Simulation of Wave and Current Processes Using Novel, Phase Resolving Models

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LONG-TERM GOALS

The long term goals of this project are to be able to predict nearshore waves, currents, and sediment transport accurately from >20m water depth through to the shoreline. We would like to accomplish this over as large an area as possible; on the order of tens of km^2, and to resolve all individual waves. Time periods simulated would be of order hours to days at maximum. We would also like to be able to directly couple these phase-resolving models with non-phase resolving models for integration into larger scale dynamics.

OBJECTIVES

The specific objectives of this project, which began 2.5 years ago, are to (1) Develop and test novel, fundamentally rotational phase-resolving wave-current systems which may have arbitrary order; (2) Code these theoretical systems and develop them into phase-resolving nearshore surf zone models; and (3) Couple with large scale wave/circulation models.

APPROACH

All of the budget for this project has gone to fund PhD student Yao Zhang, who is the major worker. Advisor and PI Dr. Andrew Kennedy is also working on this project, and graduate student Aaron Donahue (funded elsewhere) is working with us on theoretical development and implementation. We are also working on numerical implementation in concert with University of Texas Researchers Professor Clint Dawson and PhD student Nishant Panda.

Our fundamental technical approach is to represent nearshore water wave systems by retaining Boussinesq scaling assumptions, but without any assumption of irrotationality. We continue to assume a polynomial variation in horizontal velocity

$$\mathbf{u}(x,y,z;t)=\sum_{j=0}^{N}\tilde{\mathbf{U}}_n(x,y;t)\,f_n(q) \tag{1}$$

where $\boldsymbol{u}$ is the horizontal velocity, $f_n(q)$ is a polynomial function of $q\equiv(z+h)/(h+\eta)$, and $\tilde{\boldsymbol{U}}_n$ are coefficients that vary in horizontal coordinates and time. The specification of N, which controls the order of approximation, and f_n, which allows for asymptotic rearrangement, determines the system properties once the velocity expansion is integrated into Boussinesq-scaled continuity and Navier-

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Stokes equations. This is a generalization of the Boussinesq approach that allows for much more freedom in determining the system properties.

The resulting systems can have two forms: a classic Boussinesq-like appearance with mixed space-time derivatives but with several coupled equations; or a scaled pressure-Poisson-like form with polynomial vertical variation. Each has advantages for certain cases. We note that even though we are considering water wave systems, the scaled pressure-Poisson form may be quite useful for weakly nonhydrostatic ocean models.

WORK COMPLETED

Significant work has been accomplished by student Yao Zhang during this project. Systems have been developed, optimized and coded at $O(\mu^2)$ and $O(\mu^4)$. These have been implemented in Matlab and Fortran, and tested against theoretical and experimental results. We have derived and tested a new absorbing-generating sponge layer that is both more accurate and much simpler and more efficient to implement than internal wavemakers (Chawla and Kirby, 2000). Much of the past year has been spent deriving and testing the breaking and shoreline models needed to turn what were inviscid systems into fully rotational surf zone models.

One journal paper based has been accepted and published (Zhang et al., 2013a), and two more are in various stages of review (Zhang et al., 2013b; Panda et al., 2013). Two more journal papers are to be submitted in the next 1-2 months, dealing with modeling of wave breaking and runup, and on pressure-Poisson Boussinesq theory. We have made three conference presentations or posters at the AGU fall meeting, International Conference on Coastal Engineering; and Symposium on Shallow Flows.

RESULTS

Work over the past year has focused on three main goals: (A) Continued development and testing of the wave generation-absorption system, focusing on nonlinear accuracy; (B) Development and testing of the surf zone model; and (C) Theoretical development and testing of a pressure-Poisson approach to Boussinesq systems.

The wave generation-absorption system has now been shown to provide highly accurate results even for significantly nonlinear wave generation, if appropriate target waves are provided. Figure 1 shows the nonlinear accuracy using second order Stokes target waves, with excellent results to $H/h = 0.4$. These generation capabilities are well in advance of existing models, and would be straightforward to implement in other models.

