NUMERICAL SIMULATION OF REGULAR WAVES RUN-UP OVER SLOPPING BEACH BY OPEN FOAM

Parviz Ghadimi[1*], Mohammad Ghandali[2], Mohammad Reza Ahmadi Balootaki[3]
[1*, 2, 3] Department of Marine Technology, Amirkabir University of Technology

Abstract

Numerical simulation of wave tanks is an important field of interest for many researchers especially by freeware CFD tool box like OpenFoam which is an open source software. Many CFD problems that researchers encounter in ocean engineering field can be numerically solved by directly using or modifying the built in tool boxes in OpenFoam. In this paper, the Wave2Foam toolbox has been modified for generating a two dimensional regular wave, i.e. Airy wave theory or Stokes wave of first order. Toolbox WaveProperties is also utilized to change the wave properties like sea level, wave number, wave frequencies among others to get the desirable conditions. The obtained results are validated against theoretical solutions and favorable agreement is achieved. Finally, parametric studies are conducted to examine the effect of slopes and wave run-ups over different slopping beaches.

Keywords:

Regular Wave; Run-up; OpenFoam; Wave2Foam; Slopping Beach; Relaxation Zone Method

1. INTRODUCTION

In designing marine structures, behavior of structure under the influence of environmental condition such as wind, ocean waves, currents among others, is an important consideration. Specifically, pressure, force and velocity fields induced from waves must be calculated in order to examine the safety of marine structures in the ocean. This is indicative of the fact that study of wave hydrodynamics is important due to the necessity of calculating the velocity and force fields in order to satisfy the structure's designing requirements. Studying wave hydrodynamics started from past centuries when first theories of linear and nonlinear wave motions were improved and emphasis was more on the science than the design in ocean studies. Included in these theories are Airy wave for linear wave theory and Stokes of higher than first order for nonlinear water wave theories [1]. However, in twentieth and twenty-first centuries, professional researchers investigating the interaction of waves and fixed and floating structures have shown interest on them for more of design purposes. For example, Morison equation has been used for calculation of wave forces applied to the piles.

In the current decade, open source CFD software and codes have become noteworthy for researches in field of fluid dynamics and ocean engineering. The most important advantage of open source CFD software is the fact that the developed code is free and open to academic researchers and institutes. This advantage provides an opportunity for the researchers to have easy access to the source code which will enable them to further develop or modify it for solving their own CFD problems. More recently, the open source CFD software called OpenFoam has had wide range of use in the field of fluid dynamics and particularly in water wave mechanics. OpenFoam has been used for wave generation through different schemes and for creating a numerical wave tank in order to calculate the force induced waves on marine installations [2]. OpenFoam is the abbreviation of Open Field Operation and Manipulation and it is a library of C++ code which is free and accessible to every one. A researcher, depending on his or her need, may further develop and extend this CFD toolbox [2, 3, and 4]. In this paper, the OpenFoam 2.1.1 version is used for solving the described problem and the generated mesh by Gammbit software has been converted to OpenFoam mesh.

Wave generation and absorption have been investigated by many researchers by applying different methods and means [5], and in recent years by researchers like Jacobsen [6], Amini Afshar [7], and Lambert [8] by using OpenFoam software. For example, Amini Afshar [7] worked on wave generation and absorption in a wave tank. He changed the InterFoam solver in order to obtain computational solution inside the relaxation zones. The solver that was used in this study utilizes finite volume method for spatial discretization and VOF method for modeling the free surface.

Several previous numerical models for generating waves have faced several limitations like magnitude of forces induced by overturning waves on structures. This phenomenon occurs for two reasons: 1) because of depth-integrated nature of method, and 2) dependency of models on potential flow theory. In order to overcome these limitations, an alternative option is to use Reynolds averaged Navier-Stokes equations. By exercising this option, many difficult problems can be tackled, successfully. In some previous work like that by Morgan et al [9], solution did not have adequate outlet relaxation zones or in Afshar's work [7], the technique in relaxation method did not have refined computational mesh around the water surface to produce an accurate modeling of wave kinematics. These deficiencies were resolved in a work by Jacobsen [6]. Lambert [8] also developed a wave tank and generated the Stokes of second order wave and was able to simulate spilling, plunging and surging breaking waves over a sloped surface. His results were validated against an experimental data related to propagating regular waves over a submerged bar.

