A NUMERICAL STUDY OF WAVE-BREAKING TURBULENCE BENEATH SOLITARY WAVES USING LARGE EDDY SIMULATION

by

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ABSTRACT

Solitary wave breaking was investigated using a three-dimensional Navier-Stokes equation solver implemented in the OpenFOAM open-source C++ library of solvers (OpenCFD Limited, [2011]). Surface tracking was accomplished using the volume of fluid method (VOF) (Hirt and Nichols, [1981]), which was validated with physical experiments for non-breaking and breaking wave conditions. Wave generation was accomplished using the groovyBC boundary condition, which allows the free surface elevation and velocity at every grid adjacent to the inlet to be specified with a user-defined function (Gschaider, [2009]). The solitary wave equation implemented was that of Lee, et al., [1982]. Numerical dissipation was also evaluated, and the model performance was satisfactory in all these respects.

The performance of the large eddy simulation (LES) turbulence closure model was evaluated via comparison with the laboratory study of Ting, [2006]. Using the dynamic Smagorinsky subgrid closure scheme of Germano, [1991] and amended by Lilly, [1992], time series of turbulent velocity fluctuations, Reynolds stresses, and turbulent kinetic energy showed very good agreement with the experimental data. Free surface elevation of the laboratory breaking solitary wave was consistently over-predicted by the model. This was attributed to uncertainties in the numerical wave generation method, which was not able to generate a non-breaking solitary wave of
very large wave height to water depth ratio (0.73). The generation and fate of turbulent coherent structures, especially oblique descending eddies, was investigated by calculating $\lambda_2$ criterion contours ([Jeong and Hussain, 1995]) and cross-sectional vorticity, average TKE, and instantaneous TKE plots. Oblique descending eddies were seen to initiate in a highly turbulent and rotational region around surface rollers, and evolve into three-dimensional structures after detaching from the waveform and being subjected to the shear of the ambient flow. When eddies were generated in this manner, their strength was such that they eventually impinged on the bed, inducing highly focused turbulent regions.

Bed stress data were also calculated, and Shields parameter contours were plotted for typical sediment sizes. Strong correlation was observed between turbulent coherent structure presence at the bed and potential for sediment transport. Bottom shear resulting from these eddies can be about six times greater at their local peak value than that resulting from the wave motion. These events also have long residency times, implying a larger impact over the course of the wave passage.
1.1 Introduction to Turbulence Generated by Breaking Waves

Wave breaking is a well-studied phenomenon in terms of its mechanism, prediction, and energy dissipation in general. However, because of various technological limitations, certain components of this complex process are not completely understood. These include the generation and dynamics of turbulent coherent structures and the effects of wave induced turbulence on the sea bed. When waves break a great deal of turbulent kinetic energy is generated. Generally this turbulence has been parameterized in terms of energy dissipation using a Reynolds averaged Navier-Stokes equation (RANS) approach with an eddy viscosity assumption, such as the k-ε model. Although this technique performs well in terms of predicting the cross-shore wave dissipation due to wave breaking (e.g. Lin and Liu, [1998]), it cannot capture the details of the flow, such as turbulent coherent structures, their possible interaction with the sea bed, and the resulting sediment transport. Three-dimensional turbulence simulation approaches provide a way by which these details may be studied. Utilization of this technology could have a potentially large impact on the understanding of sediment transport from both an academic and engineering standpoint.
Though the turbulent flow behavior of water beneath breaking waves is not understood holistically, laboratory studies have provided several insights as a starting point for further investigations. Nadaoka, et al., [1989] conducted a laboratory study of surf zone turbulence induced by spilling breakers using various flow visualization techniques and fiber optic laser velocimeters. Their observations included verification of several wave generated vortical flow structures previously seen in laboratory tests (Miller, [1976], Peregrine and Svendsen, [1978], Nadaoka and Kondoh, [1982], Peregrine, [1983]). One such observation detailed the process by which horizontal eddy formation in surface rollers evolve into oblique descending eddies. Detailed schematics and figures were produced in order to illustrate these processes employing the flow visualization techniques. Additionally, quantification of these phenomena was achieved via filtering of flow velocity data using a 5 Hz cut-off frequency filter as the criterion for a turbulent, rotational velocity fluctuation. The authors noted that turbulent velocity fluctuations could be identified by separating the total flow velocity into mean and fluctuating rotational and irrotational components, but that extracting the rotational fluctuations, the turbulence in this case, are exceedingly difficult to extract from the data analytically. Taken together, Nadaoka, et al., [1989] were able to attach certain signatures and mechanisms to horizontal and oblique descending eddies produced during wave breaking. Importantly, the study propounds that oblique descending eddies are an inherent result of wave breaking, and describes in general how they evolve from surface rollers.
Both the qualitative and quantitative results from this study showed a connection between surface processes and activity at the bottom of the tank. Turbulence generated by the waves was measured throughout the water column as it was diffused and advected downward by coherent structures. Images of oblique descending eddies confirm this, showing their reach almost touching the bottom of the tank. The authors conjectured that this type of bottom interaction could induce a substantial amount of sediment suspension and transport. However, because the tank was smooth-bottomed and lacked measuring instrumentation near the bed, no quantitative data were provided.

*Ting and Kirby,* [1996] similarly studied turbulence dynamics under spilling periodic breakers over a sloping beach. Their results also presented a situation under which surface-generated turbulence eventually spread to the bottom. It was observed that surface rollers successively break, inducing a continuous generation of large horizontal eddies. As was also shown in *Nadaoka, et al.*, [1989], high strain rates beneath the wave are correlated with turbulence production and vortex stretching. Turbulent coherent structure length and velocity scales were shown to be determined by the size of the roller and the rate of transfer of energy from the organized to turbulent motion.

Additional work on periodic breaking waves by *Cox and Kobayashi* [2000] showed the temporal-spatial distribution of strong turbulent bursts. Flow velocities were phase-averaged and decomposed in the outer surf zone, inner surf zone, and boundary layer in the surf zone. Coherent turbulent events were measured and
classified according to a mean threshold turbulent kinetic energy value. The events were typically intense in the mid water depths and boundary layer. However, their detection was intermittent, indicating that much wider sensor coverage is necessary to capture their extensiveness. Still, the authors postulated that even if the bed is sparsely populated by these turbulent motions they may account for significant sediment suspension.

Ting, [2006, 2008] followed up on these findings with a more detailed study of solitary wave generated turbulence in a series of laboratory tests. The experiments were carried out in a 25 m long wave flume with a constant slope of 1:50. Flow field data were measured by acoustic Doppler velocimeters (ADVs), wave gauges, and particle imaging velocimeters (PIVs). Ensemble-averaged velocities, turbulent velocity fluctuations, turbulent kinetic energy, and Reynolds stress time series were reported, along with contour plots related to turbulent and vortical phenomena. The results presented provide a quantitative basis for discerning the presence of oblique descending eddies as opposed to merely visual inspection. The proposed criteria allow the identification of these structures, but prohibit an analysis of their characteristics. Ting’s dataset provides a robust benchmark by which the present numerical model will be validated.

These phenomena have been observed in the field, as well. The work of Grasso, et al., [2012] studied in more detail the turbulence associated with different classes of breaking waves. Plunging waves in the surf zone tended to induce a rate of turbulence dissipation and mixing that is more depth uniform than breaking waves whose
evolution tends toward propagating bores (surface rollers), which dissipate the majority of energy at the surface. In either situation it was determined that turbulence under breaking waves is more dependent on the breaking process than by the oscillatory bottom boundary layer flow induced by the wave motion. This work followed other studies, including work by Aagaard and Hughes, [2010], Scott, et al., [2009], and Cox and Kobayashi,[2000], in which the degree of wave breaking turbulence was better understood as a major factor in sand suspension in the surf zone. Grasso, et al., [2012] and Aagaard and Hughes, [2010], among others, point out, however, that it is extremely difficult to quantify these events in nature due to the fragility of the instrumentation, and the innate irregularity of wave conditions in the surf zone. Further there is complexity involved in separating turbulent behavior resulting from waves only from turbulence existing as a background condition.

Similarly, laboratory studies are also less than ideal, due to scaling problems (Scott, et al., [2009]). The lack of universal understanding of these processes in current coastal models may lead to a significant gap between predictions and reality (Ruessink and Kuriyama, [2008]), for which advanced numerical modeling may provide a remedy.

1.2 Breaking Induced Turbulence Effects

The interest in turbulence generated beneath and by waves is plain with respect to two fields directly related to coastal engineering. Although it is known that turbulence has a notable impact on sediment transport due to turbulent eddies
impinging on the sea bed, it is extremely difficult to predict this in currently available models. Field studies have been conducted in which it was shown that turbulence injected into the water column does indeed play a significant role in the suspension of sediment. Jaffe and Ruben, [1992] showed that sediment suspended in this manner tends to remain suspended for a significant amount of time, allowing transport to take place. Beach and Sternberg, [1996] conducted surf zone measurements of sediment response to different types of breaking waves, noting a strong relationship between an aerated wave face of a breaking wave and large sediment suspension in the water column. This sediment was seen to form clouds with size on the order of water depth which remained suspended, at times, until the next wave passage. Transport in the longshore and cross-shore directions were reported to be mainly a result of breaking wave energy. Laboratory observations by Scott, et al., [2009], followed this research showing that breaking wave induced turbulence can amplify both accretive and erosive processes in the surf and swash zones, depending on pre-existing flow field conditions and wave conditions, by 50 – 150%. This process was revealed to be at least as important as boundary layer turbulence despite the fact that turbulence originating at the free surface only intermittently interacts with the bed. The field studies by Aagaard and Hughes, [2010] confirm these observations in general, showing large sediment suspension events related to vertical turbulent coherent structures under breaking waves. Their findings concluded that despite the fact that a large degree of intermittency exists (7.7% of plunging waves were seen to produce these types of events), this may be enough to account for large inaccuracies in larger-
scale coastal models, echoing the work of Ruessink and Kuriyama, [2008]. Sediment suspension events were consistently seen in Grasso, et al., [2012]. The importance of breaking wave turbulence on sediment transport, sand bar migration, and other phenomena is garnering a larger interest in the literature.

Ting, [2011] furthered his work on turbulent structures under breaking waves with a systematic investigation of periodic waves. The study again relied on PIV and ADV velocity measurements to quantify turbulent events. PIV images were recorded 8 mm from the bed in this instance, however, allowing a more thorough glimpse into the fate of turbulent events. Correlation between the ADV and PIV measurements show that turbulent downbursts occur frequently, with a pronounced tendency to impinge upon the bed. These bed interactions consist of a large burst of turbulent kinetic energy and a coincident burst of downward directed turbulent velocity fluctuations. The effect of this is to cause a large outward and upward directed flow field around the impingement point, which could have implications for sediment transport. Many of the characteristics of turbulence generated beneath periodic breakers were observed to be similar to those associated with solitary waves, the main differences being the effects of flow reversal, developed undertow currents, and the added factor of turbulence generated in previous waves, which are of course not present when a wave is isolated.

