Development of a "Spot-Application" Tool for Rapid, High-Resolution Simulation of Wave-Driven Nearshore Hydrodynamics

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LONG-TERM GOALS

This project is driven by the desire to simulate wave-driven process in large domains with fine-resolution, while including tide, river, and wind forcings that exist across multiple orders of magnitudes of spatial scales. We aim to explicitly couple large-scale flow models, such as Delft3D, with our developed Boussinesq-type model. The vision of this project is to develop an operational tool for the prediction of O(1 m) resolution hydrodynamics in the coastal zone.

OBJECTIVES

The targeted objectives for this project are as follows:

- Identify a particular location, such as a beach, river mouth, inlet, or harbor for which detailed predictions of wave height, currents, and transport are needed
- Extract the 3D current and density fields in the area from an existing Delft3D simulation. This information will be used as the background current/density field, which the waves interact with through the domain
- Obtain wave spectra and wind information near the location, either from in-situ measurements or large-scale wave models. This information will be used to drive the offshore wave boundary condition.
- Execute the Boussinesq simulation using the above information, and extract the desired information (e.g. Hmax maps, currents, etc.)

Such a tool could be used to simulate particular "spots" along the coastline where high-resolution wave detail is desired, using output from an operational model to drive the background current and boundary conditions.

APPROACH

Our goal is to develop a validated and benchmarked model to look at nonlinear wind wave evolution in sheared and stratified nearshore environments with large-scale (10-100+ km^2 horizontal) domains and fine resolution (~ 1 m horizontal). The theory to tackle this problem is already developed, but requires further validation and numerical implementation, and these are our two main scientific interests.

The numerical tool must have the ability to be applied for domains on the scale of 100 km^2 horizontal. This is not a simple request for a model that requires a horizontal resolution on the order of a few meters to properly resolve the wind waves. An optimum approach is to implement a hybrid/coupling approach, wherein different models with various resolutions and physical approximations are meshed together (e.g. Sitanggang & Lynett, 2009; Son et al., 2011). For this study, an ideal model to match with the Boussinesq-type theory would be one which can simulate sheared and stratified currents due to large-scale (non-wave) forcings. Direct coupling the Boussinesq-type wave model with larger-scale tools such as Deflt3D would permit the efficient use of the high-resolution wave model, but also include regional forcing due to tides, rainfall, wind, and river flow.

Our initial focus has been on explicit coupling of the Boussinesq-type model with the other hydrodynamic "flow" models used in existing ONR efforts. We have utilized DEFLT3D on this component. Due to the very different physical approximations and computational needs between the two sets of models (the Boussinesq-type and the DEFLT3D model), two-way coupling may not be feasible. Thus we are developing a one-way coupling methodology, as shown in Figure 1, where:

- the DEFLT3D model is run first, without any wave effects included
- the 3D current and density field predicted by DEFLT3D is imported into the Boussinesq-type model as an external, background flow field, following the theory in Son & Lynett (2013)
- The Boussinesq-type model is run, where the simulated waves "feel" the effects of the current and density field provided by DEFLT3D

The above approach is a very efficient method for multi-scale, multi-model simulation, and allows for resolution of wave-driven processes with O(1 m) resolution while including the regional / basin-scale forcing. Once developed, the hybrid model will be used to simulate the waves and flow at field sites with available measured field data. With the field-data comparison, the fully benchmarked and validated numerical tool will be applicable to a wide-range of nearshore processes and could be utilized at coastal areas worldwide.

Simultaneous to this coupling effort, we will investigate methods to include wind stress effects on the waves in the Boussinesq model; on the large spatial scales we plan to investigate, wind effects may not be negligible on the waves and currents. Initial efforts in this area have been completed by Chen et al. (2004). In the past year, Lynett's research group has been working to develop a surface boundary layer formulation appropriate for integration with Boussinesq-type models, similar to our work on bottom boundary layers (Kim et al., 2009). These efforts have shown some promise in capturing the vertical structure of wind-induced currents, and will be coupled with nonlinear waves here.

WORK COMPLETED

Over the past year, the free version of Deflt3D-Flow module and Delft3d-Wave module (SWAN) has been downloaded, compiled, and tested. The software has been used to run different cases for standalone flow simulations, for standalone wave simulations (SWAN), and for the combined cases of flow-wave simulations. The New River Inlet bathymetry as recorded during the experiment and the experimental data collected by WHOI Raubenheimer/ Elgar group have been used in validating the Delft-3D model. To provide the tidal forcing for the simulations, the tide signal has been extracted using t-tide software from the field data and used to force Delft3D-Flow model. Comparisons are between Delft3d-Flow results and the field data for different gauge locations are shown in Figure 2. The model results agree well with the field data as shown in the following figures; note that the figures shown do not yet include the effects of the waves from the Boussinesq model.

