CHAPTER 169

Simulation of nearshore wave current interaction by coupling a Boussinesq wave model with a 3d hydrodynamic model

ROBERTO MAYERLE, ANDREAS SCHRÖTER and WERNER ZIELKE [1]

ABSTRACT

This paper describes a deterministic modelling system under development at the Institute of Fluid Mechanics in Hannover to simulate three dimensional wave induced currents and the morphological evolution in the nearshore region. It is basically a coupling of a 2d Boussinesq wave model which predicts the wave motion along the horizontal direction with a 3d hydrodynamic, sediment transport and morphodynamic models that simulate the time averaged wave induced currents and the associated changes in the bathymetry due to sediment transport. It is intended to improve the understanding of morphological processes, investigate the impact of sea level rises due to climate change, study extreme events and assess in the selection of cost effective measures for coastal protection. Results of a demonstration of the simulation of the wave induced currents along a nearshore region in the Baltic Sea are shown.

1. INTRODUCTION

Along the coast it is possible to distinguish between the erosion processes due to mean hydraulic conditions, that has an impact on large time scales (seasons, years), and due to extreme hydraulic conditions, that are restricted to small time scales (hours to days). Beach and dune erosion at large time scales are usually due to net positive, longshore sediment transport gradients. Short term erosion takes place occasionally during less frequent extreme events such as storms and hurricanes and the significant profile changes are restricted to the upper part of the coastal profile.

On the other hand, the morphological evolution in the nearshore region is the result of highly complicated three dimensional processes that combine tur-

[1]Institute of Fluid Mechanics and Computer Applications in Civil Engineering, University of Hannover, Appelstr. 9 A, D-30167 Hannover, Germany

bulent, oscillatory (wave) and current motion. In particular within the breaker zone the turbulence generated by wave-breaking is intensive. A number of hypotheses have been formulated to decribe the process of bar formation within the surf zone. Although it may involve several mechanisms, the most reasonable explanation relates to the wave driven circulation currents in the vertical plane known as undertow. If a movable bed with constant slope is exposed to waves, a bar will develop close to the point of wave breaking. This is due to the sediment transport within the breaker zone being directed away from the coast due to the undertow. Besides, intensive wave breaking generates high turbulence levels causing large amounts of sediment to suspend, thus being the transport of this suspended sediment the predominant transport mechanism under such conditions.

Until recently most of the numerical model simulations in the nearshore region have been carried out using 2d models. Although in some cases it is possible to capture the main patterns with depth or laterally averaged models, only part of the sediment transport is taken into account, i. e. either the longshore or the cross-shore sediment transport is captured. In other words the models describe either the transport along with time and depth averaged currents, or the transport due to waves and vertical circulations in a more or less cross-shore profile. In more complex situations, it makes little sense and neither transport should be neglected.

Nowadays, there are a number of numerical models under development for short term coastal profile evolution for direct incoming waves. An intercomparison among six models developed with different degrees of refinement and empirism was carried out by Hedegaard et al., 1992. The models were tested against experimental results obtained at the large wave flume in Hannover in a pure 2d depth vertical case. The results showed that it is relevant to go to full or quasi 3d modelling of currents and suspended sediment to be able to judge where the major research efforts should be spent in the years to come (Roelvik and Brøker, 1993).

The 3d modelling system under development is intended to handle short term events in the nearshore region and to reproduce wave induced currents and the associated changes in the bathymetry adequately. It is also to improve the understanding of morphological processes, investigate the impact of sea level rises due to climate changes, study extreme events and assess in the selection of cost effective measures for coastal protection. With the improvements in computer efficiency and algorithm performance, process-based or deterministic wave modelling in the time domain are within reach. However, unless the wave phenomena in the horizontal direction is properly simulated there is little gain in going to three dimensional modelling. As linear wave models do not apply well in the nearshore region, the proposed modelling system is a coupling of a 2d nonlinear time discrete Boussinesq wave model with a 3d hydrodynamic and sediment transport models. The wave model computes the wave field along the horizontal direction whereas the 3d model is responsible for the time averaged wave induced currents and the associated changes in the bathymetry due to sediment transport. The suggestions proposed by Svendson and Lorenz (1989) in solving a modified set of the Navier-Stokes equations for three dimensional wave induced currents were followed. The radiation stresses, wave set-up and wave trough level needed for the solution of these equations result from the application of the wave model. A description of the approach adopted and a demonstration of the simulation of the wave induced currents along a small stretch on the German coast in the Baltic Sea are presented.