2. GOVERNING EQUATIONS

Wave generation is simulated in the current study by Reynolds averaged Navier-Stokes equations (RANS). The Waves2Foam toolbox within OpenFoam solves RANS equations by volume of fluid (VOF) technique. Linear wave theory or Stokes wave of first order in Waves2Foam toolbox is utilized which has a symmetric surface profile about the mean water level. This basically means that crests have the same shape as troughs. Generally, RANS equations are defined as in

$$\frac{\partial \rho u}{\partial t} + \nabla.[\rho u u^T] = -\nabla p^* - g.x\nabla\rho + \nabla.[\mu\nabla u + \rho\tau] + \sigma_{T\,k_\gamma \nabla_\gamma} . \tag{1}$$

For incompressible flows, continuity equation is

$$\nabla.u = 0 \tag{2}$$

where p^* is the difference between total pressure and hydrostatic pressure, ρ is fluid density, $u = (u, v, w)$ is velocity field in Cartesian coordinates, g is gravity acceleration, and μ is dynamic molecular viscosity of the fluid. Density $\rho = \rho(x)$ varies depending on the amount of air or water in a computational cell. τ is the Reynolds stress tensor given as where μ_t is dynamic eddy viscosity and $S = (1/2 (\nabla u + (\nabla u)^T))$ is strain rate tensor, and k is turbulent kinetic energy per unit mass. The last term in Eq. (1) is surface tension

$$\tau = \frac{2}{\rho}\mu_t S - \frac{2}{3}kI \qquad (3)$$

which consists of k_γ=surface curvature and σ_T=surface tension coefficient between air and water.

3. NUMERICAL SCHEME

Using special features of OpenFoam software, generation of Airy wave or Stokes of first order has been accomplished. This has been done using the Toolbox Waves2Foam. The Waves2Foam Toolbox, by using a particular feature called relaxation technique, decreases the computational error and provides a more accurate simulation.

3.1 RELAXATION TECHNIQUE

One of the most important features of Waves2Foam is its capability in applying a special scheme called Relaxation technique [10]. By this method, the reflected waves from boundries or internally generated waves near vertical boundaries are eleminated. In this technique, relaxation zones are updated for each time step based on the mesh evolution. On the other hand, relaxation weight is recalculated in each time step to reclaim small changes in cell position that originates from the mesh motion. This basically means that large mesh motion is inappropriate inside the relaxation zones. The relaxation technique consists of four different approaches: 1) Explicit Relaxation, 2) Numerical Beach, 3) Relaxation Weights, and 4) Relaxation Shapes [11].

4. VERIFICATION AND VALIDATION

A numerical wave tank has been prepared by OpenFoam using wave2Foam toolbox [6] by applying relaxation zone for wave generation and absorption. For validation of the generated Airy wave, numerical results of OpenFoam are compared against theoretical free surface profile provided by Airy wave theory. Comparison displays favorable match with good approximation, as shown in Fig.1.

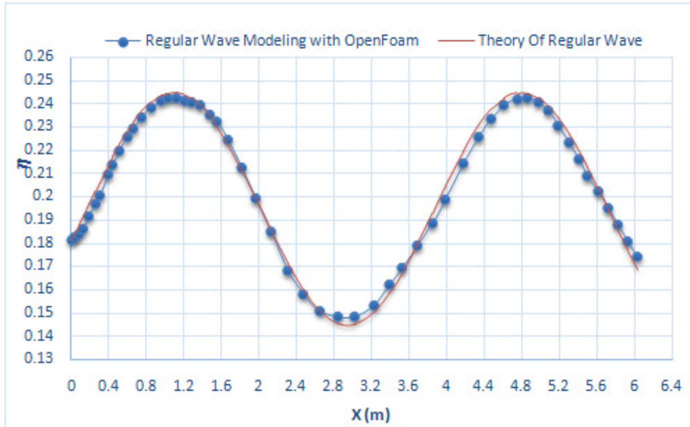

Fig.1. Comparison of the numerically generated wave against the theorical surface profile by Airy wave theory.

5. DISCUSSION OF RESULTS

A 2-D numerical wave tank has been produced using OpenFoam software. Length of the tank is 18 meter, height is 0.8 meter, sea level is considered to be 0.4 meter, and wave height is 0.1 meter. This tank is considered with different slopes ranging from 5 to 45 degrees, with 5 degrees increment. It is meshed in Gambit by an element size of 1 centimeter and converted to OpenFoam mesh. Appropriate boundary conditions are set in PolyMesh directory. The generated waves over the inclined surface of different slopes are analyzed. Gnerated profiles for different slopes are illustrated in Fig.2, while the peaks of run ups versus different slopes are complied in Fig.3.

