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 3.5 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-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). We now have derived, coded, and tested surf zone models for 1D and 2D that are now being used for process investigations.

Four journal papers based on this work have been published (Zhang et al., 2013, 2014a,b; Panda et al., 2014), and three more are in various stages of review (Zhang et al., 2014c; Donahue et al, 2014a; Kennedy et al., 2014). One more is in final stages of preparation (Donahue et al., 2014b). 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 two main goals: (A) Final model testing, writing, and publishing papers based on the surf zone model in 1D and 2D; (B) Coding, and testing a pressure-Poisson approach to Boussinesq systems. Theory and testing for the inviscid Green-Naghdi approach and nonlinear wave generation are complete and published, with good results.

The 1D and 2D breaking models have seen final development and testing. Good results have been obtained for standard tests in comparison to other models. Figure 1 shows runup comparisons for a solitary wave incident on a beach. This and many other results are given in Zhang et al. (2014b). This is the first $O(\mu^4)$ surf zone model to be implemented – all other results in the literature are of $O(\mu^2)$. Results show that the lower order models can give good surface elevation profiles, but the higher order models provide much better representations of internal velocities, as would be expected.

For 2DH, coding and testing took place this year, with one paper submitted for publication (Zhang et al., 2014c). Numerous tests were conducted, including solitary wave breaking on a conical island, wave breaking on a complex shoal, and rip current simulation. Figure 2 shows computed and measured water levels from the conical island test, with good agreement overall.

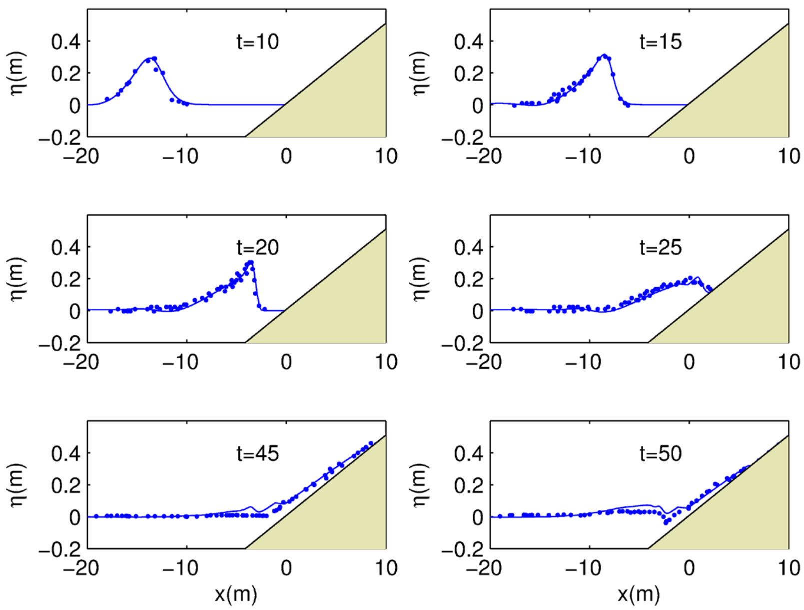

Figure 1. Runup of a solitary wave on a beach with the Boussinesq-Green-Naghdi surf zone model (from Zhang et al., 2014b).

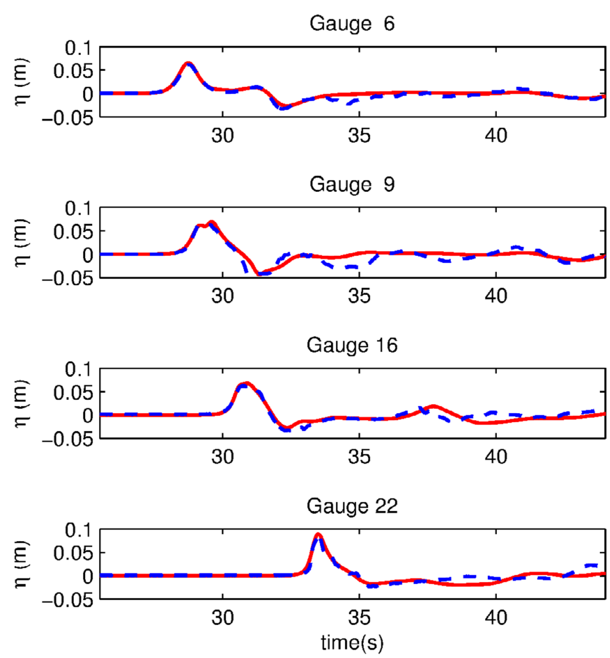

Figure 2. Water level comparisons for 2D transformation of a solitary wave around a conical island (from Zhang et al., 2014c).