2. APPROACH

The three dimensional wave induced currents are described by a set of modified Navier-Stokes and the continuity equations that are solved respectively for the velocities along the horizontal plane and vertical. The velocities along each direction (x, y and z) are replaced by three contributions respectively: the mean (current) component (U, V and W); a purely periodic component correspondent to the wave motion (u_w, v_w and w_w) and a turbulent velocity fluctuation (u', v' and w') as follows:

$$\left.\begin{aligned} u &= U + u_w + u' \\ v &= V + v_w + v' \\ w &= W + w_w + w' \end{aligned}\right\} \tag{1}$$

The resulting set of modified Navier Stokes equations (Svendson and Lorenz, 1989) are:

$$\begin{aligned} \frac{\partial U}{\partial t} + \frac{\partial U^2}{\partial x} + \frac{\partial UV}{\partial y} + \frac{\partial UW}{\partial z} + \frac{\partial(\overline{u_w^2} - \overline{w_w^2})}{\partial x} + \frac{\partial \overline{u_w v_w}}{\partial y} + \frac{\partial \overline{u_w w_w}}{\partial z} &= \\ - g\frac{\partial b}{\partial x} - \frac{\partial(\overline{\tilde{u}'^2} - \overline{\tilde{w}'^2})}{\partial x} - \frac{\partial \overline{\tilde{u}'\tilde{v}'}}{\partial y} - \frac{\partial \overline{\tilde{u}'\tilde{w}'}}{\partial z} & \end{aligned} \tag{2}$$

$$\begin{aligned} \frac{\partial V}{\partial t} + \frac{\partial V^2}{\partial y} + \frac{\partial UV}{\partial x} + \frac{\partial VW}{\partial z} + \frac{\partial(\overline{v_w^2} - \overline{w_w^2})}{\partial y} + \frac{\partial \overline{u_w v_w}}{\partial x} + \frac{\partial \overline{v_w w_w}}{\partial z} &= \\ - g\frac{\partial b}{\partial y} - \frac{\partial(\overline{\tilde{v}'^2} - \overline{\tilde{w}'^2})}{\partial y} - \frac{\partial \overline{\tilde{u}'\tilde{v}'}}{\partial x} - \frac{\partial \overline{\tilde{v}'\tilde{w}'}}{\partial z} & \end{aligned} \tag{3}$$

In the equations t is the time, g is the acceleration due to gravity and b is the wave set-up. The superscripts $\tilde{}$ and $\bar{}$ have been used to denote respectively ensemble-averaging and averaging over a wave period. The terms $\partial U^2/\partial x$ and $\partial V^2/\partial y$ represent the momentum flux from the cross-shore and long-shore currents whereas the UV-term represents the coupling between the two current components. The $\overline{u_w^2}-\overline{w_w^2}$ and $\overline{v_w^2}-\overline{w_w^2}$ are the wave radiation stress components. The $\partial/\partial x$-component is one of the key elements in the driving mechanism for the undertow although it is generally small in comparison to other components such as the pressure term $\partial b/\partial x$. The $\overline{u_w v_w}$ is the tangential radiation stress term reponsible for creating the longshore flow $\partial\overline{u_w v_w}/\partial x$ and the crossshore flow $\partial\overline{u_w v_w}/\partial y$. The terms $\partial\overline{u_w w_w}/\partial z$ and $\partial\overline{v_w w_w}/\partial z$ represent the horizontal stresses created by the oscillatory wave components. The remaining terms are the Reynolds' stresses.

The vertical velocity is obtained by solving the continuity equation similarly to the approach used by Pechon, 1992:

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0 \tag{4}$$

The equations are applied only within the central layer, from the bottom boundary layer to the wave trough level. Above the wave trough level, where there is water only part of the time, a current velocity component cannot be defined. Their solution assumes knowledge of the oscillatory wave motion to determine the radiation stresses and to define the wave set-up elevation and the wave trough level. An eddy viscosity model based on the mixing length is used for computing the Reynolds stresses. At the bottom, a partial slip boundary condition related to the logarithmic law is used. At the wave trough level, the wave induced currents are computed similarly to the other nodes located within the central layer, since it is also within the water body. The pressure distribution is assumed uniform along the vertical and the radiation stresses come from the application of the wave model.