Further onshore, the effects of wave induced coherent structures are also important, especially to coastal structures. Following the Indian Ocean tsunami in 2004, a series of field studies by Okal, et al., [2006] revealed significant damage due
to large turbulent coherent structures, eddies in this case, appearing in high
commercial activity harbors after the retreat of the tsunami wave. These events were
successfully modeled by Son, et al.,[2011]. The model included simulation from the
generation point across the Indian Ocean to the port in question, and therefore
employed relatively a large numerical mesh. That the coherent structures were seen
indicates the scale of these events. Small scale laboratory studies have shown that
eddies tend to induce significant scour around structures, including breakwaters
(Sumer and Fredsoe, [1996]). Recent laboratory work has corroborated this, showing
sediment transport initiated both by plunging breaking waves and the drawdown of
these waves after inundation. For example, the laboratory work of Sumer, et al.,
[2011] showed that the bed stress in the rundown of a solitary wave could be as much
as eight times greater than that typically associated with solitary wave boundary layer
processes. In the event of catastrophic waves like tsunami, then, neglecting the stress
and turbulence related to a receding wave may underestimate the design conditions of
a tsunami for typical coastal structures. It is still prohibitive to construct a model
capable of resolving lengths scales from on the order of 100 km to 100 mm. However,
a better understanding of the small-scale phenomena may be gleaned from high-
resolution numerical models, which may eventually allow for the development of a
more descriptive parameterization for large-scale models.
1.3 Numerical Modeling of Breaking Waves

To depict accurately the overt effects of turbulence, many of the small-scale processes must be resolved rather than simply parameterized in fulfillment of the energy balance equation. It is only recently that computational power and efficiency are sufficient for utilizing large eddy simulation (LES) for studying breaking waves. LES is a turbulence modeling method in which most of the energy in the computational domain is resolved. This resolution is easily achieved in a laminar flow regime, because the equations of motion are analytically solvable with recourse to potential flow theory. However, this assumption is invalid in a breaking wave field, due to the rotational nature of the flow and the addition of flow instabilities and chaotic motions. From a modeling standpoint the equations are no longer analytic, but must be solved numerically. If one is concerned only with satisfying the energy constraints of the problem, the entire turbulent field may be parameterized using the Reynolds averaged Navier-Stokes (RANS) approach in conjunction with a closure scheme, such as the k-ε model. This approach takes the average of the Navier-Stokes equations, and decomposes the solution into mean and fluctuating (turbulent) components. One then solves a set of equations for the transport of turbulent kinetic energy (k) and dissipation of turbulent energy (ε) to close the equation. Using the RANS approach allows turbulent energy and Reynolds stresses to be quantified, and the governing equations to be satisfied without using prohibitively high spatial resolution. However, the physical processes of turbulent flow are not resolved.
LES, on the other hand, resolves a much broader range of phenomena to the point where the physical turbulent mechanisms are visible in the model. Obviously, this requires additional computational power, but the results attained thus far seem to justify its use. In a pioneering study of breaking waves using LES, Christensen and Diegaard, [2001] corroborated many empirical observations of turbulence. Their numerical model simulated plunging and spilling periodic waves using a traditional Smagorinsky subgrid-scale closure method. By taking the spanwise average of their flow field and subtracting out the mean, they found numerous instances of turbulent coherent structures, including oblique descending eddies and the interaction of horizontal eddies with the tank bottom. The original model relied on a two-dimensional solution to the governing equations until a certain point in the domain, where the third dimension was activated, and free surface tracking method that did not account for air. These drawbacks may have artificially lowered turbulent kinetic energy levels, according to the authors. Later, the model was re-evaluated following the laboratory observations of Ting and Kirby, [1994], again using the Smagorinsky closure method, but this time using a fully three-dimensional domain and a volume of fluid (VOF) free surface tracking method (Christensen, [2006]). The model showed comparable results with the laboratory-measured data set, despite disagreement on the location of the break point of the wave, implying that subsequent turbulent behavior is somewhat insensitive to the exact point of breaking and wave generation in general. While one-to-one comparisons were within order of magnitude agreement, the somewhat coarse spatial resolution of the model, Smagorinsky subgrid closure
method, and neglect of air in the computation led to consistently high representations of turbulent kinetic energy (Christensen, [2006]).

Watanabe, [2005] improved on the previous LES work with an intensive investigation of vorticity dynamics and turbulence. The model presented also utilized LES with a Smagorinsky subgrid closure scheme, but used a density function surface tracking method, similar to the VOF method. Watanabe’s results showed an intense aeration present with breaking cnoidal waves, absent from the work of Christensen and Diegaard. The results also supplied a thorough theoretical treatment of the lifecycle of vorticity. Echoing the work of Nadaoka, [1989], the numerical results indicate that horizontal eddies initially form within surface rollers. These horizontal eddies are strained and form a complex network of “vortex tubes” that dictate the rotational direction and fate of these two-dimensional structures that eventually become three-dimensional due to excessive shear and strain. These are the classic oblique descending eddies seen often in the literature (Nadaoka, [1989], Ting and Kirby, [1996], Ting, [2006, 2008], etc.). Eddies such as these are revealed to have effect on both the surface, causing depressions due to pressure gradients, and the bottom, through the ultimate descent of some of them. Vortex characteristic length scales are seen to be typically associated with breaker type and size.

Lubin, [2006] implemented a three-dimensional two-phase Navier-Stokes solver with a mixed scale LES closure scheme (see Sagaut, [1998]) to investigate periodic breaking waves. The numerical model simulated a highly nonlinear wave over constant water depth in a periodic domain to investigate air entrainment and
vortex generation at the breaker surface. Using a VOF method, counter- or co-rotating vortices were generated depending on plunger strength. These vortices were seen to entrap air, causing high shear regions between the cores, and a correspondingly high turbulence level, shown by proxy by looking at eddy viscosity in those areas. The vortices had a strong tendency for motion downward to the bed, and length scales on the order of water depth. Overall behavior indicated that an important mechanism for sediment suspension is found in strong plunging breakers, while sand bar erosion would be more expected of weak plungers. However, no absolute TKE levels were presented because the simulated tank was too narrow for transverse averaging, as was used in Christensen and Diegaard, [2001]. General agreement in terms of vorticity dynamics was observed with respect to previous studies in the literature, despite implementing an unrealistic case of wave breaking.

Apart from the VOF method, wave dynamics modeling is also being studied using smoothed particle hydrodynamics (SPH). Instead of taking an Eulerian approach, wherein fluid behavior is modeled as a continuum discretized into cells or grids, SPH instead tracks discrete particles in a mesh free domain. Preliminary analyses by Dalrymple and Rogers, [2006] on breaking waves on a beach corroborate previously recorded instances of counter-rotating vortices formed by surface rollers. Farahani and Dalrymple, [2012] have employed this method for breaking rip currents, and ongoing work by the same investigators [personal correspondence] on solitary wave breaking has shown promise in capturing the more complex features of the flow field. The main difference at present between the model used in this study and in an
SPH model is the wave generation technique discussed more below. SPH modeling employs a numerical wave maker at the inlet boundary rather than specifying velocity and elevation, as many VOF models do.

This work aims to present the results of the use of OpenFOAM, a C++ library of Navier-Stokes equation solvers, when applied to turbulent flow fields generated by breaking waves. First a description of the theoretical groundwork necessary for the model will be given, accompanied by the details of the model used to fulfill these requirements. Then the results of model validation will be presented. The validation stage consisted of quantifying the numerical dissipation of the solver, testing the accuracy of the free surface tracking method for non-breaking and breaking waves (Zelt, [1991], Synolakis, [1987]), and assessing the model’s prediction capability with respect to velocity and turbulent kinetic energy (Ting, [2006]). Given the acceptability of the model performance, further results will be presented pertaining to turbulent coherent structure generation and behavior, with special attention to the effects on the bed. Finally, a summary of the conclusions will be discussed, and questions for future investigation will be identified.
Chapter 2

NUMERICAL MODEL OVERVIEW

The numerical model implemented for this study incorporates a combination of well-established theoretical concepts in order to describe accurately the variously-scaled phenomena involved in solitary wave breaking. The solution of the problem depends first upon the Navier-Stokes equation for the larger, resolvable length scales. For turbulence modeling, large eddy simulation (LES) has been employed whereby the Navier-Stokes equations are filtered, separating resolved from unresolved length scales in the simulation. The unresolved energy is parameterized using a subgrid-scale closure scheme. To initiate the wave a specific boundary condition is imposed which, in conjunction with the remaining boundary conditions, sets the limits for the problem.

OpenFOAM, an open-source library of C++ Navier-Stokes equation solvers, combines these various elements, and has been utilized here. A brief overview of these components will be given.

In this study, the computational domain is comprised of three-dimensional cells. By default the grids are rectangular, formed by orthogonal lines in three directions. However, modifications to the geometry (via the introduction of slopes, or other user specifications) can cause corresponding changes to the mesh components. Grid spacing increments are user-defined, and may be non-uniform in any or all
directions. Each cell comprises a certain volume, wherein multiple phases can co-exist, which lends itself to free surface tracking via the volume of fluid method (VOF).

2.1 Governing Equations

The Navier-Stokes equations of motion for an incompressible fluid can be written in the following manner:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_i \partial x_j}$$

(1)

$$\frac{\partial u_i}{\partial x_i} = 0$$

(2)

where, in tensor notation, $i, j = 1, 2, 3$, $u_i$ is flow velocity, $\rho$ is the fluid density, $p$ is pressure, $g_3$ is the gravitational acceleration, oriented, in this study, in the negative $z$ direction, and $\nu$ is the kinematic viscosity of the fluid. OpenFOAM solves the equations of motion in all three dimensions. This provides the advantage of being able to resolve turbulence in a detailed way without a heavy reliance on parameterization.

The Navier-Stokes equations extend to any fluid flow, including air, which is also simulated in the model using OpenFOAM’s interFoam solver. This option allows for two-phase flow, in which air is treated as a fluid with its own density and viscosity. This study assigns values of 1000 kg/m$^3$ and 1 kg/m$^3$ for the densities, and $1 \times 10^{-6}$ m$^2$/s
and $1.48e^{-5}$ m$^2$/s for the kinematic viscosities of phase one, water, and two, air, respectively.

Large eddy simulation was employed for turbulence modeling to balance the need to resolve a large portion of the energy in the numerical domain and maintaining reasonable computational times. In LES the Navier-Stokes equations are filtered numerically such that only motions with length-scales greater than the filter scale within the simulation are directly solved. For our purposes the filter length is defined simply as

$$\Delta = (\Delta x \cdot \Delta y \cdot \Delta z)^{\frac{1}{3}}$$

(3)

or the cube root of the average grid volume, where $\Delta x$, $\Delta y$, $\Delta z$ are the average grid dimensions in each dimensions, and $\Delta$ is the filter size. The filtered equations are given as:

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \left( \bar{u}_j \bar{u}_j \right)$$

(4)

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

(5)

where an overbar represents a filtered quantity, and the final term in the equation is the subgrid stress tensor, which requires a closure approximation.
2.2 Large Eddy Simulation Subgrid-scale Closure

Calculation of subgrid-scale energy is accomplished by incorporating a closure scheme in the LES that parameterizes the subgrid motions. The subgrid-scale velocity is what leads to the stress represented by the final term of equation (4). The dynamic Smagorinsky closure model based on the work of Germaino, [1991] and modified by Lilly, [1992], was utilized in the present study. An inter-comparison was carried out with the dynamic Smagorinsky, standard Smagorinsky, and a modeled TKE balance equation (the so-called one-equation model) closure scheme, as well. The results from this comparison will be treated below. Because the Smagorinsky closure methods are of more importance in this study, only the governing equations for this model will be discussed.

Using a standard Smagorinsky closure, the subgrid-scale stress tensor is solved using the following closure assumption:

\[
\tau_{ij} = (\hat{u}_i \hat{u}_j - \hat{u}_i \hat{u}_j)
\]

(6)

\[
\tau_{ij} - \frac{1}{3} \delta_{ij} \tau_{kk} = 2C\Delta^2 \langle \vec{S} \rangle \vec{S}_{ij}
\]

(7)

where \( C \) is the Smagorinsky coefficient (a value of 1.048 is chosen here), \( \Delta \) is the grid filter scale (see equation (3)), and \( \vec{S} \) is the strain rate tensor obtained from the resolved velocity field. Instead of maintaining a constant value, \( C \), throughout the
computation, the dynamic Smagorinsky model applies a second test filter to the equations of motion \((\text{Lilly}, \ [1992])\), yielding a test scale stress tensor of the form
\[
T_{ij} - \frac{1}{3} \delta_{ij} T_{kk} = 2C\hat{\Delta}^2 \left| \hat{\mathbf{S}}_y \right|
\]  
(8)

where \(T_{ij}\) represents the sub-test scale stress. Subtraction of the subgrid-scale stress tensor from the test-grid-scale stress tensor reveals the range of resolved motion between the two scales. This allows a comparison of the resolved energy in this range with the standard Smagorinsky closure model. A proper selection of the dynamic Smagorinsky coefficient is then chosen to minimize the discrepancy between the two terms. This method has the advantage over the traditional Smagorinsky closure method of being able to treat non-turbulent and transient flows without damping excessive amounts of energy. In the traditional case a constant coefficient is applied throughout the entire computation.