Results indicate that, for a larger angle of inclination, run-up of the wave expectedly becomes smaller, but for a 5 degree slope, there is an exception to the general trend and run-up is lower than the others. The low nature of the run up at smaller slope is due to its particular way of breaking (plunging breaking) as opposed to others. Water surface profile for special case of 5 degrees slope is presented in Fig.4. As wave approaches the inclinded surface, for the purpose of demonstrating how exactly the breaking occurs in this case, snap shots of the run ups are illustrated at different time frames.

Fig.2. Airy wave run-ups on different slopping beds, ranging from 5 to 45 degrees.

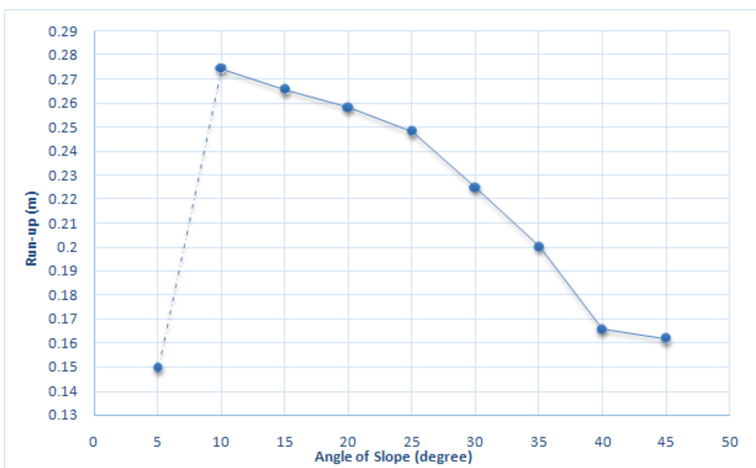

Fig.3. Plot of Airy wave run-ups versus different slopes.