3. MODELLING SYSTEM

The modelling system includes a wave module that computes the wave related quantities (wave trough level, wave set-up and radiation stress) and 3d hydrodynamic, sediment transport and morphodynamic modules responsible respectively for the three dimensional wave induced currents, sediment transport (bed plus suspended loads) and bed evolution.

The wave module is based on an extended form of the Boussinesq wave equations with improved dispersion and shoaling properties in deeper water (Schröter et al., 1994). Refraction, diffraction, reflection and interaction of the different directions of incoming waves and components are included (Prüser and Zielke, 1990). Short and long water waves of arbitrary shape with high resolution up to depth to wave length ratio of about 1.5 can be handled adequately. It should be stressed that although the equations are solved for the depth averaged wave induced currents along the horizontal directions, a vertical velocity distribution is implicit in the derivation of the Boussinesq equations. A parabolic and linear distribution along the vertical apply respectively for the horizontal and vertical velocities. Besides, since the resulting velocities are already wave induced components, the current component contribution needs to be subtracted in order to determine the oscillatory wave motion and thus the radiation stress distribution along the vertical.

The hydrodynamic module uses a numerical model originally developed at the Center for Computational Hydroscience and Engineering in Oxford, USA. The first author participated in the development, improvement and verification of the model. It was originally developed to solve two Navier-Stokes for the velocities along horizontal directions, the kinematic condition on free surface for the surface elevation and the flow continuity equation for the vertical velocity component (Wang et al., 1992). The model was changed to solve the modified set of Navier-Stokes and continuity equations from the bottom to the wave trough level. It uses quadrilateral structured grids with constant number of nodes along the vertical. Along the horizontal the grid system is kept troughout the simulation wheareas along the vertical it adjusts itself to the changes in the wave trough level and bathymetry.

In the sediment transport module, the total load is obtained by adding bed to suspended loads. The bed load is based on empirical equations and the suspended load results from the solution of the covection-diffusion equation.

The influence of the waves on the sediment transport is included. The morphodynamic module or the bed evolution module is assumed to be governed by the sediment continuity equation.

The wave induced currents and the associated changes in the bathymetry are obtained in sucessive steps using alternatively the wave, hydrodynamic and morphodynamic modules (Figure 1). Along the horizontal directions the grid system is kept the same. A constant number of nodes throghout the domain is defined along the vertical direction for the three dimensional simulations. The simulations for a given bathymetry begin with the wave module and are carried out until the changes in the time integrated wave related quantities are no longer significant. Then the time averaged radiation stressess (at every node within the three dimensional domain), wave set-up elevation and wave trough level are determined. Next, a nearly steady state three dimensional wave induced current is computed below the wave trough, for the same bathymetry, by the hydrodynamic module. In the sediment transport module the total sediment transport is evaluated. Finally, the resulting wave induced currents are used to compute the bed elevation changes by the morphodynamic module. Once the bed evolution anywhere in the domain is significant, the wave module is recalled and updated wave related quantities are determined for the new conditions. This sequence is carried out repeatedly advancing the solution in time.

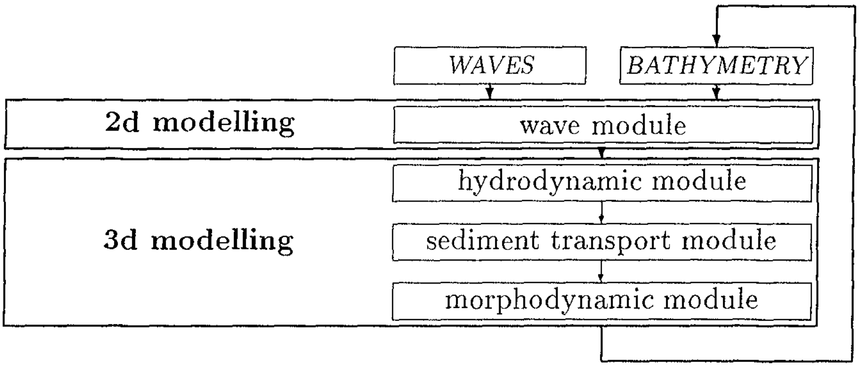

Figure 1. Modelling system.