2.3 Boundary Conditions and Interface Tracking Method

OpenFOAM’s interFoam solver employs a volume of fluid (VOF) method for free surface tracking. Using this method, a relative volume fraction is computed for each computational cell. The volume fractions, \(\alpha\), are treated as scalar values which can be tracked with a transport equation as the fluid moves around the numerical tank. Here the balance equation for \(\alpha\) is simply stated as
\[
\frac{\partial \alpha}{\partial t} + \nabla \cdot (\mathbf{u} \alpha) + \nabla \cdot [\mathbf{u}_i \alpha (1-\alpha)] = 0
\]  
(9)
where $\alpha$ is the volume fraction of the water phase contained in a cell. The value of $\alpha$ may vary between zero and one, with a value of 0.5 indicating that the computational cell is intersected by the interface between the two fluid phases present in the simulation. This intersection represents the free surface. A relative velocity term, $u_{r,i}$, is included for interface compression, as detailed in Klostermann, et al., [2012]. The relative velocity is the difference between the velocities of the two phases; for the present purposes, the phases are water and air, with densities of 1000 kg/m$^3$ and 1 kg/m$^3$, respectively. Using the interface compression method ensures minimal numerical diffusion between cell faces. However, only a mixed velocity value is solved for in OpenFOAM, which is composed of a weighted average of the velocities in each phase. Therefore, the relative velocity is back calculated from the flux between cell faces in regions containing phase transition. If $(u_c)_f$ is taken to be the velocity in this transition region, the compression flux is defined as

$$\Phi_r = (u_c)_f \cdot (\hat{n}_i)_f$$

(10)

where $(\hat{n}_i)_f$ is the normal vector to the cell face. Because this transitional velocity is not solved directly, it is found by:

$$ (u_c)_f = \min \left( c_f, \frac{\Phi}{|\vec{S}|}, \left| \frac{\Phi}{|\vec{S}|} \right|_{\text{max}} \right) $$

(11)

in which $|\vec{S}|$ is the cell face vector, and $c_f$ is a coefficient controlling the magnitude
of the compression flux of order one. This coefficient may be set to zero in order to ensure a compression flux of zero, however in this study it is set to be unity (Klostermann, et al. [2012]).

Accurate solution of the Navier-Stokes and transport equations given above depends on the prescribed boundary conditions given to the numerical tank. For the purposes of this study, walls are treated as no-flux boundaries for scalar quantities and as no-slip surfaces for velocity. When the simulation carried out is three-dimensional, the subgrid-scale viscosity term employs a near-wall model for solid boundaries. Also, side walls are not treated in this manner but are instead modeled as periodic boundaries for analysis purposes which will be discussed below. A schematic of a typical wave tank can be seen in Figure 2.1.

![Figure 2.1: Generic schematic of numerical wave tank domain.](image)
Wave generation is also included as a boundary condition in these simulations. A user-defined function for wave generation, groovyBC, allows for the input of water wave free surface elevation and velocity profiles via analytical solutions (Gschaider, [2009]). This boundary condition serves as the inlet condition for an initially quiescent tank. The present solitary wave formulation follows the first order work presented in Lee, et al., [1982], which is governed by the following equations for free surface elevation and velocity in the streamwise and vertical directions:

\[
\eta(x,t) = H \sec^2 \left( \sqrt{\frac{3H}{4h^3}} [-ct+x_s] \right)
\]  \hspace{1cm} (12)

\[
u(x,t) = \sqrt{gh} \frac{H}{h} \sec^2 \left( \sqrt{\frac{3H}{4h^3}} [-ct+x_s] \right) \left( 1 - \frac{H}{4h} \sec^2 \left( \sqrt{\frac{3H}{4h^3}} [-ct+x_s] \right) \right)
\]  \hspace{1cm} (13)

\[
w(x,z,t) = \sqrt{gh} \frac{h}{h} \left[ 1 - \frac{H}{2h} \sec \left( \sqrt{\frac{3H}{4h^3}} [-ct+x_s] \right) \right] \\
\times \left[ 2H \sqrt{\frac{3H}{4h^3}} \tanh \left( \sqrt{\frac{3H}{4h^3}} [-ct+x_s] \right) \sec^2 \left( \sqrt{\frac{3H}{4h^3}} [-ct+x_s] \right) \right]
\]  \hspace{1cm} (14)

\[c = \sqrt{gh(1+\frac{H}{h})} \]  \hspace{1cm} (15)
where $H$ is the wave amplitude, $h$ is the initial still water depth, $t$ is time, $z$ is the vertical position derived from the free surface equation, $c$ is the wave speed, $x_s$ is a constant that defines the origin and effective length of the solitary wave. Because the solitary wave is in theory infinitely long, an equation is incorporated into the constant $x_s$ to set the “length” of the wave.

Each volume of fluid in the cells adjacent to the inlet of the tank is prescribed a vertical location, streamwise velocity, and vertical velocity by the boundary condition. Upon the inception of each subsequent time step, the values previously adjacent to the inlet are displaced from their original position and are from thence governed only by the equations of motions valid in the domain. This method differs from the Goring method in which a wave paddle motion is simulated in the domain. The groovyBC wave maker only specifies velocity and free surface displacement values. The use of this method has shown some drawbacks, which will be shown in the validation section of the paper. Goring generation stands as a possible solution to these problems, but has not yet been implemented into the OpenFOAM library.
2.4 Numerical Schemes

For the purposes of this study, the same solving schemes were used in each trial run. A first-order implicit Euler scheme was used in time stepping. A second-order Gaussian scheme was used in the spatial discretization and a total variation diminishing (TVD) scheme was used for convection.
Chapter 3
VALIDATION OF OPENFOAM NUMERICAL MODEL

The OpenFOAM library of solvers has not garnered much attention in the literature with respect to coastal engineering applications, being developed initially with an eye more toward studying traditional fluid mechanics such as channel flows and aerodynamics. More importantly, the particular wave generating boundary condition used in this research has not been rigorously tested previously. The lack of a definitive dataset with which OpenFOAM may be validated as an accurate numerical tool for wave modeling, necessitates a thorough preliminary comparison with established results from previous experiments. This particular validation consists of two parts. First, to assess the numerical dissipation inherent in the model, a stable solitary wave was propagated over a long tank of constant depth and compared to the theoretical solution. After finding sufficient evidence of the model’s accuracy, it was used to simulate the laboratory experiments of Zelt, [1991] and Synolakis, [1987], in which non-breaking and breaking solitary wave evolution and run-up were measured. Finally, the work of Ting, [2006] was recreated to assay the performance of the large eddy simulation model and further check the basic agreement of the model with experimental data with respect to velocity and turbulent kinetic energy predictions.
3.1 Solitary Wave Propagation over a Constant Depth Tank

Following the work of Ma, [2012], the estimate of the numerical dissipation present in the interFoam solver was undertaken by propagating a theoretically stable solitary wave over a constant depth. After travelling a significant number of wavelengths, a comparison between final and initial wave height was made, with the difference resulting primarily from numerical dissipation.

The tank geometry consisted of a streamwise length of 200 m and height of 2 m. Water depth was set as constant at 1 m throughout all computations, and various wave heights were tested to investigate the numerical dissipation of the solver. A theoretical solitary wave is expected to remain stable until the wave height to water depth ratio reaches about 0.78. Ma, [2012] specifies a ratio of 0.5 in his test, well below the theoretical breaking point, yet still highly nonlinear. At the beginning of the trial, another wave generation tool implemented for OpenFOAM by Jacobsen, [2011], called waves2Foam, was used. This technique differs from the generation method of groovyBC in that instead of defining velocity and free surface values for the flow at the inlet, a solitary wave is created based on user specified parameters and placed inside the domain at the beginning of the computation. In essence, a mound of water exists in the tank, having the velocity of the theoretical solitary wave assigned to it. Waves2Foam has the advantage of being a more convenient wave generator in that it has a collection of built in wave theories. However, the tests showed that this solitary wave generation style produces unacceptably large deviations from theory. Due to its
generation mechanism, the model sees a large instability in the domain and attempts to correct it. This involves the wave collapsing in on itself and dispersing higher frequency waves until the wave reaches a stable wave height. Generally, the initial decay observed was about 20% of the specified height, followed by subsequent fluctuations until the stable mode was attained, typically 90% of the initial height. At this point propagation proceeded regularly.

Such large instabilities led to the abandonment of the waves2Foam toolbox in favor of the groovyBC boundary condition. The same test was carried out using groovyBC instead in order to properly quantify numerical dissipation. GroovyBC does not generate the excessive instabilities that waves2Foam does. However, it does generate a slightly larger wave than specified, and does exhibit smaller instabilities which are corrected by higher harmonic dispersion. Still, the amplitude decay is not nearly as intense.

After propagating about one wavelength, the wave has reached its peak value, about 1% greater than specified, and from this point decays to a stable amplitude. By about four wavelengths this stabilization seems to have taken place, settling at a wave height about 5% smaller than the specified 0.5 m. For the remainder of the run, negligible dissipation is seen, on the order of about 0.7% absolute decay, and about 0.1% decay per wavelength propagated. These results are shown in Table 3.1.
Table 3.1: Dissipation statistics for $H = 0.5$ m, $h = 1.0$ m case

<table>
<thead>
<tr>
<th>$x/L$</th>
<th>$H/h$</th>
<th>% Deviation from Theory</th>
<th>% Change per Wavelength</th>
<th>% Relative Change/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.208</td>
<td>0.500</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.0962</td>
</tr>
<tr>
<td>1.10</td>
<td>0.505</td>
<td>1.00</td>
<td>1.02</td>
<td>1.14</td>
</tr>
<tr>
<td>4.78</td>
<td>0.474</td>
<td>-5.24</td>
<td>-6.18</td>
<td>-1.68</td>
</tr>
<tr>
<td>9.74</td>
<td>0.471</td>
<td>-5.84</td>
<td>-0.633</td>
<td>-0.128</td>
</tr>
<tr>
<td>11.8</td>
<td>0.470</td>
<td>-5.96</td>
<td>-0.127</td>
<td>-0.0630</td>
</tr>
</tbody>
</table>

The same tests were carried out with smaller waves to assess the sensitivity of the model to different degrees of nonlinearity. Although the 0.5 wave height to water depth ratio is not unreasonably nonlinear, it is still a significant departure from, say, linear theory, and therefore may be a contributing factor to the time required to establish stabilization. For example, the $H/h = 0.5$ wave does not enter the domain as a smooth solitary wave profile, but instead the peak is slightly concave and skewed. This is eventually smoothed out through dispersion. When an $H = 0.2$ m solitary wave was propagated over the same tank, similar results were seen, except the magnitude of the changes decreased proportionally with the wave height.

