize the equations due to its simplicity and stability that can be maintained over the large value of time step. The concept of shallow water is based on the smallness of the ratio between water depth and wavelength, and the model is fundamentally developed for the shallow water condition. However, to test the accuracy of the numerical model comprehensively, three different types of wave are simulated in this thesis: (1) tidal wave, (2) roll wave, and (3) solitary wave. For the tidal wave case, the numerical model is proven to be accurate indicated by the relatively-small errors for both water level and velocity. For the roll wave case, the numerical model is fairly accurate to capture the periodic permanent roll waves despite showing a higher water level than the one measured caused by the neglect of the turbulence terms. Finally, for the solitary case, as expected, the numerical model shows significant errors compared with the analytical result due to the neglect of the dispersion term.

Keywords: Preissmann scheme, roll wave, shallow water equations, solitary wave, tidal wave, wave propagation

PEMODELAN NUMERIK UNTUK PENJALARAN GELOMBANG DENGAN MENYELESAIKAN PERSAMAAN AIR DANGKAL MENGGUNAKAN METODE BEDA HINGGA

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FEBRUARI 2022

ABSTRAK

Teori air dangkal telah banyak digunakan untuk memodelkan penjalaran gelombang. Pada tesis ini, penjalaran gelombang satu dimensi dimodelkan penggunakan persamaan air dangkal dan skema implisit Preissmann digunakan untuk mendisktritisasi persamaan karena kemudahan dan stabilitas perhitungannya dapat dipertahankan pada langkah waktu yang besar. Konsep air dangkal didasarkan pada kecilnya rasio antara kedalaman air dan panjang dari gelombang, dan pemodelan secara fundamental dikembangkan untuk kondisi air dangkal. Namun, untuk menguji tingkat akurasi model numerik secara komprehensif, tiga tipe gelombang yang berbeda akan disimulasikan pada tesis ini: (1) gelombang pasang surut, (2) gelombang gulung, dan (3) gelombang soliter. Untuk kasus gelombang pasang surut, pemodelan numerik terbukti akurat, terindikasi dari kecilnya eror untuk perhitungan kedalaman air dan kecepatan. Untuk kasus gelombang gulung, pemodelan numerik juga terbilang cukup akurat untuk menangkap gelombang gulung permanen meskipun menunjukkan kedalaman air yang lebih tinggi dibandingkan dengan kedalaman air terukur disebabkan oleh pengabaian suku turbulen. Untuk kasus gelombang soliter, seperti yang telah diperkirakan, pemodelan numerik menunjukkan eror yang cukup besar dibandingkan dengan hasil analitis karena pengabaian efek dispersi.

Kata Kunci: gelombang gulung, gelombang pasang surut, gelombang soliter, persamaan air dangkal, penjalaran gelombang

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Bandung, February 2022

Prilla Lidyana

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CHAPTER 1 INTRODUCTION

1.1 Background

Ocean wave or water wave is one of the most concerning oceanography aspects in infrastructure planning in coastal area. Such wave might be generated by several external and internal factors, i.e. wind, geometry of the sea, astronomical tide, earthquake on the seabed, etc. (Pratomo et al., 2016). The researchers had put great practical interest in investigating the ocean wave propagation due to intensive human activities in coastal areas. To get more effective measures for protection works, the evaluation of local wave threats, such as tsunami is of importance. Furthermore, the massive loss of casualties and the destruction of infrastructures associated with the natural hazard caused by water waves have underscored the need to implement the hazard mitigation system (Allam et al., 2014). To minimize the negative impacts, the forecasting, proper monitoring, and warning system thus need to be continuously developed.

Nowadays, significant improvements in developing numerical models have been made possible to describe and predict the process of wave propagation. However, modeling the wave propagation is admittedly not an easy task, and thus, finding the best method and solution for this remains challenging. Understanding the mechanisms such as the generation, propagation, inundation of the waves, and predicting possible parameters such as the wave height, length and velocity are therefore of importance.

Various studies used the shallow water theory to investigate the mechanism of ocean waves. (Ginting & Mundani, 2019) applied the shallow water equations (SWE) to modeling the wave propagation caused by the tsunami phenomena. (Allam et al., 2014) analyzed the effect of the stochastic bottom topography on the generation and propagation of the tsunami waveform using the linearized shallow water-wave theory. In addition to modeling the wave propagation, the SWE can also be applied to various open channel flow computations, see (Ginting, Yudianto, & Wicaksono, 2021), (Ginting, Yudianto, Willy, et al., 2021), (Ginting, 2019), (Ginting & Mundani, 2019), (Ginting & Ginting, 2019), (Ginting & Mundani, 2018), (Ginting, 2017). The concept of shallow water model is based on the smallness of the ratio between the water depth and the wavelength. To this regard, the shallow water numerical modeling process may be classified into two groups, i.e., dispersion and non-dispersion SWE models. The main difference between the dispersion and non-dispersion SWE models lies on the non-hydrostatic terms. Some different forms of the dispersion SWE models are the Boussinesq-type models, non-hydrostatic shallow water models, or vertically averaged and moment equations models, see (Ginting & Ginting, 2020).