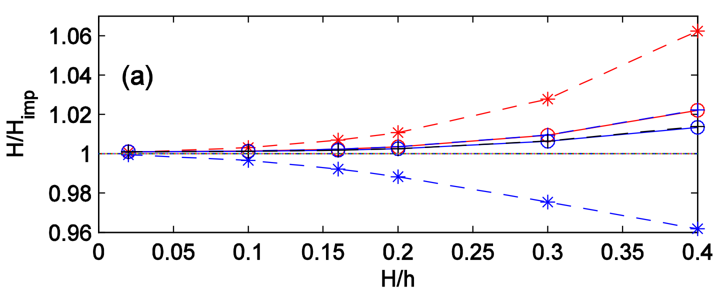

Figure 1. Maximum and minimum wave height envelopes using linear and second order generation and absorption. (-*-) Envelope for first order generation; (-o-) Envelope for second order generation; (-+-).

Most of the work over the past year has been focused on development and testing of the surf zone model, with particular emphasis on internal velocities and runup. It has typical Boussinesq abilities for the evolution of wave statistics as seen in Figure 2, and gives good results for this and other tests in the surf zone.

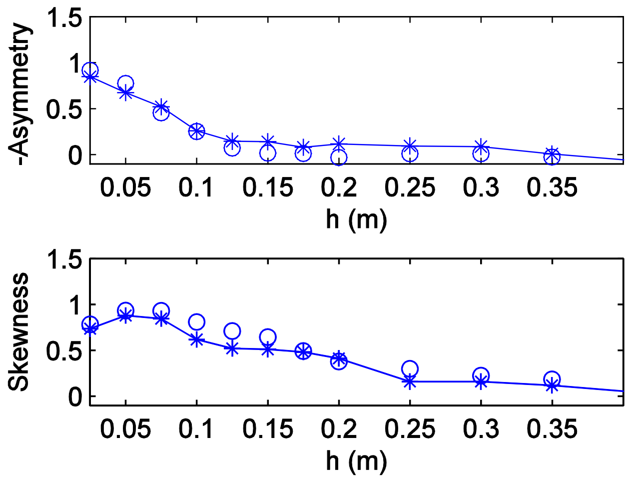

Figure 2. Asymmetry and skewness for irregular wave evolution. (-*-) Computations; (o) measured data.

However, the present rotational system has advanatages compared to quasi-irrotational Boussinesq models for representation of surf zone velocities. Figure 3 shows time-averaged horizontal velocities in the surf zone, demonstrating the ability of the system to represent undertow in a phase-resolving Boussinesq model. This is one of the major advantages of the present system, as compared to existing Boussinesq models.

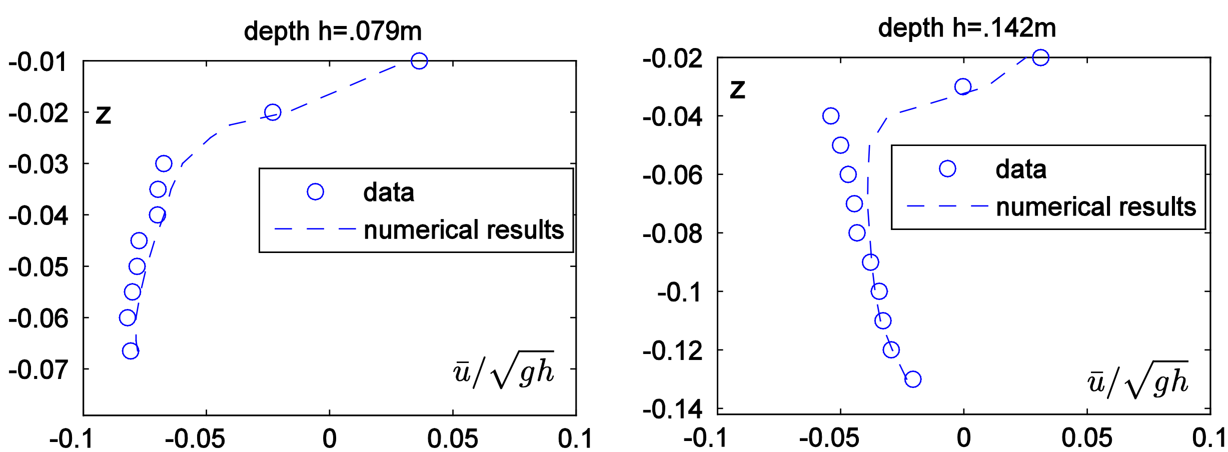

Figure 3. $O(\mu^4)$ variation of time-averaged horizontal velocity with depth for Plunging Breaking

Figure 4 shows wave runup on a sloping beach, demonstrating the importance of moving shorelines in the present model. When combined with the rotational capabilities of the present model, good results can be expected for the entire surf zone with reasonable computational costs. A journal paper based on this work is in its final editing stages, and will be submitted very shortly.