In this run the number of wavelengths necessary to reach the maximum wave height and stable wave height is nearly the same as in the previous case. Similarly, the dissipation per wavelength after a stable height is reached is comparable, settling in around 0.8% after about ten wavelengths propagated. Again, this stable wave height is about 3% smaller than the specified.
Table 3.2: Dissipation statistics for H = 0.2 m, h = 1.0 m case

<table>
<thead>
<tr>
<th>x/L</th>
<th>H/h</th>
<th>% Deviation from Theory</th>
<th>% Change per Wavelength</th>
<th>% Relative Change/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.479</td>
<td>0.204</td>
<td>1.85</td>
<td>1.85</td>
<td>3.86</td>
</tr>
<tr>
<td>2.58</td>
<td>0.199</td>
<td>-0.60</td>
<td>-2.41</td>
<td>-1.15</td>
</tr>
<tr>
<td>4.68</td>
<td>0.196</td>
<td>-2.15</td>
<td>-1.56</td>
<td>-0.741</td>
</tr>
<tr>
<td>8.90</td>
<td>0.194</td>
<td>-3.05</td>
<td>-0.920</td>
<td>-0.218</td>
</tr>
<tr>
<td>10.2</td>
<td>0.1937</td>
<td>-3.15</td>
<td>-0.103</td>
<td>-0.0815</td>
</tr>
</tbody>
</table>

GroovyBC presents a better alternative for solitary wave generation than the waves2Foam toolbox. More importantly, regardless of the method employed, interFoam is not unacceptably dissipative, a characteristic that would eventually taint turbulent flow solutions where the turbulence closure dissipation would become indistinguishable from numerical dissipation. Several attempts were made to alter the solving scheme with no appreciable difference in the initial instability of the wave. The model results were virtually the same after attempting to implement a third-order approximation solitary wave solution; employing the Crank-Nicholson second order implicit time scheme; and setting the surface compression coefficient in the VOF solver to zero. Most likely, the solution to this problem may be found in the implementation of a simulated wave maker, as in the Goring method of wave generation. This would negate the need for the model to correct immediately what it may see as very large, unreal perturbations in the system when only free surface elevation and velocity are specified.
3.2 Non-breaking Solitary Wave Run-up on a Steep Plane Beach

Zelt, [1991] measured the offshore free surface evolution and run-up profile over time of a solitary wave of amplitude 0.024 m in water initially 0.20 m deep onto a plane beach with a 20° slope. This wave was numerically recreated using OpenFOAM, and the results were compared to those given by Zelt. Because the wave was non-breaking, the flow was considered laminar and two-dimensional. The tank dimensions were 11.099 m by 0.6 m. The tank mesh was discretized in two parts, one with constant depth over which the wave was generated and measured by a wave gauge, and the other comprising the slope, the toe of which began ten meters from the inlet.

In the first block 1000 grid points were used in the horizontal direction and 300 grid points were used in the vertical direction, yielding grid sizes of $\Delta x = 1$ cm and $\Delta z = 0.2$ cm. The second block was comprised of 300 grid points in both the horizontal and vertical directions. Because of the mesh discretization technique employed by OpenFOAM when a slope is introduced, the grid size in the vertical direction was non-uniform. At the toe of the slope, the vertical grid dimension was 0.2 cm while at the end of the tank it shrank to 0.06 cm. The decrease in grid size arises from the fact that for any given block only one value may be specified for the number of grids used in a certain direction. Because the slope changes the height of the tank, then, while the number of comprising grid points remains constant, the grids necessarily shrink to accommodate the constant quantity.
On the inlet the groovyBC boundary condition patch was utilized to generate the solitary wave. The bottom boundary condition was specified as zero-gradient for the alpha1 variable, which accounts for the volume of fluid in each cell, and free-slip for the velocity. The sidewalls were set to empty, which by convention in OpenFOAM indicates a two-dimensional simulation. The numerical model simulated the physical experiment for 20 seconds. Offshore wave gauge data was collected at the same point indicated in Zelt’s study, and instantaneous free surface profiles were matched by considering time zero as the point at which the peak of the solitary wave crossed the wave gauge. The results from Zelt’s paper were digitized using a Microsoft Excel macro, in which points are selected from an uploaded image file by selecting them with the cursor.

Figure 3.1: Schematic image of simulated Zelt, [1991] wave tank. Black vertical line indicates wave gauge location.
The offshore free surface profile is shown in Figure 3.2. OpenFOAM predicts the behavior very well for the initial incoming wave and first reflected wave. The tail end shows slightly worse agreement, but this may be due to the effects of run-down which are discussed below.
Figure 3.3: Non-dimensionalized run-up profiles at instantaneous non-dimensionalized times. Numerical model results shown by red line; experimental data shown in black circles.

A favorable overall comparison was made between the predicted behavior and the empirical data. Some discrepancies are present on run-down. For example, a depression forms at the interface of the beach and the waveform at the end of the run-
down process in the model, which is not as dramatic in the laboratory data set. This could be due to insufficient resolution of the region directly above the dry surface, where the thin layer of water is much smaller than the grid size. Also, in reality swash zone processes would be three-dimensional. Forcing this to be two-dimensional may have triggered unreal numerical instabilities in the model.

3.3 Solitary Wave Breaking over a 1/20 Slope Beach

To test the free surface tracking accuracy in a three-dimensional breaking wave setting, the laboratory procedure given in Synolakis, [1987] was followed. A wave with a height of 0.0588 m was propagated over an initially flat bottom with water depth 0.21 m. The tank contains a slope of 1/20 positioned 3.65 m after the wave enters. The numerical tank was composed of two blocks, one for each of the regions mentioned. A schematic of the tank can be seen in Figure 3.4. The first block was 3.65 m long by 0.2 m wide by 0.5 m tall, and was divided into grids sized 2 cm x 1 cm x 0.5 cm. The second block was 7.35 m x 0.2 m x 0.5 m with grids specified as the same size as the first block. However, because of the slope effect which compresses the vertical size of the grids farther downstream, the x-direction grids were non uniform such that the last grid in the second block was smaller than the first by a factor of 0.3. This was done to try to maintain the grid size ratio so as to prevent any artificial behavior by the wave either during breaking or during the run-up process. The total number of grid points used was 1,100,000, with 550 in the x-direction, 20 in the y-direction, and 100 in the z-direction.
Figure 3.4: Schematic image of simulated Synolakis, [1987] wave tank.

Side wall effects were not considered in this run, because periodic boundary conditions were employed. Essentially the periodic boundary condition ensures that the information adjacent to the first boundary in the set is identical to the information at the second boundary. This allows the problem to be considered as quasi-infinite in the transverse direction. Because the present problem is assumed to be statistically homogeneous in the spanwise (y-) direction, this approach is appropriate. As long as the size of the spanwise domain is larger than the largest turbulent eddy, the simulation results can be averaged over the y-direction to obtain ensemble-averaged quantities.

Other boundary conditions were similar to those used in the Zelt case. The main difference between the two cases was the use of a no-slip bottom boundary
condition for velocity, since the flow in this trial is three-dimensional. Turbulence variables were also included in this run in order to utilize the LES dynamic Smagorinsky model. These included a turbulent kinetic energy \( (k) \), turbulent kinematic viscosity \( (\nu_t) \), subgrid-scale viscosity \( (\nu_{sgs}) \), and subgrid-scale stress tensor \( (B) \). For the variable \( k \), a value of \( 1 \times 10^{-5} \) (m\(^2\)/s\(^2\)) was prescribed at the inlet, \( 1 \times 10^{-11} \) for the bottom, outlet, and top. Turbulent kinematic viscosity, \( \nu_t \), was initialized as zero (m\(^2\)/s) at every boundary condition. The subgrid-scale viscosity \( (\nu_{sgs}) \) (m\(^2\)/s) was assigned as a no-flux variable at each boundary except the bottom wall. At this boundary a wall function was used to model near-wall behavior. Finally, the subgrid-scale stress tensor \( (B) \) was initialized as zero (m\(^2\)/s\(^2\)) at the inlet and top, and no-flux for the bottom and outlet. As stated, the side wall boundary conditions for all variables were periodic.

*Synolakis, [1987]* presents only instantaneous free surface profiles of the breaking solitary wave, which are compared to the numerical results below. Instantaneous free surface profiles were taken at non-dimensional times 10, 15, 20, 25, 30, and 50. The horizontal length units and free surface elevation are normalized by the water depth, \( h \). The wave shape and breaking pattern compare well as seen in Figure 3.2. In the initial profile there is a slight time lag between the numerical and laboratory results. After this point temporal agreement is much better between the two datasets. The numerical output was obtained from model output written at a low sampling rate (~0.05 sec). Due to this relatively coarse resolution, a minor discrepancy is a distinct possibility.
Another point in which the model varies from the laboratory results is in the beach run-up. The model over-predicts the magnitude of the run-up and the speed at which it reaches that extent. This may point to shortcomings in the volume of fluid method when the volume becomes vanishingly small, as happens during run-up. Additionally, the flow in this region is more affected by friction and shear near the bed, and may have behaved more realistically if the grid resolution near the bottom was finer rather than relying on a wall function to parameterize the behavior. In this simulation the grid resolution was much too coarse to accurately resolve the type of effects that dominate near solid boundaries. Unfortunately, Synolakis [1987] does not provide additional times detailing run-down more closely.
Figure 3.5: Non-dimensionalized run-up profile comparison for non-dimensional times ($t' = t(gd)^{1/2}$) 10, 15, 20, 25, 30, and 50. Numerical model results in shown in blue dots; Synolakis laboratory results shown in red circles.

Overall, the main concern of the comparison, evolution of a solitary wave from generation to breaking, was favorably resolved with respect to OpenFOAM’s free surface tracking capabilities.
3.4 Solitary Wave Breaking over a 1/50 Sloping Beach

In a series of laboratory experiments, Ting, [2006] analyzed the free surface evolution and velocity statistics of a breaking solitary wave. The laboratory tank was 25 m long by 0.90 m wide by 0.75 m deep with a constant slope of 1/50 extending the length of the tank. A highly nonlinear solitary wave of height 0.22 m was sent into still water with an initial depth of 0.30 m. Wave gauges placed along the length of the tank recorded the free surface evolution, and a series of ADVs recorded the velocity at a fixed streamwise location at different depths. The same wave was generated 29 times, allowing ensemble-averaging of the data and subsequent Reynolds decomposition of velocity into mean and turbulent components.

Using OpenFOAM, the tank was replicated numerically with minor modifications. In the interest of time constraints and computer processing capacity availability, the numerical tank dimensions were specified as 18.2 m long by 0.60 m wide by 0.60 m tall; the 1/50 constant slope was maintained. All wave characteristics were followed according to the laboratory procedure, and data measurements were taken at the same locations. The cross-shore portion of the physical tank that was neglected in the model plays no significant role in the time series measurements made in this experiment.

As stated, using groovyBC a first-order solitary wave was generated with amplitude 0.22 m into an initially quiescent tank of depth 0.30 m. Large eddy simulation with a dynamic Smagorinsky closure was used to model turbulence. A no-slip bottom boundary condition for velocity was employed by specifying a value of
zero at that boundary. That boundary also used a built in wall function to approximate near bed stress for the subgrid-scale viscosity term. Periodic boundaries were used for the side walls. This allowed for the ensemble-averaging technique, used throughout this study, of taking the average of the data at each y-normal plane. The periodic boundary conditions neglect any side wall effects that might be physically present and instead idealize the tank as if it were in fact infinitely long in the spanwise direction. By viewing the tank in this manner, every y-normal plane can be thought of as a unique actualization of the solitary wave, analogous to the multiple runs of the same experiment by Ting in his study. In practice, then, instead of placing one wave gauge in the tank at one point, the numerical model in effect deploys a line of gauges across the tank at a specific streamwise location. The individual collections of data are then averaged across the tank to produce a data set comparable to that given in Ting, [2006].

The numerical mesh was comprised of 2427 grid points in x, 80 in y, and 80 in z, totaling 15,532,800 computational cells. Due to the sloping geometry of the tank, the grid sizes shrink in the z-direction further downstream, necessitating a non-uniform grid in the x-direction to keep the grid size ratios approximately constant. As a result, the largest grid size in the x-direction was 11.5 mm, while the smallest was 4.6 mm; in the z-direction the largest grid size was 7.5 mm and the smallest was 3 mm; the grid size was constant, 7.5 mm, in the y-direction. A schematic of the tank can be seen in Figure 3.6.
Figure 3.6: Schematic image of simulated Ting, [2006] wave tank. Black lines indicate wave gauge locations, black dots represent velocity gauge locations, and orange line below black dots represents Ting’s PIV recording location.