4. DEMONSTRATION

Results of a demonstration of the modelling system to the simulation of three dimensional wave induced currents without sediment transport along a nearshore stretch were carried out to show its applicability. The domain simulated (300m longshore by 120m cross-shore) is a small stretch on the German coast in the Baltic Sea (Figure 2) with two lines of groynes (150m apart) normal to the coastal line. The bathymetry was defined from five cross-shore profiles. Wave conditions measured in June 1992 at three gauges located in the center, just upstream of the simulated domain were considered in the simulations. The estimated wave spectrum used in the simulations is shown in Figure 3. Wave lengths from 15m to 70m and mean water depths from 0.2m to 2.9m were observed. The simulations were carried out for the conditions described above. Only wave induced currents without sediment transport were considered.

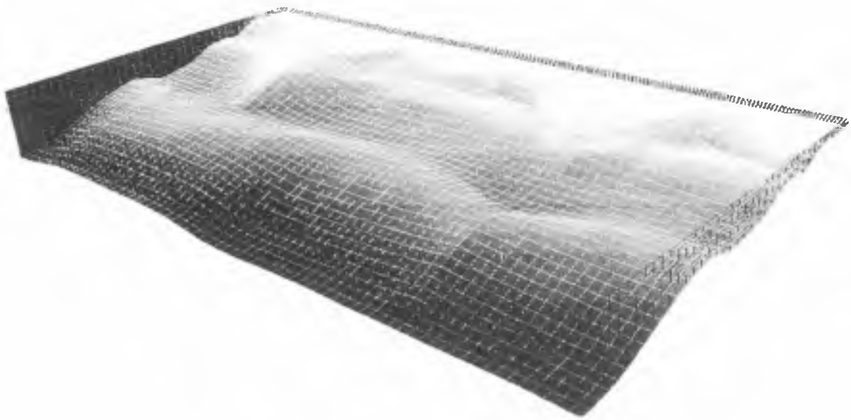

Figure 2. Bathymetry of the simulated domain.

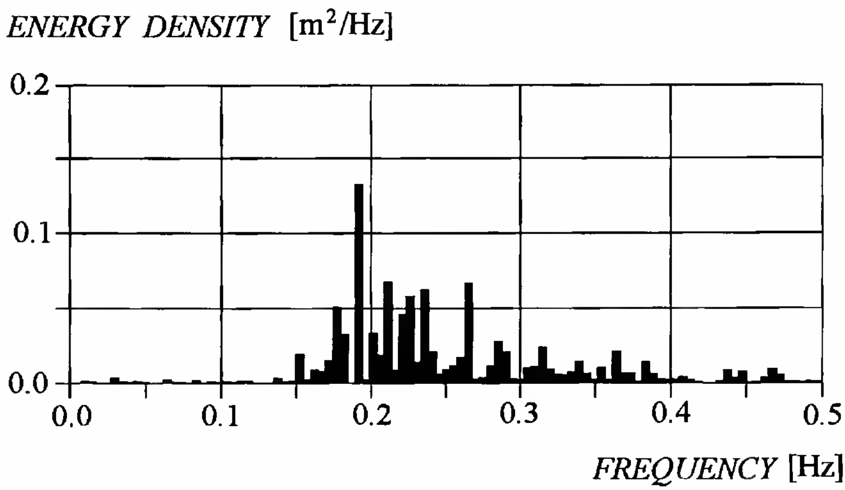

Figure 3. Measured spectrum of the incoming waves.

The simulations with the wave module (Boussinesq model) were carried out for 500s. Results at this time level are shown in Figure 4. Experience shows that at least 10 nodes are required per wave length in order to capture the main wave phenomena properly. Therefore, a highly refined finite difference grid with 152 by 292 nodes ($\Delta x = \Delta y = 1$m) in conjunction with time steps equal to 0.1s were used. The information needed to define the three dimensional domain and to solve Eqns. 2 to 4 were obtained by averaging the results obtained in the application of the wave module from the time levels 250s to 500s.