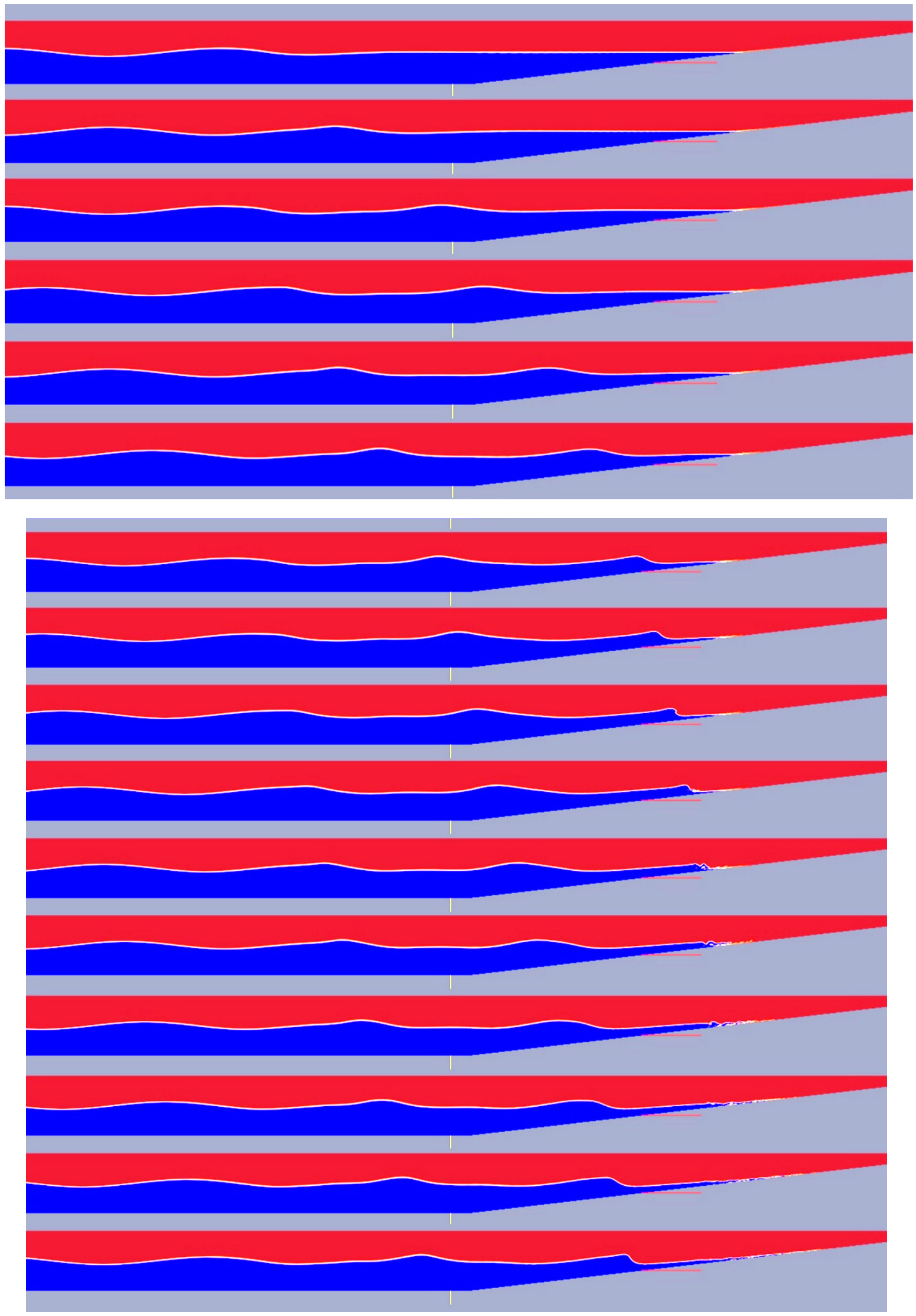

Fig.4.Water Surface profiles over 5 degrees sloped surface and presentation of wave breaking at different time frames.

6. CONCLUSION

A 2-D numerical wave tank has been produced using OpenFoam software. This has been accomplished by solving the Reynolds averaged Navier-Stokes equations (RANS). The Waves2Foam toolbox within OpenFoam solves RANS equations by volume of fluid (VOF) technique. The Toolbox WaveProperties is also utilized to change wave properties like sea level, wave number, wave frequencies among others to get the desirable conditions. Airy wave or Stokes wave of first order in Waves2Foam is generated. The numrically obtained waves are compared against theoretical Airy wave theory profile and favorable accuracy is demonstrated.

Subsequently, interaction of the generated waves with an inclined surface is simulated. A parametric study is conducted to examine the effects of different slopes of the surface on the wave behavior. Different wave breaking trend is observed for different slopes. Wave run-ups for most of the inclined surfaces follow a general trend, but for a slope of 5 degrees, the run-up exhibits a slightly different behavior.

REFERENCES:

[1] G. G. Stokes (1847), On the Theory of Oscillatory Waves, Proc. Camb. Philos. Soc, Vol. 8, pp. 441-455.

[2] http://www.openfoam.com, The open source CFD toolbox and OpenFOAM User Guide.

[3] Jasak, H., Jemcov, A., and Tukovi´c, Ž. (2007), OpenFOAM: A C++ Library for Complex Physics Simulations, in International Workshop on Coupled Methods in Numerical Dynamics: Dubrovnik, Croatia.

[4] CFD Online, http://www.cfd-online.com, 2011, An Online Center for Computational Fluid Dynamics.

[5] Lecture Notes For the Course in Water Wave Mechanics by Thomas Lykke Andersen & Peter Frigaard, DCE Lecture Notes No. 24, Alborg University Department Of Civil Engineering Water And Soil, July 2011.

[6] Jacobsen, N G and Fuhrman, D R and Freds, A Wave Generation Toolbox for the Open-Source CFD Library: OpenFoam, INTERNATIONAL JOURNAL FOR NUMERICAL METHODS IN FLUIDS,vol.70,No.9(2012),pp. 1073-1088.

[7] Amini Afshar, M, Numerical Wave Generation In OpenFOAM,Master of Sciences Thesis,CHALMERS UNIVERSITY OF TECHNOLOGY,Department of Shipping And Marine Technology,Goteborg,sweden.2010.

[8] Lambert, RJ, Development of Numerical Wave Tank Using OpenFOAM, Universidade de Coimbra, Master of Science Thesis,2012.

[9] Morgan GCJ, Zang J, Greaves D, Heath A, Whtilow CD, Young JR. Using the rasInterFoam CFD model for wavetransformation and coastal modeling Proceeding to Coastal Engineering Conference, Shanghai, China, 2010; 1-9.https://journals.tdl.org/ICCE/.

[10] Mayer S, Garapon A, Sørensen LS. A fractional step method for unsteady free-surface flow with applications to non-linear wave dynamics. International Journal for Numerical Methods in Fluids 1998; 28(2):293–315.

[11] http://openfoamwiki.net/index.php/Contrib/waves2Foam A wiki for OpenFOAM users the wiki page of wave2foam tool box.