Wave heights were recorded at 12 locations (x = 0.55, 2.2, 3.2, 4.25, 5.25, 6.25, 7.25, 8.25, 9.25, 10.3, 11.3, and 12.3 m) along the length of the tank. Figure 3.7 presents the wave profile comparisons at those locations. Recognizing that cross-tank variations are expected in three-dimensional waves, every realization of the time series has been plotted, in order to show an envelope of possible heights the wave may take on at any given location. It is believed that this gives a better representation of the comparison, since the average wave height compiled in the laboratory is taken from a series of measurements at the same point, while the average that would be taken from the model is the average of the wave at each point across the tank, which may introduce more spatial variation.
Figure 3.7: Wave height time series data recorded (from top to bottom, left to right) at cross-tank locations: $x = 0.55, 2.2, 3.2, 4.25, 5.25, 6.25, 7.25, 8.25, 9.25, 10.3, 11.3, \text{ and } 12.3\ m (h = 0.289, 0.256, 0.236, 0.215, 0.195, 0.175, 0.155, 0.135, 0.115, 0.094, 0.074, 0.054)$. Numerical model realizations in red; Ting ensemble-averaged wave heights in black.

Initial discrepancies are present at points near the wave generator when comparing the free surface elevation data from the model to that provided by Ting.
Additionally, the numerical wave breaks sooner than its laboratory counterpart, almost immediately upon entering the domain, and then sustains a greater amplitude throughout the breaking process. Specified wave height does not seem to be the controlling factor in the over-prediction seen below. A height of 0.22 m was specified in groovyBC, while the initial wave described in Ting seems to be slightly smaller, around 0.208 m, despite specifying a wave height of 0.22 m. The cause of this mismatch is not known with certainty. Because the wave generators employ philosophically different approaches, it is likely that groovyBC misses some physical mechanisms that are manifested in real wave tanks. However, the target wave height is achieved by the model.

Early breaking seems to be a model related problem. Not only does the numerical wave break sooner than the laboratory, it also does not achieve the same wave breaking height to water depth ratio \((H_b/h) = 0.865\) in OpenFOAM, \((H_b/h) = 0.962\) in the laboratory flume). The most likely explanation for this difference is the initial wave instability that is seen in the generation of larger waves when using groovyBC, as described in a previous subsection. Sending in an initially unstable wave, which immediately begins shoaling, likely accelerates the breaking process artificially as the model tries to attain a level of equilibrium.

Perhaps as a result of early breaking, the modeled wave then is over-estimated throughout the rest of the run. Two factors may play a role in this, either singly or in tandem. First, because the predicted breaking wave height is not as large as its observed counterpart, the breaking process may be less energetic, and therefore less
dissipative, allowing the predicted wave to remain higher. Second, it is possible that
the turbulence model and closure method being utilized are not dissipative enough.
Although at each gauge the observed wave does fall somewhere near the minimum of
the envelope of readings from OpenFOAM and the decay rate of the wave seems
similar, the average magnitude of the wave is always higher, and thus warrants further
investigation.

In order to test the sensitivity of initial wave conditions to the decay rate of the
breaker, smaller and larger wave cases were tested. One case specified a wave height
of 0.208 m, which is the first recorded wave height measurement in Ting’s dataset.
The larger case employed a wave of height 0.23 m, the rationale being that a larger
wave should break in a more energetic manner, and thereby dissipate more quickly.

As seen in Figure 3.8, groovyBC consistently hits the target wave height at x =
0.55 m. However, there is no discernible relationship between the decay rate, decay
magnitude, and initial wave height. While the largest wave does show the largest
decay of the simulated waves, the H =0.208 m wave decays more than the H = 0.22 m
wave at the most landward sensor (x = 6.25 m). This implies that simply specifying a
larger initial height will not necessarily produce greater dissipation and that the
relationship between the initial wave height and its evolution is not straightforward.
In other words, the decay rate and magnitude associated with a wave of a particular
height in this model does not directly depend on the specified wave height. This
complicates the choice of the initial wave height, then, if the goal is to match the
onshore state of the wave. Therefore, due to this uncertain relationship, the original H
= 0.22 m wave case has been investigated for the remainder of the study, as it is indeed the specified wave condition in the laboratory and matched the laboratory shape and time progression favorably, if not the absolute magnitude.

Figure 3.8: Comparison of wave height decay using different specified wave conditions.

A final point to note in the wave gauge readings is the presence of higher frequency behavior in the waves, with a signature of double-peakedness in the wave shape around the break point. The governing wave equations employed here are derived from the original Korteweg-de Vries equations for cnoidal and solitary waves.
Waves built on this theory are assumed to be formed and propagated in an irrotational, inviscid, incompressible fluid. But, as seen previously, imperfections are generated in this model, perturbing the system and inciting some higher frequency motion and consequent dispersion by the wave. This dispersion is manifest in the double peaks at the wave crests in some of the earlier wave readings. When the wave height was increased to 0.23 m, this effect became even more pronounced, lending additional evidence that the instabilities in the wave generation technique implemented here are sensitive to more highly nonlinear initial conditions. This dispersiveness is also apparent in the small trailing waves behind the leading wave, which do not appear in the laboratory data.

Velocity measurements were taken at seven vertical locations where the depth of the water was 15.25 cm ($x = 7.375$ m). Taking $z = 0$ as the free surface, the locations measured were $z = -0.0225$, $-0.0425$, $-0.0525$, $-0.0825$, $-0.1025$, $-0.1225$, and $-0.1425$ m (or, alternatively, measuring elevation from the bottom, $z = 130$, $110$, $100$, $70$, $50$, $30$, and $100$ mm). The numerical velocity data results were averaged using the same procedure detailed above for recording the wave heights. Average horizontal velocity data is shown in Figure 3.9. Again, the comparison between the model and empirical data corresponds favorably, with slight under prediction of the velocity. This difference between the two datasets could be a symptom of the less energetic wave condition seen in the model. However, the magnitude of these differences is not of the same order as that seen in wave height, which at this point is approximately $3$ cm ($\sim 38\%$), lending some credibility to the argument that minor changes to the offshore
conditions do not impact the onshore sub-surface phenomena to a large extent (Christensen, [2006]). Similar to the noticeable peaks in the free surface seen above, dips in the maximum average velocity crest are detectable, an artifact of the alluded to wave dispersion.
Figure 3.9: Average streamwise velocity where $x = 7.375$ m (water depth, $h = 0.1525$ m), taken at different vertical locations above the bed. Numerical model results in red; Ting experimental data in black, averaged over 15 time series for $z = 130, 100, 70, 50, and 30$ mm, 20 for $z = 110$ mm, and 19 for $z = 10$ mm. Z-locations relative to elevation above the bed.
Average vertical velocity data is shown in Figure 3.10. The magnitudes of the data correspond well here, slightly better than the in the cross-shore velocity, with some notable qualitative exceptions again related to higher harmonic phenomena. Regardless of the vertical location of the probe in the water column, a brief spike in average velocity is observed between the local maximum and minimum, around the inflection point of the curve. Individual time series at different transverse points indicate that the spike is not anomalous, but is present at almost every point with some variation in magnitude. The intensity of the effect on vertical velocity implies that the dispersive response of the system and the vertical velocity component are of a similar order of magnitude, whereas the streamwise component is more dominant and less sensitive to the perturbation. At deeper locations the effect of this second peak is felt less, and the velocity curve becomes smoother. In general, vertical velocity is attenuated to a greater extent than cross-shore velocity, and near the bottom is more prone to random noise, as seen at the $z = 10$ mm mark in the figure. The comparison is not made at $z = 130$ mm because this location was not recorded in Ting’s dataset.
Figure 3.10: Average vertical velocity where $x = 7.375$ m (water depth, $h = 0.1525$ m), taken at different vertical locations above the bed. Numerical model results in red; Ting experimental data in black, averaged over 15 time series for $z = 100$, 70, 50, and 30 mm, 20 for $z = 110$ mm, and 19 for $z = 10$ mm. Z-locations relative to elevation from the bed.
Finally, the root mean squared values of the velocity fluctuations and turbulent kinetic energy were compared at different depths. The data from elevations above the bed (where depth, $h$, is 152.5 mm) $z = 110, 100, 70, 50,$ and $30$ mm are presented in Figure 3.11. Elevations $z = 130$ m and $z = 10$ mm are neglected due to incomplete data with which to compare, and excessive noise, respectively.

At the highest elevation, $z = 110$ mm, the time series comparison shows a more bimodal prediction than in the observed data. Order of magnitude comparisons are still mostly favorable, with the greatest discrepancy being in the vertical component. A phase shift is noticeable in the second peak between the two sets in the time series, while magnitudes are comparable. The spanwise component gives the best comparison at this point.

The comparison at $z = 100$ mm is very favorable, with slight phase shifts with respect to the peaks in the spanwise and vertical velocity fluctuations. The main discrepancy appears in the vertical fluctuation component, where the magnitude of the main peak is not matched by the model, leading to a larger difference in the overall energy prediction.

Results at $z = 70$ mm show perhaps the greatest agreement in the entire dataset, with qualitative and quantitative measures both agreeing very well. At this point in the water column the overall levels of turbulent kinetic energy is not unduly influenced by the bottom, nor subject to the intensities of wave breaking processes at the surface, which may be a contributing factor to this large agreement. Vertical velocity
Figure 3.11a: Root mean squared turbulent kinetic energy and streamwise, spanwise, and vertical turbulent velocity fluctuations at $z = 110$ mm above bed and $x = 7.375$ (h = 0.1525 m). Numerical model results in solid lines (Smagorinsky model in blue, k-equation model in green, dynamic Smagorinsky model in red); Ting experimental data in black dotted line, averaged over 20 time series.
Figure 3.11b: Same as Figure 3.11a, except $z = 100$ mm.
Figure 3.11c: Same as Figure 3.11b, except $z = 70$ mm.
Figure 3.11d: Same as Figure 3.11c, except $z = 50$ mm.
fluctuation at this point is slightly underpredicted, but the effect on $k$ magnitude is not large.
At $z = 50$ mm the predicted TKE levels are consistently higher than the observed results. The bulk of this overprediction, though, is in the transverse fluctuations. Vertical and cross-shore fluctuations in both datasets display a double peak, despite a slight disagreement in time. The overall comparison is reasonable.

Finally, nearest the bed, at $z = 30$ mm, the average TKE is within order of magnitude agreement, though the modeled time series misses the second spike in energy. This is also manifest in the streamwise and vertical component turbulent fluctuation, where a second peak is either missed or smoothed over. Agreement is much better in matching peaks in the spanwise component. Overall turbulent behavior at this location is under predicted, an apparent reversal from 20 mm higher in the water column, but not to an unreasonable degree.

Overall, the comparison between the laboratory data and numerical model results is satisfactory. Depending on the depth at which the measurement was taken, OpenFOAM has been seen to over-predict, under-predict, and almost exactly match the RMS TKE levels present in the flume; the peak predicted energy level is always within 50% of the observed. Some differences may be a result of the different averaging techniques, or the difference in the number of realizations each data set is averaged over (between 15 and 20 for the laboratory results and 80 for the numerical model). An additional factor is that the model has been shown to predict earlier breaking. If the subsequent breaking process is not as energetic, it would be expected that the turbulent levels would also be lower.
Although the dissipation of the height of the numerical solitary wave is not as great as the laboratory generated wave, the LES model is nonetheless well-resolved, as seen in the turbulent kinetic energy spectrum in Figure 3.12. Typically the energy spectrum is calculated over a spatial domain with uniform grid spacing. However, because the geometry of the tank in the present simulation contains non-uniformity in the streamwise and vertical directions. The spanwise direction is uniformly spaced.

![Energy spectrum in spatial domain. Wave number length scale on abscissa (m$^{-1}$), resolved energy as a function of length scale on ordinate (m$^2$/s$^2$). Model resolved energy represented by blue line, typical -5/3 slope decay rate of isotropic turbulence represented by black line.](image_url)
However, the number of grid points over which the calculation is done in the transverse direction is not large enough to adequately calculate the spectrum. Therefore, in this instance the grid has been linearly interpolated over using a 3 mm increment. Interpolation creates a suitable space to perform the calculation over. The increment was chosen as representative of the smallest grid size in the domain being sampled.