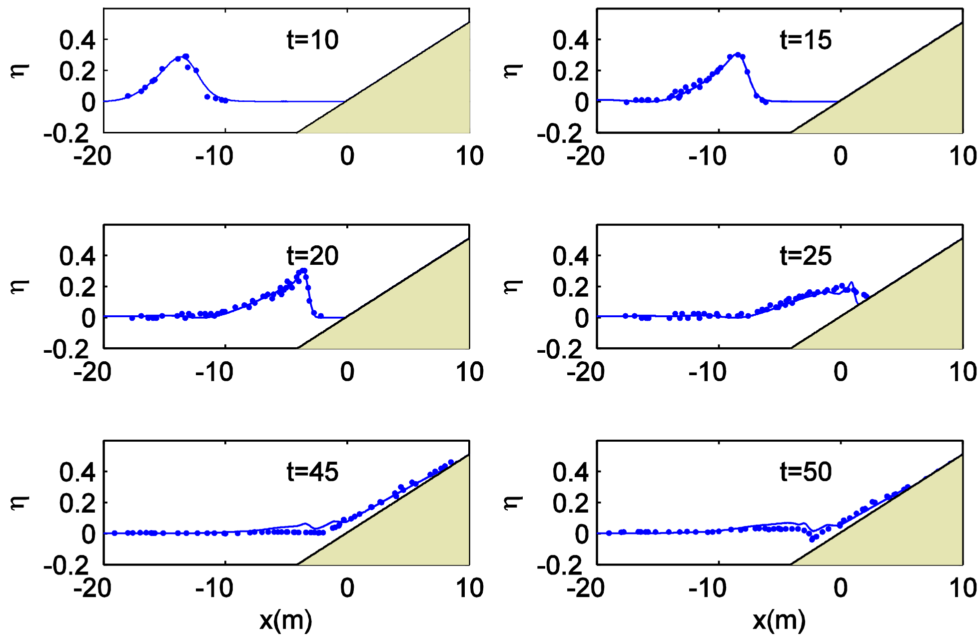

Figure 4. Wave runup on a sloping beach (dots: data; lines: numerical results).

Development of the pressure-Poisson Boussinesq theory has been one of the most exciting developments of the past year. In concert with graduate student Aaron Donahue (separate funding), we have developed Boussinesq models without the traditional mixed space-time derivatives. These have the form of shallow water equations with a modified pressure term, which may allow this type of system to be applied to existing shallow water ocean models. For both $O(\mu^2)$ and $O(\mu^4)$ systems, this means that systems are much simpler than comparable traditional systems, particularly if representative velocities are chosen wisely. Accuracy remains comparable to the most accurate $O(\mu^4)$ systems developed, with comparisons to the Dingemans shoal (Dingemans, 1994) that are as accurate as the fully nonlinear $O(\mu^4)$ system of Gobbi and Kirby (1999), but with much lower complexity. A journal paper based on this work is nearing completion and will be submitted in the next few months.

IMPACT/APPLICATIONS

The systems developed and tested here form a bridge between existing moderate accuracy, irrotational Boussinesq systems that can be used to simulate waves and large scale currents over relatively large coastal areas, but can not give details of hydrodynamics in the surf zone; and highly accurate Navier-Stokes models that can give excellent results over small areas but can not be used for large regions.

We expect them to be particularly useful for studies in the surf zone, including sediment transport and depth-varying undertow where standard Boussinesq models do not perform well. Variants of the main system being worked on by student Aaron Donahue will be useful in converting hydrostatic circulation models to nonhydrostatic models that may either be used in the surf zone or for other purposes.

The systems continue to be actively developed, and more complete and tested 2DH versions are expected within the next year. These will then be available for application on many coastal hydrodynamics problems.

RELATED PROJECTS

This project is directly tied to NSF project 1025519, which is a collaboration between Notre Dame, the University of Texas, and the Ohio State University. The present project has funding for a PhD student, Yao, Zhang, to work on these topics in collaboration with the other workers.

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