To bring the effects of the waves into the simulation framework, the Boussinesq model "COULWAVE" is employed. With this Boussinesq-type model, we modify the concept of wave-current modeling as presented in Son and Lynett (2014) to combine the Boussinesq waves with the Deflt3D currents. To date, we have implemented this method, and tested with Boussinesq model with "simple" one-dimensional currents provided by Deflt3D. An example of these comparisons are shown in Figure 3, which is a recreation of the experiments of Swan (1990), for single harmonic waves over following and opposing currents. The model agreement with the measured velocity time series are excellent.

RESULTS

The project is still in the model development stage, and thus as yet there are no substantial results related to the Boussinesq-Delft3D model coupling to discuss yet. This project has been funded and actively worked on at USC for just over one year. As part of the wave-current and wave-surface stress coupling theory, we have completed an effort to efficiently include the boundary layer profile within a Boussinesq-like wave model. The underlying concept of this approach is to divide the flow field into a potential component and rotational / viscous component, where the potential component is driven by the wave field and the rotational component by the boundary (bottom or free surface) stresses. Nonlinear terms allow for these two components to interact. This model has been demonstrated to be very accurate at predicting the bottom shear stress under nonlinear and dispersive waves (see Figure 4). A paper on this topic is currently under review.

IMPACT APPLICATIONS

The overall objective of this project is to setup the modeling system for operational-like usage. A simple model interface will be created such that a "complete" tides+waves simulation can be run with only the specification of the date/time (to provide the DELFT3D tidal forcing) and an offshore wave & wind condition. It is the hope and expectation that the end result of this effort will provide a demonstration of the operational usability of Boussinesq-type models.

RELATED PROJECTS

This modeling ability to be developed in this project will be useful for simulating the data recorded during the RIVET I and II field surveys.

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PUBLICATIONS

El Safty, H. and Lynett, P. (2014) "Bottom Boundary Layer Motions Forced by Long and Short Free Surface Waves." in review for Journal of Waterway, Port, Coastal, and Ocean Engineering (ASCE)