The resolved energy spans three orders of magnitude, which is sufficient for a well-resolved large eddy simulation. Other grid sizes were used to test the sensitivity of the calculation to the interpolation increment. Changing this increment does not alter the spatial scale range that is resolved, however it does change the amount of energy resolved at each length scale. In essence, the shape of the curve is independent of the increment used, but translates up or down with a decrease or increase in the interpolation increment. That decreasing the grid size increases the calculated resolved energy makes intuitive sense, because larger velocity fluctuations are allocated to smaller grids. Therefore the absolute amount of energy resolved in Figure 3.12 is not to be taken as the actual value, however the trend of the curve is taken to be accurate with regard to resolved length scales.

Given this condition, large turbulent kinetic energy regimes, especially related to wave breaking, will in fact be directly dissipated by the numerical model. However, it has already been seen that in some ways not enough energy has been drawn out of the system, leading to inaccuracies in free surface evolution prediction. It is possible
that much of this energy is dissipated in the very initial phase of wave generation, when the wave is still stabilizing. The wave flume solitary wave does not undergo this transformation, allowing it to retain much of its energy until the observed break point. Therefore it is possible that energy levels tend to be lower due to the breaking problem seen previously. Although the discrepancies are not overwhelming, this does point to the importance and difficulty of accurately depicting all processes from large scale breaking to small scale turbulent fluctuations, because of the intertwined nature of different scales of phenomena.

To ensure that the LES subgrid closure method chosen was optimal, the simulation was run using two different closure schemes, the standard Smagorinsky subgrid closure and the k-equation model closure. The Smagorinsky model employs the same concept of parameterizing unresolved turbulence with an eddy viscosity term, but differs in that it uses a constant coefficient throughout the computation, rather than checking how turbulent the flow is in each grid and consequently adjusting the viscosity. Alternatively, the k-equation model solves a modeled turbulent kinetic energy transport equation throughout the domain, similar to the method behind the k-ε model. The comparison results are shown in Figure 3.11.

The use of the Smagorinsky model has a noticeable effect on both the free surface evolution (not shown here) and the TKE magnitude and decay rate at different depths in the time series. Initial wave behavior using this model is generally the same, with early breaking still present. However, in this run the wave amplifies more after breaking, and sustains a larger wave height than the dynamic Smagorinsky wave until
well onshore, when the profiles collapse onto each other when the shallower water of the depth-limited breaking regime is met. Increase in wave over-prediction seems to be indicative of insufficient energy dissipation. The sudden decrease in very shallow depths, however, signals a sharp jump in the dissipation rate. Because the Smagorinsky coefficient remains constant throughout the domain, while the extent of the turbulent flow regime in the tank is not completely established, such as immediately after breaking into the surf zone, the dissipation rate is artificially low, whereas after the wave has essentially transformed into a propagating bore and turbulence production is very high, the dissipation rate either becomes artificially high, and thereby matches the results seen with the dynamic Smagorinsky model, or simply matches that dissipation rate.

The time series RMS turbulent kinetic energy measurements vary from both the empirical and dynamic Smagorinsky model results, as well (Figure 3.11, blue line). Very near the surface where turbulence is very high (z =110 mm), the Smagorinsky model underpredicts the maximum values seen in the laboratory. At mid-depth (z = 70 mm) the maxima of the laboratory and constant coefficient model are equal and greater than the dynamic model, but the constant again shows a much slower dissipation rate. Below this depth (z = 30 mm), very near the bed, the standard Smagorinsky model dramatically over-predicts both the laboratory data and the results obtained using the dynamic Smagorinsky model, maintaining the low dissipation rate.

This is in line with the pattern observed in the free surface elevation. In regions of very high turbulence, such as very near the surface, the constant coefficient model
becomes excessively energy damping. In regions where the turbulent behavior is lower, such as near the bed, the model does not dissipate enough energy. At each depth the spike in TKE is followed by a much slower dissipation rate. This trend is more pronounced nearer the bed, where the magnitude of the spike is larger. Again, the larger turbulence levels and slower decay result from the use of a constant coefficient, which does not damp sufficient amounts of energy. Qualitatively, as well, the disagreement is greater between the empirical data and the constant coefficient model. The spikes in TKE are much wider due to the decreased dissipation rate, and there is also usually a time lag between the two data sets.

Using the one-equation model also produces results that differ significantly. In the transverse-averaged free surface evolution, initially the wave height prediction is actually slightly larger at the first wave guage. Unlike the other two closure schemes and the laboratory measurements, the wave modeled using this closure does not increase in wave height before breaking. As a result wave breaking occurs even sooner. The dissipation of wave height due to breaking does not tend to be as great compared to both Smagorinsky models. Once the mid-depth regions are reached, though, the decay rate matches the other two closure schemes very closely, with the magnitude remaining just slightly greater than the dynamic Smagorinsky wave. Again, this may be a function of entering a depth-limited breaking regime. In general, the wave prediction capability does not seem to be improved in any significant way through this closure scheme.
The main difference noted between the dynamic Smagorinsky model and the k-equation model when looking at the turbulent kinetic energy time series at \( z = 110 \) mm, is the lack of distinct energy peaks in the data. Whereas the dynamic Smagorinsky displays a well defined bi-modal TKE time evolution at this location, the k-equation model smooths this feature out. Perhaps as a result the maximum value occurs for this model between those two peaks. This maximum under-predicts the laboratory measurements by an even greater degree than the dynamic Smagorinsky model, as well. In the middle of the water column \((z = 70 \text{ mm})\) the k-equation closure results in the greatest under prediction seen in any of the models. There is again a lag in the maximum TKE value, this time occurring very near the peak predicted with the standard Smagorinsky model. Finally, very close to the bottom \((z = 30 \text{ mm})\) the same behavior continues with the large under prediction of TKE levels accompanied by a phase lag.

Using a k-equation model equation for the subgrid closure scheme in this simulation appears to decrease the amount of variability in turbulent fluctuations over time, while additionally leading to consistently low magnitudes of turbulent kinetic energy. One argument for this response is that the assumptions that might merit the use of this model do not apply to this specific case. Whereas the assumption for this study, as has been shown through the TKE spectrum, is that this model is well-resolved, a modeled \( k \) balance equation more likely assumes the opposite, and consequently averages over and parameterizes much of what is actually directly calculated by the model. The use of a k-equation is also found in RANS turbulent
model approaches, where the spatial resolution is indeed very coarse. In this instance this averaging approach is necessary. But when using a well-resolved, fine resolution LES model, much of the work done by the model is redone by the k-equation, leading to less variations in the results, and less energy in the system. This hypothesis is presented as only a possible explanation for this model behavior, and would require a rigorous testing across multiple numerical meshes with coarser and finer resolution to determine its correctness.

This highlights some of the difficulty using functional LES models in general. There are apparent differences in results due to the different assumptions made by each model. It is also possible that the results are dependent on the grid resolution. Still, for the present study it is clear that the dynamic Smagorinsky model provides the most consistently accurate results through the validation process, and will be the LES closure model employed for the remainder of this study.
Chapter 4
VISUALIZATION AND QUANTIFICATION OF THE TURBULENT FLOW FIELD

4.1 Point Sensor Detection of Turbulent Coherent Structures

Several approaches were taken to understand the coherent behavior of turbulence in the simulation. As an entry point, Ting presented a quantitative schematic with which one may identify an oblique descending eddy, based on the orientation of the streamwise, spanwise, and vertical velocity fluctuations (Ting, [2006]). A particular correspondence of the three velocity fluctuation components in a time series is evidence of an eddy. An oblique descending eddy may be divided into four quadrants, each with a different combination of $u'$, $v'$, and $w'$ orientation.

Presented below, in Figure 4.1, are the instantaneous time series of turbulent velocity fluctuations, turbulent kinetic energy, and Reynolds’ stress taken at $x = 7.371$, $y = 0.5625$ m, $z = -0.0825$ m (70 mm above the bed), compared with Ting’s data at the same $x$ and $z$ locations, but in the middle of the tank, $y = 0.45$ m. At around $t = 4.34$ s there is a coincidence of a positive $u'v'$ with negative $u'w'$ and $v'w'$ spikes, indicative of the behavior within the third quadrant of an oblique descending eddy. From this perspective, when viewed from the top the eddy will rotate clockwise, and the quadrants refer to their locations in a Cartesian coordinate reference system. A
counter-clockwise rotating eddy would simply have inverted signs of the turbulent shear stress components.

Figure 4.1: Model-data comparison of instantaneous turbulent velocity fluctuations time series at 70 mm above bed. OpenFOAM in red, laboratory data in black.
Although a one-to-one comparison is not possible due to the indeterminate nature of turbulent flow, comparison of the two data sets is still illustrative. Despite not being measured in the same location, there is in fact a time and magnitude correlation between the two phenomena.

This implies that although spatially indeterminate, the model predicts similar characteristics of coherent structures to those measured under breaking waves. These measurements also have a clear signature, despite being the “random” turbulent fluctuations. This signals some type of determinism in turbulent flow behavior, and further that the total flow may be more accurately described as being composed of a mean, “random” turbulent, and “coherent” turbulent mode.

Due to time constraints, the time series data with this resolution was only taken at each spanwise point at the same depths used in Ting. [2006]. Still, this coherence is detectable at other depths, as seen below in Figure 4.2a-f. These particular time series represent the instantaneous fluctuations at one spanwise location out of eighty. Oblique descending eddies do not exhibit themselves at each of these eighty points, so the data were analyzed to locate these structures. These time series do not necessarily correlate with one another, i.e. they do not represent the descent of one particular eddy.

Noticeable variability in magnitude exists, although the orientation at this streamwise location seems to remain constant. All of the behavior here corresponds to the 3rd quadrant of an eddy, and the measurements are relatively close to one another in the transverse direction, indicating they may perhaps be related in some way, if not
specifically being the result of only one structure. Some of time series are not as clean as others, especially when comparing data from near the bed with near the surface (compare Figure 4.2e with 4.2b). This is quite possibly the effect of energy attenuation through the water column. Near the more energetic surface one would expect to see more noise in the data, while toward the bottom only the strongest signals have not been dissipated. Still, even in the more energetic conditions this signature is identifiable. Very near the bottom, Figure 4.2f, the signal has dropped below the background turbulence levels seen higher in the water column.
Figure 4.2a: Coherent turbulent velocity fluctuations 130 mm above the bed, $y = 0.00375\text{m}$ in numerical domain.
Figure 4.2b: Coherent turbulent velocity fluctuations 110 mm above the bed, \( y = 0.00375 \text{m} \) in numerical domain.
Figure 4.2c: Coherent turbulent velocity fluctuations 100 mm above the bed, $y = 0.075\text{m}$ in numerical domain.
Figure 4.2d: Coherent turbulent velocity fluctuations 50 mm above the bed, $y = 0.015m$ in numerical domain.
Figure 4.2e: Coherent turbulent velocity fluctuations 30 mm above the bed, $y = 0.0225$ m in numerical domain.
Figure 4.2f: Coherent turbulent velocity fluctuations 10 mm above the bed, $y = 0.255m$ in numerical domain
Typically the time series data a few grid points laterally removed from the locations seen in Figures 4.1 and 4.2a-e are influenced by the turbulent coherent structure, but the signals become increasingly noisy, as would be expected, until no detectable coherence is present.

4.2 Oblique Descending Eddy Flow Field Signatures

Contour plots of the x-y plane in Figure 4.3, near the gauge location at which time series evidence of turbulent coherent structures (i.e. \( x \sim 7.37 \text{ m}, y \sim 0.3 \text{ m}, z = -0.0825 \text{ m} \)), render another perspective. Because of difference in output between the write intervals of the complete model results (every 0.1 sec) and the gauge output (approximately every 0.001 sec), a complete time history of these plots is unavailable.

The plots represent the behavior of vertical velocity fluctuations, instantaneous TKE, and z-normal vorticity. Again, instantaneous TKE values are calculated by subtracting the instantaneous velocities from the spanwise averaged mean flow at one instant in time. As shown in Ting, [2008], signature characteristics of oblique descending eddies include counter-rotating vorticies correlated with a large shear in the vertical velocity. This shear develops between the counter-rotating vortices, and is accompanied by a spike in turbulent energy. For example, near \( X = -25 \text{ mm}, Y = 75 \text{ mm} \) in the figure, there is a break in the fluid between a positively and negatively oriented vertical vortex. Coincident at this location is a high shear region of vertical velocity. In the negative vortex to the right, an uprush of fluid (positive \( w' \)) is seen,
whereas a downrush (negative $w'$) appears in the vortex with positive orientation. This simultaneity of fluid-fluid interaction is a turbulence source, as evidenced by the dark red region in the middle plot. In these figures it could be argued that three distinct eddies have been generated, all exhibiting the same tendencies.

