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13. ABSTRACT (Maximum 200 words)

A curvilinear grid version of a Boussinesq model for application to tidal inlets and other complex domains has been completed and a resulting manuscript published. The resulting model will be transferred to Army labs at their request. A means for extending the Boussinesq formulation to account for a correct description of vertical vorticity has been found, and the code has been extended to include an edc viscosity formulation to damp vortical motions resulting in strongly sheared flows. Recent tasks include

(1) Completed the description of the vorticity-conserving model and report findings to a technical journal.

(2) Tested the model against experimental data on separation and vortex generation in the context of solitary wave scattering by a thin wall. Completed a Master's thesis related to this work.

(3) Completed comparison to lab data from the Ponce de Leon Inlet model study conducted by the Coastal Hydrau Lab, USACOE WES.

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Final Progress Report
Boussinesq Modelling of Waves in Harbors and Tidal Inlets

DAAG55-98-1-0173

James T. Kirby and Robert A. Dalrymple

July 12, 2001

Statement of Problem Studied

Our first project goal was to develop a curvilinear grid version of a Boussinesq model for application to tidal inlets and other complex domains. This goal has been achieved , and the model has been documented (Shi et al, 2001a). The resulting model has the flexibility of modeling wave breaking and shoreline runup, and is thus fully applicable to studies of realistic inlet geometries and adjacent coastal areas. Extensive comparisons with lab data for the Ponce de Leon Inlet model study, conducted by the Coastal Hydrodynamics Lab, USACOE WES, have been completed as a further test of the curvilinear model. This work will be reported shortly (Shi et al, 2001b), 2001c

During this work, a means for extending the Boussinesq formulation to account for a correct description of vertical vorticity has been found, and the code has been extended to include an eddy viscosity formulation to damp vortical motions resulting in strongly sheared flows. This extension to the formulation has been tested in comparison to lab data on flow separation and vortex formation during the passage of wave crests past thin barriers. The ability to reproduce this behavior is crucial to the problem of determining entrance losses for flows in constricted harbor entrances, and has not been previously accessible with this category of models. In order to study this problem, laboratory experiments on flow separation induced by solitary waves passing through gaps have been conducted. Experimental results have been compared to model predictions in order to test the formulation of eddy viscosity terms in the curvilinear model. A Masters thesis has been completed, and results have been reported at a conference.

Numerical and analytical properties of staggered and un-staggered grid versions of the Boussinesq code have been investigated, and the level of noise in the two models has been found to be comparable. The staggered grid model has been found to be more accurate in terms of linear wave propagation as grid resolution decreases. These aspects as well as a basic stability analysis are presently being documented.

The model has been tested against field data from the DELILAH field experiment (Duck, N.C.) and has been found to give accurate reproduction of time averaged mean flows. A journal manuscript describing this work is in preparation (Chen et al, 2001).

Although the topic was dropped during the initial evaluation of the scope of the project, we have had a chance to pursue the second goal of developing a model which is applicable to three-dimensional current fields with both horizontal and vertical vorticity distributions. This work has led to the development of a model of weakly dispersive waves in one horizontal dimension, riding on currents with arbitrary vertical distribution of horizontal vorticity. The model is presently being tested against laboratory data and will be presented by Rego et al (2001).

Summary of Most Important Results

A curvilinear grid version of a Boussinesq model for application to tidal inlets and other complex domains has been completed and a resulting manuscript published. The new model code is based on high-order finite differences applied on a staggered grid scheme. The resulting model is more stable than the existing FUNWAVE code (Kirby et al, 1998), requiring considerably less numerical filtering and iteration to achieve accurate results. The curvilinear model can also handle complex areas with more flexibility than the original Cartesian grid model. The model has been applied to the study of waves in Ponce de Leon Inlet, Florida (Shi et al, 1999, 2001b, 2001c), and to the generation and shedding of vertical vortex cores during the passage of wave crests past vertical breakwater edges (Hommel et al, 2000, 2001).

Errors in the original formulation of Wei et al (1995) and Chen et al (2000a) pertaining to the representation of the second order correction to vertical vorticity have been identified and corrected by Chen et al (2000b) and Chen et al (2001), and extensive calculations of nearshore wave fields have been conducted using the corrected model. We have shown that the Boussinesq model is capable of correctly modeling mean longshore currents in field situations, as well as rip currents in laboratory settings (Chen et al, 1999). Model predictions of unsteady longshore current fluctuations have been collected and will be compared to field data in the near future.

The results of the present study are presently being incorporated in an updated release (to be designated version 2.0) of the Boussinesq model code FUNWAVE (Kirby et al, 1998, 2001). The new code provides extensions to cover curvilinear coordinate systems and enhancements to vertical vorticity transport described above. In addition, several enhancements to nonlinear properties in the model (Kennedy et al, 2001a, Kennedy et al, 2001b) are incorporated in the release. A review of the present state of the FUNWAVE model and the Boussinesq modelling technique in general is being prepared by Kirby (2002) for inclusion in the book *Advances in Coastal Modeling* by Lakhan (2002) and will provide a detailed overview of the results of this project.