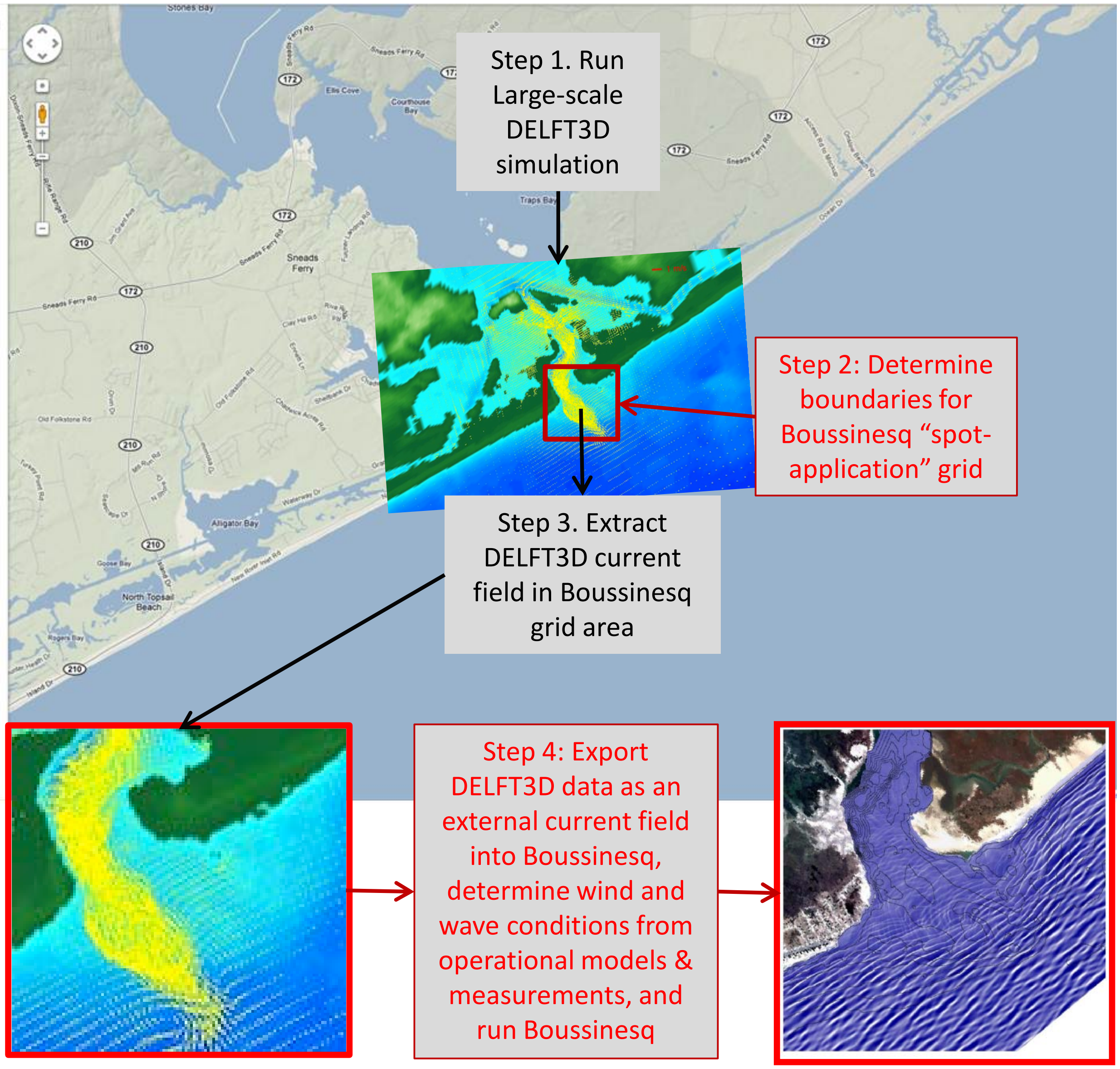

Figure 1. Procedure for coupling DELFT3D and Boussinesq model for combined circulation and wave simulations.