The dispersion SWE models are typically suitable for deep-water wave (short wave) simulations, where the wave speed depends on the wavelength making the vertical-length scale much greater than the horizontal one, and therefore, the non-hydrostatic effects cannot be neglected. In contrast, the non-dispersion SWE models are suitable for shallow-water wave (long wave) simulations, where the wave speed is independent of the wavelength, and thus, the vertical velocity component does not affect the pressure distribution and it satisfies the hydrostatic assumption. Based on this explanation, the dispersion SWE models should be employed for both short and long wave modeling especially for the simulations that include the wave transformation processes from the deep to the shallow water. However, this is not an easy task to be performed as the solution of the dispersion SWE is in general more difficult and more expensive to be computed than the non-dispersion ones.

The 1D SWE have been widely used as the governing equations to model wave propagation. Such equations are derived from the Navier-Stokes equations that describe the motion of fluid based on the conservation of mass and momentum. The dispersive effect is neglected in the original SWE by assuming a uniform vertical velocity distribution, and thus, a hydrostatic pressure assumption applies. In the recent work of (Audusse et al., 2021), the SWE were solved, where tsunami arrival time at the coast was computed precisely, but the wave's amplitude was not well predicted, especially the second and third waves that were more destructive than the first one. (Audusse et al., 2021) has also compared both dispersion and non-dispersion SWE models in simulating tsunami generated by a landslide; the former was in the form of the Boussinesq-type model. Interestingly, it was discovered that the non-dispersion model performs better than the dispersion one in the generation zone. However, in the propagation zone, the Bousinessq-type model behaves better than the non-dispersion SWE model because it considers the dispersive effects. In terms of complexity, the non-dispersion model has less complex computational procedures than the dispersion one. The other examples of accurate prediction for tsunami propagation using the non-dispersion model are shown in (Ginting & Mundani, 2019), (Arcos & LeVegue, 2014) and (Meister et al., 2016).

Being a partial differential equation, the SWE can be solved numerically using the finite difference methods. The Preissmann scheme is one of the most widely-used methods to conceptualize the 1D shallow flow governed by the SWE. Besides being robust and stable, another advantage of using this scheme is that the stability could be maintained over much larger time step values, thus being suitable for wave propagation modeling that typically includes a long simulation time. The application of the Preissmann scheme can be found in several popular commercial and non-commercial codes, e.g., DUFLOW (Clemmens A. J., 1993) and HEC-RAS (Brunner, 2021). Despite being simple and having a wide range of applications, the numerical solutions of Preissmann scheme may suffer from false oscillations, particularly when the flow conditions shift from free-surface flow to pressurized flow, and therefore, thorough studies need to be undertaken to investigate the accuracy of the Preissmann scheme.

Recently, (An et al., 2018) proposed a new hybrid numerical solution of the Preissmann scheme to solve this problem by combining the upwind flux solver and the centered flux solver. The Preissmann scheme is generally created for non-transcritical flows, but (Sart et al., 2011) employed this implicit finite difference scheme to solve transcritical flows by modifying the formulation only in transcritical zones while keeping its conservative properties. In this thesis, the accuracy of this scheme will be tested against three cases of different wave propagation problems: tidal wave, roll wave, and solitary wave. More details about the waves will be explained in the next chapter.

1.2 Problem Formulation

The non-dispersion SWE is discretized using the Preissmann scheme. Fundamentally, the numerical model is developed only for shallow water condition. However, to test the accuracy of the Preissmann scheme in modeling 1D wave propagation, three different cases of wave propagation are simulated. The first case is to simulate the tidal wave, which is typically a long wave problem. Secondly, the periodic permanent roll wave propagation is simulated without the turbulent term. Finally, the solitary wave propagation is simulated to observe the largest discrepancy the Preissmann scheme produces for such a case that has significant dispersion effect.

1.3 Objectives

The objectives of this research are formulated as follows:

- to solve the 1D SWE using the finite difference method (the Preissmann scheme) for modeling wave propagation;
- to conceptualize and investigate the wave characteristics, including water level and velocity based on the numerical model; and
- to provide a model framework by developing an in-house code that can be used for other similar cases.

1.4 Scope of Discussion

This research will focus on modeling 1D wave propagation using the SWE solved by the Preissmann implicit scheme. The model will be tested against some benchmark cases related to wave propagation: tidal wave; roll wave; and solitary wave.

1.5 Research Question

The main research question arising in this thesis is how accurate is the Preissmann implicit numerical scheme in modeling the different types of 1D wave propagation?