Figure 4.3: Contour plots of vertical velocity fluctuations ($w'$), instantaneous turbulent kinetic energy ($k$), and the z-normal component of vorticity at $z = 70$ mm above the bed near $x = 7.37$ m, $y = 0.3$ m at $t = 4.4$ s. Axes are not representative of absolute tank location, but are included for scale purposes only.
Around these areas of high shear and vorticity, the fluid is relatively quiescent, especially in terms of TKE. Despite the relative strengths of these eddies, they appear to be highly focused upon generation, while the rest of the near-field flow is mostly unaffected. The energy in these eddies is highly focused. These features are seen to be advected downstream at later times. Based on the transverse extents of the predominant eddy in this visualization, the typical eddy size is roughly 10 cm, or about 1/6 of the width of the domain. Eddies of this size were also seen in the laboratory through PIV measurements, further validating the agreement with experimental data the model displays.

This behavior is rather ubiquitous in the planform views at all depths and practically everywhere in the regions which the wave crest has passed. Many of these eddies are much larger than the time series readings indicate; in fact, the eddy seen in the time series of Figure 4.1 is a rather small eddy when compared with those seen elsewhere in the tank. For example, in Figure 4.4 we see the generation of an eddy near the surface, with a maximum $k \approx 5500 \, \text{(cm/s)}^2$, or nearly five times as strong as the time series eddy described in previous figures.
Figure 4.4: Contour plots of vertical velocity fluctuations ($w'$), turbulent kinetic energy ($k$), and the z-normal component of vorticity at $z = 130$ mm above the bed near $x = 7.37$ m, $y = 0.3$ m at $t = 3.8$ s.

This structure is not captured by the data collected from the numerical gauge, because its formation point is slightly downstream, and therefore lacks a time series record. Interestingly, this dominant eddy is apparently flanked by a smaller eddy which does coincide with the velocity gauge point. The separation between the two
formations is approximately 10 cm, or roughly one eddy-size. Vertical velocity
gradient and vorticity magnitudes are similarly smaller at this point. It is uncertain
how these eddies relate to each other, but it has been reported in the literature that
eddies may certainly exist with separation of as little as one eddy diameter (Ting and
Nelson, [2011]).

Figure 4.5: Contour plots of vertical velocity fluctuations ($w'$), turbulent kinetic
energy ($k$), and the $z$-normal component of vorticity at $z = 110$ mm
above the bed, near $x = 7.37$ m, $y = 0.3$ m at $t = 3.8$ s.
Two centimeters below this position the dominant eddy formation is still very strong, if slightly attenuated, as seen above in Figure 4.5. By this depth the smaller eddy has been damped significantly. Coincidence of eddy behavior at multiple depths and locations in both time series data and instantaneous contour maps both corroborates previously developed theory and gives an idea of the pervasiveness of this type of turbulence under a wave crest.

4.3 Turbulent Coherent Structure Visualization Using the $\lambda_2$ Criterion

Three-dimensionality is implicit in these analyses, and the amalgamation of this information may be visualized in an organized way through the use of the $\lambda_2$ criterion described by Jeong and Hussain, [1995]. This criterion was developed in order to identify vortices without recourse to merely qualitative characteristics. Instead, the second eigenvalue of the addition of the square of the symmetric (strain rate) portion of the velocity gradient and the square of the antisymmetric (spin) portion of the velocity gradient is calculated (always negative for coherent structure identification) and plotted in three-dimensional contours. Use of this criterion is common in turbulent flow analyses where coherent non-mean motions are important, although typically it has been used in smaller scale studies. Figure 4.6 presents the $\lambda_2$ contours evolution over time. Contours represent a $\lambda_2$ value of -40, which was chosen to filter out some of the smaller scale contributions of the turbulent field which crowd the figure.
Figure 4.6: Time evolution of $\lambda_2 = -40$ contours under the breaking wave. First image corresponds to $t = 2.5$ s. Each subsequent image occurs 0.2 seconds after the preceding. Final image occurs at $t = 5.1$ s. Images span $x = 4$ m to $x = 11$ m.
Immediately after the wave breaks, a surface roller is generated. Due to the wave overtopping this air void formation is forced into the water column and loses the velocity it had when attached to the wave. Bands of $\lambda_2$ wrap around this roller, as expected. Essentially the roller is a large spanwise vortex, which the $\lambda_2$ criterion was developed to identify. While the wave breaking is still in its early stages, the bands are very coherent and uniform across the tank. This is indicative of the relatively low levels of turbulent kinetic energy in the tank. Even further upstream from this main roller are two smaller ones, existing in a still quieter flow field. The $\lambda_2$ contours quantitatively characterize what are known to be the main contributors to turbulence further downstream. As the breaker propagates the initial void which is wrapped in $\lambda_2$ contours is seen to decrease in diameter, and though the roller is becoming more displaced from the wave front, $\lambda_2$ fingers can be seen connecting the two regions. This is indicative of the straining that is taking place within the flow field, and which will eventually lead to the breakdown of the two-dimensional roller into a three-dimensional one. In the propagating bore stage of wave evolution ($t > 5$ sec), these small three-dimensional structures permeate the water column. A detailed evolution of $\lambda_2$ can be seen in Figure 4.7 below.

Once the breaking has reached a certain critical point, the well-defined two-dimensional rollers are no longer generated due to excessive strain beneath the wave crest, and the rollers that lag behind also devolve into small three-dimensional structures. These coherent structures pervade the region directly under the wave to the
point where there is virtually no space without a $\lambda_2$-contour. Behind the wave, however, the $\lambda_2$ contours follow what will be seen in the turbulent kinetic energy cross-sections, namely that packets detach from the wave and become isolated from the subsequent packets in the tank. At $t = 4.2$ seconds this is visible, where three distinct regions of high $\lambda_2$ concentration are discernable. Also at this point we see evidence of large fluid strain on the bed, evidenced by the $\lambda_2$ structures near the extreme left and bottom of the figure which appear to be cut off. As more time passes the correspondence between the vorticity and TKE trends and the $\lambda_2$ shapes continues, and when the former begin to dissipate, the concentration of $\lambda_2$ decreases accordingly.
Figure 4.7: Instantaneous free surface elevation and corresponding $\lambda_2 = -40$ contours (viewed left to right, top to bottom).
4.4 Co-evolution of Vorticity and Turbulent Kinetic Energy

Looking at the cross-sectional detail is similarly illuminating. Figure 4.8 presents the development of spanwise averaged TKE (equivalent here to ensemble-averaged TKE), instantaneous TKE, and x-, y-, and z-oriented vorticity at the transverse location $y = 0.5625$ m (the location at which turbulent velocity fluctuations were compared with Ting’s data). The horizontal length scale at first spans $x = 4$ m to $x = 8$ m, and shifts in two meter increments as necessary to follow the wave crests. The scales of magnitude do not represent the absolute maximum or minimum of a given variable at any particular point in time, but was chosen to maintain consistency over time and show a broad enough range that would represent the major processes.

Generation of turbulent kinetic energy seems to be coincident with the evolution of transverse vorticity under the incipient breaking wave. Once overturning takes place, the other vorticity components immediately begin to develop, and some pockets of the initial cross-tank vorticity begin to lag behind the leading face, as seen in Figure 4.8b. This trailing part is accompanied by a very small packet of ensemble-averaged TKE. This packet becomes more pronounced as the trailing vorticity pocket develops into a counter-rotating spanwise vortex, and also develops up a vertically downward oriented spin.
Figure 4.8a: Spanwise averaged TKE, instantaneous TKE at \( y = 0.5625 \, \text{m} \), and x-, y-, and z-components of vorticity at \( t = 2 \, \text{s} \), from \( x = 4 \, \text{m} \) to \( x = 8 \, \text{m} \). Units in \((\text{m/s})^2\) for TKE, and \(\text{s}^{-1}\) for vorticity.
Figure 4.8b: Same as figure 4.8a except at t = 2.5 s, x = 6 m to 10 m.
Figure 4.8c: Same as figure 4.8b except at $t = 2.8$ s.
Figure 4.8d: Same as figure 4.8b except at $t = 3.0$ s.
Figure 4.8e: Same as figure 4.8b except at $t = 3.2$ s.
Figure 4.8f: Same as figure 4.8b except at $t = 3.4 \text{ s.}$
Figure 4.8g: Same as figure 4.8b except at $t = 3.6$ s.
Figure 4.8h: Same as figure 4.8b except at $t = 3.8$ s.
Figure 4.8i: Same as figure 4.8b except at $t = 4.1$ s.
Figure 4.8j:  Same as figure 4.8b except at $t = 4.3$ s.
Figure 4.8k: Same as figure 4.8b except at $t = 4.5 \text{ s.}$
Figure 4.8l: Same as figure 4.8b except at $t = 4.7$ s.
Figure 4.8m: Same as figure 4.8b except at $t = 4.9$ s.
Figure 4.8n: Same as figure 4.8b except at $t = 5.1$ s, $x = 7$ m to 11 m.
Figure 4.8o: Same as figure 4.8n except at $t = 5.3$ s.
Figure 4.8p: Same as figure 4.8n except at t = 5.5 s.

It is worth noting that voids are visible in the figures. This air has important implications on velocity fluctuation, because the buoyancy of an air pocket could induce a rapid net upward movement in the water column which is otherwise unrelated to the fluid velocity. However, these air pockets are not well captured in that the size to which they would eventually decay is presumably smaller than the average grid size of the model. Still, significant fluid motions do follow these pockets. For example, at t = 3 seconds the trailing roller formation discussed previously has a high localized content of energy and vorticity. Similarly under the leading wave crest in the same
instant the same congregation is seen around another air pocket. The differences between the exact configuration of the TKE burst at any plane and the average cross-section can be seen quite clearly around this time. At $t = 3$ seconds the average TKE cloud is larger and stronger than the instantaneous one, indicating that the dominant energy process is taking place somewhere else in the tank. After the passage of 0.2 second, however, the profile shapes look qualitatively more similar. Cross-shore and vertical vorticity directly under the wave crest at this point do not appear to have much large-scale structure, being largely dispersed into smaller vortex components that typically have a counter-rotating partner. The main packet of TKE shed off the tail indeed has this characteristic, also. A final thing to note at this time is the thin layer of $y$-oriented vorticity present at the tank bottom beneath the wave. This may be the result of resolving some of the bottom boundary layer, where a large gradient of cross-shore velocity would develop, inducing a $y$-oriented rotation. However, because this is a single wave, the conditions are largely unreal, because in a periodic wave domain on a real beach wave set-up and a corresponding undertow would develop, probably changing this predicted bottom vorticity dynamic.

By $t = 3.6$ seconds all vorticity components under the wave crest manifest themselves as fairly random. The initial TKE cloud that formed beneath the roller upon the initial wave breaking begins to trail the leading face, leaving a larger burst than the previously shed packets. The variance between mean and local values is also very stark, as a strong eddy forms at $y = 0.5625$ m which does not match the comparitively mild average profile. This indicates that at this time it may be the
dominant process in the cross-tank. Here also we begin to see the process by which these eddies are generated. Upon each turn over of the water surface at the leading edge a large amount of TKE and spanwise vorticity is generated. Essentially, the subsequent touch down “rolls over” the previous packet, usually creating an accompanying air pocket, due to which the initial packet detaches from the leading edge. Consequently, this packet loses the momentum imparted to it by the leading face of the wave, and enters a flow field with lower shoreward directed velocity. The eddies then maintain roughly the same distance relative to the other detached eddies, and decelerate until the wave completely passes them. At this point they cease all forward motion for the most part and only move downward (see t = 4.4 seconds). In the vorticity field the same pattern is observed, where regions of high vorticity in any direction are largely isolated once they leave the influence of the wave. This process happens at least eight times in the averaged space.