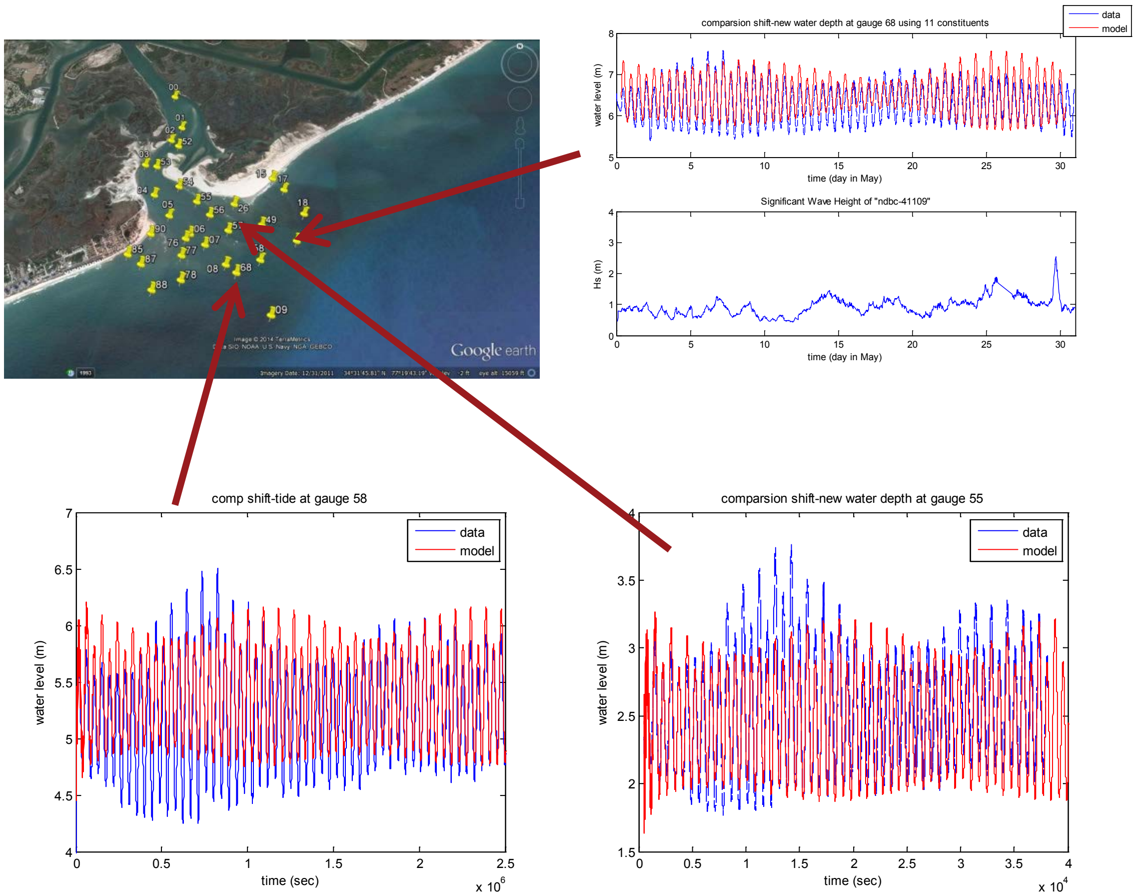

Figure 2. Comparison between measurement water surface elevation (blue) and tide-only simulations (red).

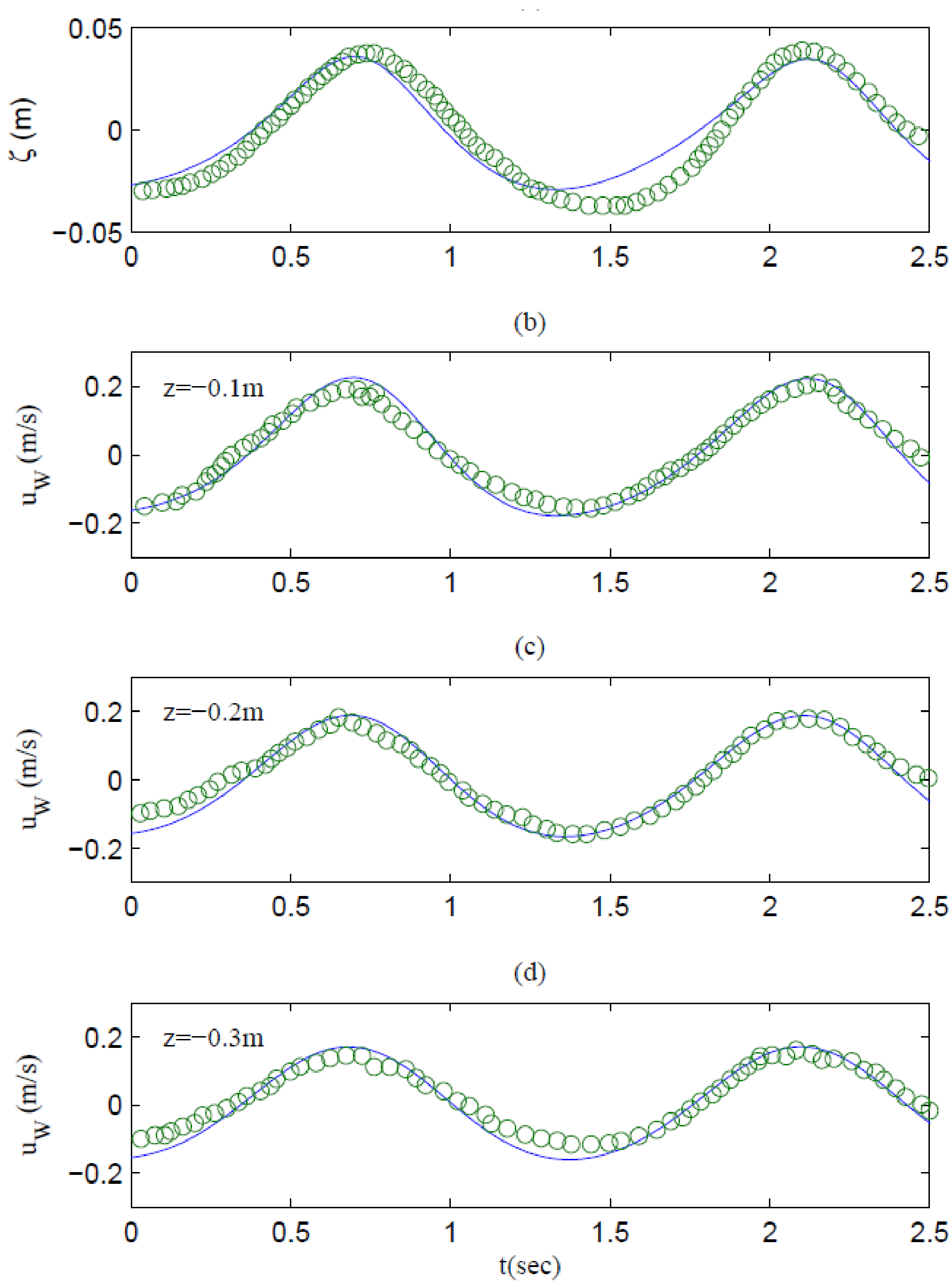

Figure 3. Comparison of wave records under following, uniform current (Case 1F in Swan, 1990) between experiment (o) and numerical solution(-): surface elevation(a) and oscillating velocities at z=-0.1m(b); at z=-0.2m(c); at z=-0.3m(d)