The model has seen its first applications for field data, and is being used to compute runup driving boulder transport for Typhoon Haiyan (2013), which saw 30 tonne boulders transported to 8m above sea level. Figure 3 shows computed transport for different storm wave heights, and measured boulder transport. This and other results using the model are in submitted paper Kennedy et al. (2014).

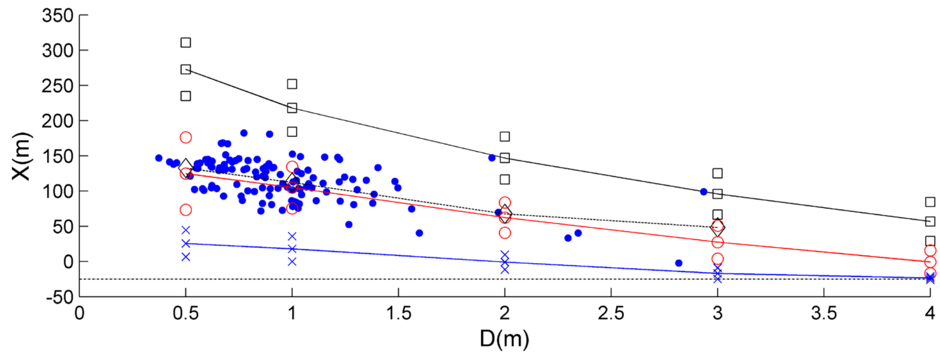

Figure 3. Computed and measured terminal locations for boulders with varying sizes. (●) Individual Measured; (-◊-) Measured Binned Means; (□) Computed±1 standard deviation using 1.0Hs; (o) Computed±1 standard deviation using 0.75Hs; (x) Computed±1 standard deviation using 0.5Hs; (-·-) Initial location.

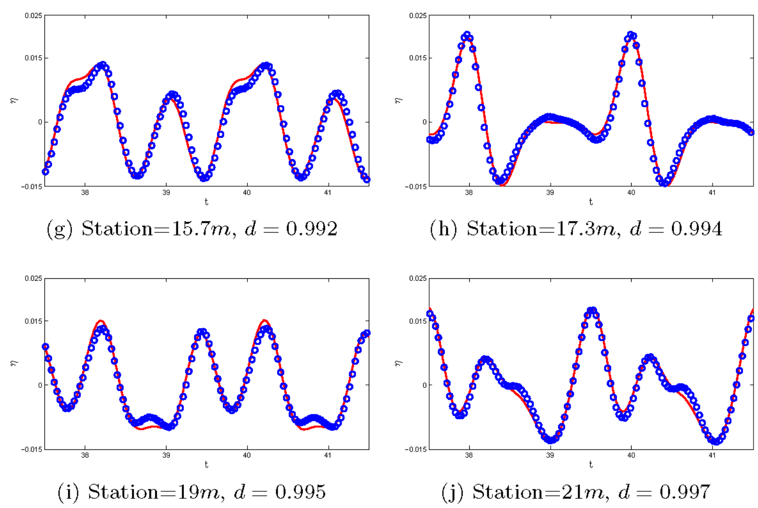

Figure 4. Comparison for the PP4 simulation on Beji and Battjes Case (A), between the observed data (circles) and modeled data (line), d represents the index of agreement.

Further development of the pressure-Poisson Boussinesq theory has been one of the most exciting developments of the past year. These have developed Boussinesq models without the traditional mixed space-time derivatives, which means that systems are much simpler than comparable traditional systems, particularly if representative velocities are chosen wisely. One paper (Donahue et al., 2014) has been submitted and is nearing final acceptance. Figure 4 shows computed and simulated waves over a submerged shoal using the $O(\mu^4)$ version of the equations. Results are excellent, and comparable to the best ever recorded over this setup. Further work on surf zone extensions in 1D and 2D are ongoing, and a paper will be submitted soon.

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. These are being inserted into the ONR-funded model FUNWAVE-TVD as a model physics option.

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 (who just graduated), to work on these topics in collaboration with the other workers.

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