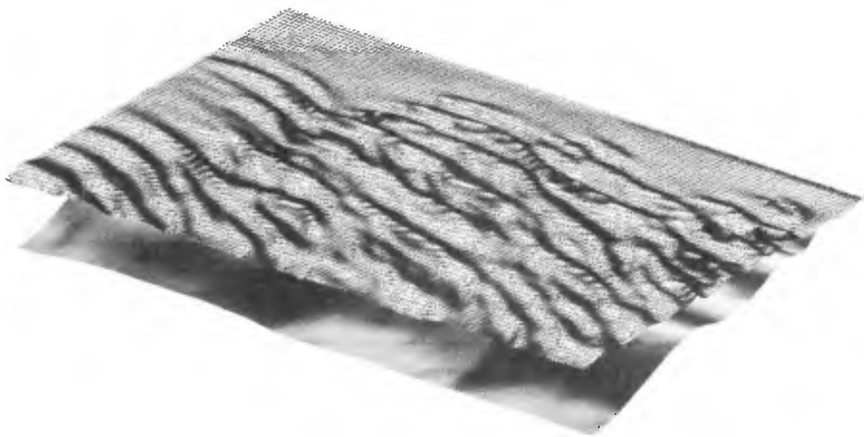

Figure 4. Simulated waves with the Boussinesq wave model.

The three dimensional simulations used a slightly coarser grid along the horizontal directions. The domain was defined by 73 x 38 nodes respectively along the longshore and cross-shore directions. A 4m grid spacing was considered along the horizontal directions. Along the vertical, 10 nodes were placed from the bottom to the elevation of the wave trough level. On the sides of the domain, total slip boundary conditions were used. Results of a quasi-steady state wave induced current field are shown in Figures 5 to 7. In Figures 5 and 6 the resulting three dimensional wave induced currents respectively at the bottom and at the elevation of the wave trough level are shown. Although the circulations are mainly along the horizontal directions, vertical circulations are also present. Notice that in the vicinity of the sand bank the velocities are directed seawards especially near to the bottom.

The tracks of several particles released from two different velocity profiles (see Figures 5 and 6) are shown in Figure 7 to illustrate the highly three dimensional conditions in the vicinity of the sand bank. Although it is difficult to judge without direct comparisons with measurements whether the resulting wave induced currents were adequately captured, it can be seen that they are highly three dimensional.

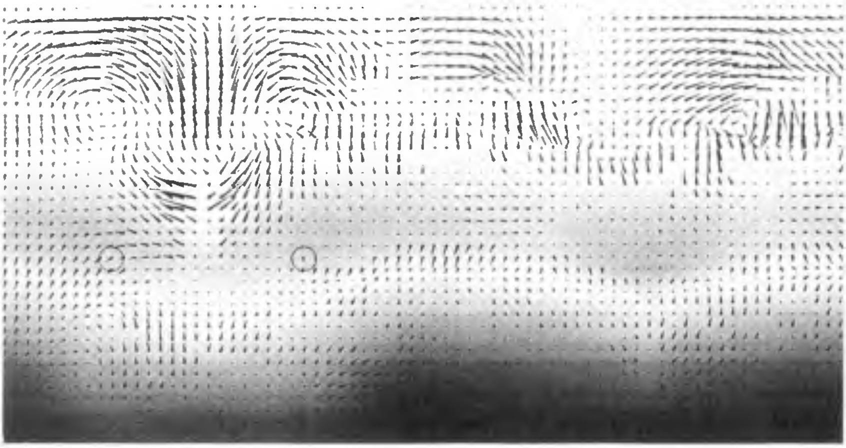

Figure 5. Three dimensional wave induced currents at the bottom.

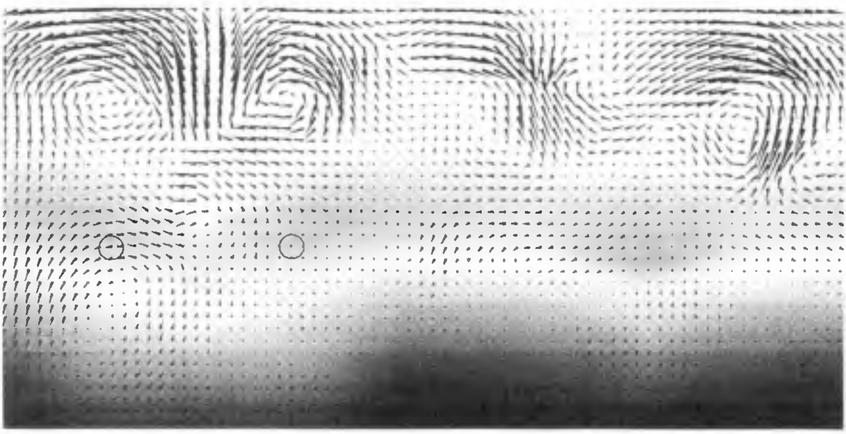

Figure 6. Three dimensional wave induced currents at the wave trough level.