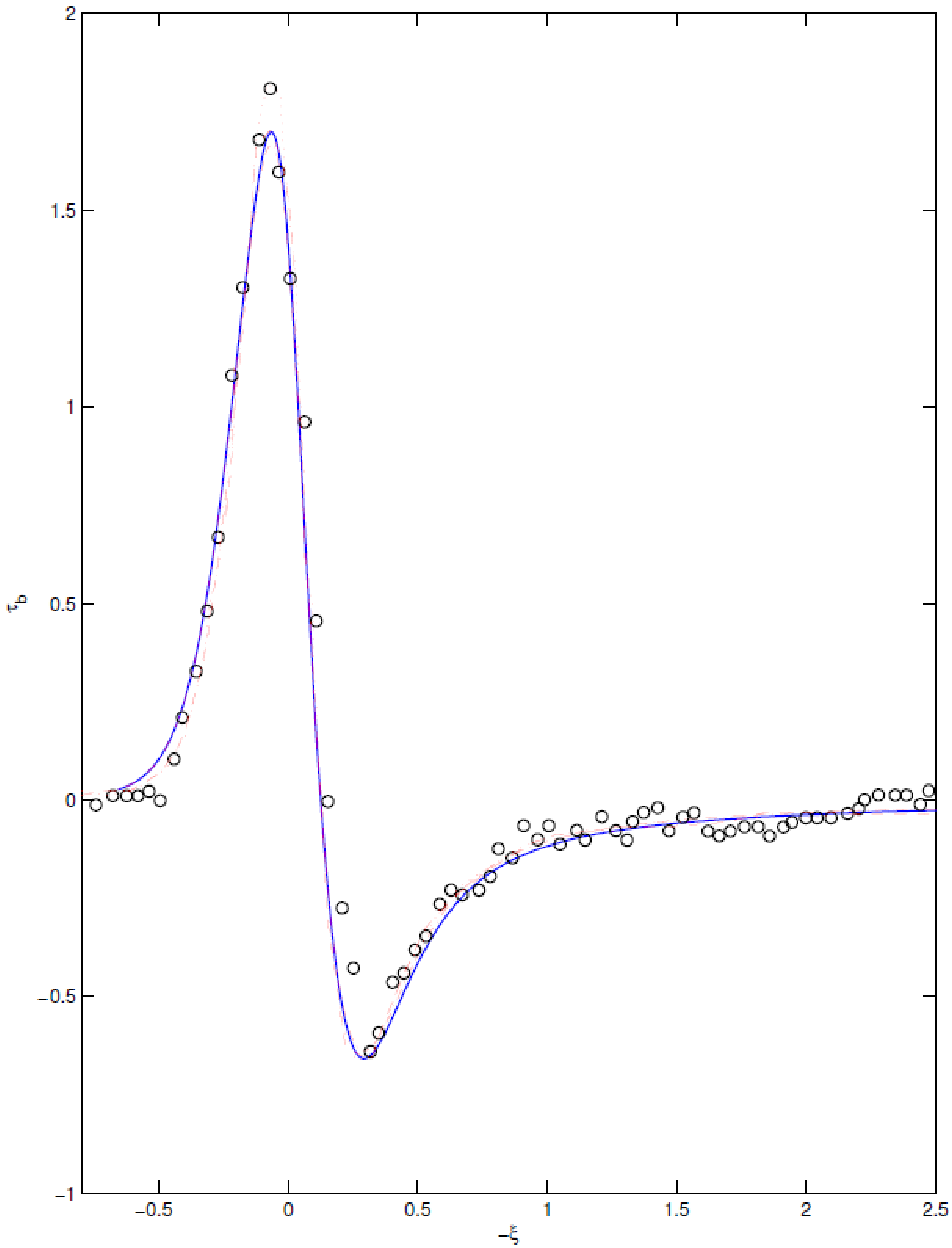

Figure 4. Time history of the dimensionless bottom bed shear stress under a solitary wave. Solid line: model solution; circles: Experimental data of Liu et al. [2007].