Publications and Technical Reports

(a) Peer-reviewed journal articles

Shi, F., Dalrymple, R.A., Kirby, J.T., Chen, Q. and Kennedy, A., "A fully nonlinear Boussinesq model in generalized curvilinear coordinates," *Coastal Engineering*, 42, 337-358, 2001a.

(b) Conference proceedings

Chen, Q., Kirby, J.T., Dalrymple, R.A., Kennedy, A.B., Thornton, E.G. and Shi, F., "Boussinesq modelling of wave and longshore currents under field conditions," *Proc. 27th Int. Conf. Coastal Engineering*, Sydney, 651-663, July, 2000b.

Hommel, D., Shi, F., Kirby, J.T., Dalrymple, R.A. and Chen, Q., "Modelling of a wave-induced vortex near a breakwater," *Proc. 27th Int. Conf. Coastal Engineering*, Sydney, 2318-2330, July, 2000.

(c) Papers presented at meetings

Kirby, J. T., presentation at "Waves in Inlets" Workshop, U. S. Army Corps of Engineers, San Francisco, CA, 9/30-10/1/99.

Shi, F., Kirby, J.T., Dalrymple, R.A., Chen, Q. and Zhen, F., "Wave simulations in Ponce de Leon inlet using a curvilinear Boussinesq model," presented at American Geophysical Union Fall Meeting, San Francisco, December 13-17, 1999. (Abstract published in EOS, Transactions AGU, 80, F497, 1999.)

Kirby, J. T., presentation at "Joint ARO-ONR Coastal Research Discussion Meeting", Duck, NC, Jan. 22-23, 2001.

(d) Manuscripts submitted or in preparation

Chen, Q., Kirby, J.T., Dalrymple, R.A., Shi, F. and Thornton, E.G., "Boussinesq modelling of longshore currents," to be submitted to *J. Geophys. Res.*, 2001.

Shi, F., Kirby, J. T., Dalrymple, R. A. and Chen, Q., "Wave simulations in Ponce de Leon Inlet using a curvilinear Boussinesq model", to be submitted to *Coastal Engineering*, 2001b.

Shi, F., Kirby, J. T., Dalrymple, R. A. and Chen, Q., ``A curvilinear Boussinesq model and its application", to be presented at Waves'01, San Francisco, September 2001c.

Rego, V. S., Kirby, J. T. and Thompson, D., ``Boussinesq waves on flows with arbitrary vorticity", to be presented at Waves'01, San Francisco, September 2001.

(e) Technical reports submitted to ARO

Hommel, D. L., Kirby, J. T. and Shi, F., "Vortex formation resulting from solitary wave interaction with a breakwater", Report CACR-01-03, Center for Applied Coastal Research, University of Delaware, July 2001.

Participating Scientific Personnel

(1) James T. Kirby, Professor

(2) Robert A. Dalrymple, Professor

(3) Fengyan Shi, Visiting Scholar

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(5) Lisa Hommel, Graduate Research Assistant, Master of Civil Engineering, Fall 2000. Thesis: Vortex formation resulting from solitary wave interaction with a breakwater.

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Chen, Q., Kirby, J. T., Dalrymple, R. A., Kennedy, A. B. and Chawla, A., "Boussinesq modeling of wave transformation, breaking and runup. II: Two horizontal dimensions", *J. Waterway, Port, Coastal and Ocean Engrng.*, 126, 48-56, 2000a.

Kennedy, A. B., Kirby, J. T., Chen, Q. and Dalrymple, R. A., ``Boussinesq-type equations with improved nonlinear behavior", *Wave Motion*, 33, 225-243, 2001a.

Kennedy, A. B., Kirby, J. T. and Gobbi, M. F., ``Simplified higher order Boussinesq equations. 1: Linear simplifications", submitted to *Coastal Engineering*, January 2001b.

Kirby, J. T., "Modeling shoaling and breaking surface waves and resulting currents using Boussinesq models", in preparation for *Advances in Coastal Modeling*, C. Lakhan (ed), Elsevier. To be published in 2002.

Kirby, J. T., Wei, G., Chen, Q., Kennedy, A. B. and Dalrymple, R. A., ``FUNWAVE 1.0. Fully nonlinear Boussinesq wave model. Documentation and user's manual", Report CACR-98-06, Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware., 1998

Kirby, J. T., Wei, G., Chen, Q., Kennedy, A. B., Long, W., Shi, F. and Dalrymple, R. A., ``FUNWAVE 2.0. Fully nonlinear Boussinesq wave model. Documentation and user's

manual", Report CACR-01-?? (in preparation), Center for Applied Coastal Research, Department of Civil and Environmental Engineering, University of Delaware., 2001.

Lakhan, C., *Advances in Coastal Modeling,* to be published in the series *Elsevier Oceanography Series,* 2002.

Wei, G., Kirby, J. T., Grilli, S. T. and Subramanya, R., "A fully nonlinear Boussinesq model for surface waves. I. Highly nonlinear, unsteady waves", *Journal of Fluid Mechanics*, 294, 71-92, 1995.

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