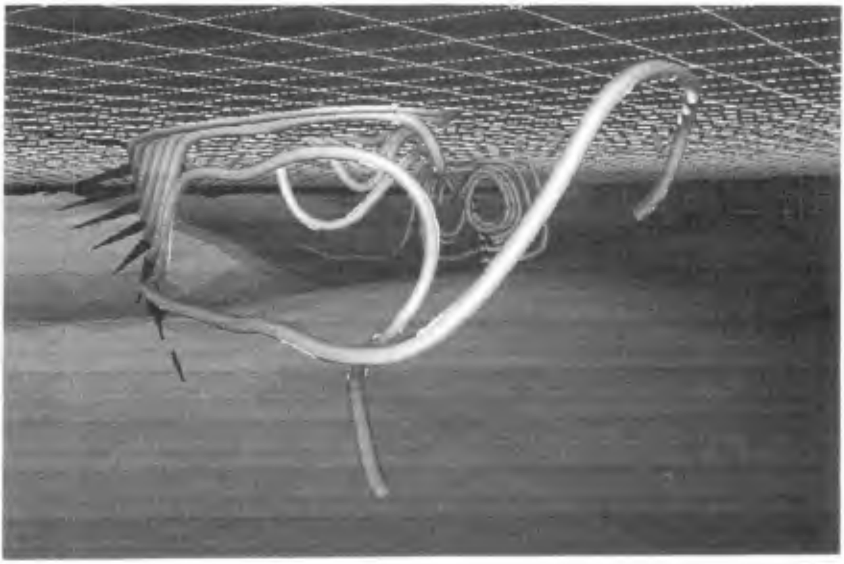

Figure 7. Particle tracks.

5. CONCLUSIONS

This paper shows the results of a simulation of a stretch on the German coast using a 3d deterministic wave modelling system under development. The results show the models ability in describing highly complicated conditions within the surf zone. The coupling of a Boussinesq wave model with a 3d model implemented with a set of modified Navier-Stokes equations enables the most important wave phenomena of interest to the coastal engineer to be captured. Further improvements and verifications of individual models, treatment of boundary conditions and of the layer between wave trough and wave crest, incorporation of hydrodynamic pressure, improvements to the sediment transport module as well verifications of the modelling system with three dimensional measurements are envisaged.

6. ACKNOWLEDGEMENTS

This work is part of the project SFB205 TP B4 sponsored by the German Research Association (*Deutsche Forschungsgemeinschaft*). The authors would like to thank Mr. F. Behrendt for his assistance in the preparation of the figures with an Application Control Environment based on AVS/UNIRAS Visual Systems(Germany) and Dr. Schönfeldt of the Zingst Maritime Observatory - Leipzig University for providing the measurements.

7. REFERENCES

Hedegaard, I. B., Roelvink, J. A., Southgate, H., Pechon P., Nicholson, J. and Hamm, L. *Intercomparison of coastal profile models.* International Conference on Coastal Engineering, Delft 1992

Pechon, P. *Numerical modelling of wave-driven currents and sediment transport in the surf-zone.* Electricite de France, Internal Report HE-42/92-15, 1992.

Prüser,H.-H. and Zielke, W. *Irregular waves on a current.* International Conference on Coastal Engineering, Delft 1990.

Roelvik, J. A. and Brøker, I. *Cross-shore profile models.* Coastal Engineering, 21, 163-191, 1993

Schröter, A., Mayerle, R. and Zielke, W. *Optimized dispersion characteristics of the Boussinesq wave equations.* Proceedings of the International Symposium: Waves-Physical and Numerical Modelling. University of British Columbia, Vancouver, Canada, August 1994.

Svenson,I. A. and Lorenz, R. S. *Velocities in combined undertow and longshore currents.* Coastal Engineering, 13, 55-79, 1989.

Wang, S. S. Y., Hu, K. K. and Mayerle, R. *3d free surface flow modeling by efficient finite element method.* In ASCE, editor, Hydraulic Engineering, 1021-1029, August 1992.