The regions of vorticity appear to be connected in determinate ways, possibly the manifestation of the vortex tube phenomenon described by Watanabe, [2005]. In the x-direction especially, long, thin filaments of rotational fluid are generated at the wave face, often surrounded by similarly shaped masses of opposite sign. The configuration of the horizontally-oriented vorticity field is perhaps the most sensitive to changes in the surrounding domain, as evidenced by the qualitative change evinced between t = 4 and 5 seconds. Whereas the evolution of the other two fields retains recognizable shapes between the time steps, x-directed vorticity is liable to change the most quickly, with certain packets disappearing completely between time increments.
Obviously, this change does not happen spontaneously, but at this output interval the model does not capture the small scale, rapid changes the flow field undergoes.

Spanwise-oriented vorticity does not behave this way, because its generation is a function of the roller motion, which is always forward and therefore always causes clockwise rotation. It is not until after an eddy detaches from the main wave form that we see significant counter-clockwise y-vortices. Strain induced by the rotation in the other two directions may be important in this development, when eddy motion becomes more dominant compared to the wave-roller motion. Vertically-oriented vorticity is more similar to the streamwise-oriented component, but the resultant structures more frequently cluster in counter-rotating pairs, which are coincident with the intense TKE regions. This hearkens to the planform contours shown previously. Based on the coexistence of the x- and y-directed vorticity with vertical vorticity, the final piece of the planform picture, vertical velocity fluctuation, seems to be embedded in the shearing flow field which is more globally responsible for fluid rotationality.

Looking at the average TKE plots, the evolution trend is apparently an initial highly concentrated area of energy in the wave breaker, which slowly disperses into an elongated cloud from which some of the first eddies detach. Around $t = 4.1$ seconds this cloud looks to be at its maximum length, with almost a uniform average value throughout it, except at the very edge of the wave face. From this point the wave is more of a propagating bore, and each time the face envelops itself a small concentrated packet is developed and shed. This process repeats itself until around $t = 5$ second, when the energy again tends to bunch up in the wave face. Much of the
wave momentum has been dissipated by this point, and even when the wave appears to be on the brink of overturning, it seems that the water is merely pushed forward. Without the overturning process eddies apparently still form, but they are much smaller than further upstream, when the wave was larger. By $t = 5.5$ seconds the averaged field is permeated with very dispersed turbulent kinetic energy and accompanying vorticity. This is manifest by investigating the $\lambda_2$ contours, as well (Figure 4.6). The main generation of $\lambda_2$ at this point in the simulation consists of small worm-like structures which do not persist for as long as those which arise from the more robust formations that wrap around the rollers.

An interesting feature of this series of images is the visualization of coherent structure-bed interaction. At various points after $t = 4$ seconds, vorticity packets of all three orientations are seen to touch the bed. In the x- and y- directions the vorticity strength remains roughly equal to its mid-stream levels. Y-vorticity touchdown tends to be associated with the development of its negative component, whereas in the absence of touchdown only the thin layer of clockwise rotation exists. The z-vorticity damps more as it approaches the bottom, but still reaches that point. Turbulent kinetic energy similarly approaches the bed, but at a much more attenuated level.

Advection of these eddies still proceeds at very minimal levels when they meet the bed, at a rate similar to that which they undergo midstream. The ambient flow in the tank and the fractional amount of momentum which these eddies still retain play a role in this. From this view it is uncertain how long the actual bed interaction persists in a non-negligible way, but the vertical structure of the eddy extending up into the
water column does seem to maintain its form for a fairly long time. For example, the eddy which begins interaction with the bed around $t = 4.2$ seconds in the instantaneous slices at $y = 0.5625$ m still shows bed level effects 1.2 seconds later. This is mostly vorticity contribution, as most TKE is really manifested only above the bed at this point. Similar patterns are seen at other cross-shore locations. These interactions could have important implications for boundary layer processes and sediment transport.

### 4.5 Turbulent Coherent Structure Bed Impingement and Resulting Bed Stress

Bed interactions have been observed in both the cross-sectional planes and $\lambda_2$ contours. This behavior is reported in the literature in both the laboratory setting and in the field, but specificity is lacking with regards to it spatial and temporal distribution at the bed. Figure 4.9a-d shows contour plots of the instantaneous turbulent kinetic energy at the first grid point above the bed. The exact distance from the bed varies somewhat due to the nonuniformity of the grid, ranging in the plots below from about 3 mm ($x = 6$ m) to 1 mm ($x = 18$ m). In his work on periodic breaking waves, Ting, [2011] measured the TKE at 8 mm above the bed. Although this spacing may be a number of times greater than, say, the typical grain size of sand on the sea bed, the effect of turbulence is not expected to attenuate that significantly in that interval, considering its continued existence from the free surface to near the bed.
Figure 4.9a: Nearest-bed grid point TKE (cm/s)$^2$ at times 3.2 – 4 s in 0.2 s intervals.
Figure 4.9b: Nearest-bed grid point TKE (cm/s)$^2$ at times 4.2 – 5 s in 0.2 s intervals.
Figure 4.9c: Nearest-bed grid point TKE (cm/s)² at times 5.2 – 6 s in 0.2 s intervals.
Negligible turbulence can be seen entering the domain (truncated to begin at x = 6 m) at t = 3.1 seconds. This coincides with a large cloud of TKE which begins to detach from the wave crest and will eventually form an eddy as seen in the average TKE cross-section at t = 3.2 seconds. Initially the distribution nearly encompasses the entire width of the tank, basically shadowing the bore above it. Soon, though, the energy focuses in one location, near the left edge of the tank. This coincides with the first large cloud of turbulence seen detaching from the wave. An intensification follows immediately, and then a gradual dispersion ensues until its effects are seen to encompass over half the tank again. Once the turbulent energy reaches the bed in its concentrated form, it advects downstream only about 0.5 m over roughly one second.
The effects linger after this time, as well, but the formation by this point has lost the tightness it once had, and is merely dissipating very slowly.

About 0.6 seconds later a second touchdown is observed in the center of the tank, approximately 1 m downstream from the original. This eddy correlates with the second large packet of TKE shed from the wave. In this instance the initial build up and consolidation of energy is not observed. Its subsequent behavior replicates that of the first eddy, though, as dissipation begins once the maximum focusing has occurred. While this dissipation process is taking place another formation appears slightly diagonally from the main eddy. It is not known whether this structure is unique in itself or a diffuse part of the original. One indication may be that the focusing in this energetic region is mild to non-existent as compared to the first two examples, which points to its being a part of the other eddy. In time these two regions merge. At the interface of this combined region there is an enhancement of TKE, interrupting the energy dissipation. This differs from the first eddy whose strength uniformly decays over time. However, this does not affect its downstream displacement, moving only about 0.5 m, despite the longer duration of bed interaction (approximately two seconds compared to about one for the first).

After this eddy has been largely damped, dominant structures of this type are not manifested. Smaller scale touchdowns do take place, but the nature of their relation to coherent structures is unknown, and could have more to do with the diminishing water depth. In shallower water, where breaking processes are depth-limited, the bore exists closer to the bed than in the deep water regimes, making
energy transfer from the free surface to the bed much easier. By the time turbulence is observed at the bed after the second large eddy touches down, the water depth is merely 9 cm ($x \sim 10.5$ m), approximately equal to wave height. These interactions are generally less intense and less focused, but are more frequent and more closely spaced. Once the wave reaches $x = 14$ m, the depth has dropped to 2 cm, and the interactions at this point may all be characterized as direct interaction of the propagating bore with the bed.

Taking the first two high intensity TKE regions as representative of oblique descending eddy-bed interaction, the touchdown length scale of the eddy is roughly 10 cm, similar to the length scale exhibited higher in the water column. Their spacing was said to be about 1 m in cross-shore distance, however the controlling factor in their spacing is more likely related to the propagation speed of the wave, which controls the rate at which turbulent rollers are generated and shed. Taking the averaged TKE cross-section as a rough estimate, these packets are generated approximately with $\sim 20$ cm of separation, which by the time both are shed increases to $\sim 60$ cm.

Finally, the prevalence of highly turbulent regions at the bed suggests appreciable consequences for sediment transport. Sediment was not modeled in this simulation. However, by taking a representative grain size for surf zone sediment and finding the friction velocity, the bed stress can be non-dimensionalized as the Shields parameter using the equation:

$$\theta = \frac{u^2}{(s-1)gd}$$  \hspace{1cm} (16)
where $u_*$ is the friction velocity, $s$ is the specific gravity of sediment (taken here as 2.65), $g$ is the gravitational acceleration, and $d$ is the grain size. Sediment transport is often described in terms of the critical Shields parameter, $\theta_c$. When the calculated Shields parameter exceeds this value, the shear stress on the particles is large enough to induce motion. For typical coastal applications $d$ is taken to be 0.2 mm, and $\theta_c = 0.05$. However, because the critical Shields parameter actually depends on the particle Reynolds number, it may not be a constant value. Therefore the ratio here is considered only as a rough estimate of behavior in the field. The Shields parameter contour plots are presented below in Figure 4.10.
Figure 4.10: $\theta/\theta_c$ ratio for interval $t = 3.2$ s to $t = 7$ s in 0.2 s intervals, from $x = 5$ m to $x = 15$ m.
The friction velocity here is calculated as part of the wall function employed at the tank bottom boundary condition. This function parameterizes the near-wall velocity through use of the shear stress at the first grid point above the bed, from which friction velocity is calculated. OpenFOAM does not output these results by default, but the code was modified by Zheyu Zhou of the University of Delaware to do this.

Under the propagating wave, the Shields to critical Shields ratio is always high as a result of the wave induced motion. The progress of the wave follows the deep red zone through the wave tank. Behind the wave, though, the high Shields parameter zones which develop coincide directly with the high TKE zones created by coherent structures impinging on the bed. The largest values of $\theta$ are seen well on shore under the wave, in the region of heavy free surface-bottom interaction. Typically, the ratio in the coherent structure zones does not exceed about five, still well above the level of incipient motion of sediment.

From the instantaneous results it is difficult to determine the importance of separate events. For example, the passing wave appears to be the most important component in the generation of bed stress, but because it is transient, the lasting effects are not captured. Therefore, spatial and time averaging were applied to the Shields parameter. For each instantaneous plane for which Shields information is available, the plane-average (spanwise average) was taken, allowing decomposition akin to the Reynolds decomposition of velocity into a mean and fluctuating part. In this situation, the transverse averaged Shields parameter for a given time is subtracted from the instantaneous value at each point in that plane, resulting in a “fluctuating” Shields parameter. Further, this value is normalized by dividing by the plane-averaged
mean value. The results are shown in Figure 4.11. In essence, the contours filter out the sediment transport implications of wave motion, because under the wave the flow is still mostly homogeneous in the spanwise direction, especially near the bed.

The regions with large positive deviations from the transverse averaged Shields parameter correspond closely with those with high TKE. Time evolution agrees in this way, as well. Two large, dominant regions exist near the beginning of the field of view, followed by a less active region, and finally the highly active region near the shoreline appears where sediment transport is expected to be large. The dominance of the eddy structures in the surrounding flow field is corroborated by looking at those regions close to the touch down zones. Negative fluctuating values are typically associated with these surrounding regions because the Shields values are high enough inside the eddy that the local mean is significantly greater than zero.
Figure 4.11a: Normalized instantaneous deviation from plane-averaged mean Shields parameter \(((\theta - \langle \theta \rangle)/\langle \theta \rangle)\) where angular brackets represent transverse averaging) at the bed, for \(t = 3.2\) sec to \(t = 4\) sec in 0.2 second intervals.
Figure 4.11b: Same as Figure 4.11a, except for $t = 4.2$ sec to 5 sec.
Figure 4.11c: Same as Figure 4.11b, except for \( t = 5.2 \) sec to 6 sec.
Figure 4.11d: Same as Figure 4.11c, except for \( t = 6.4 \) sec to 8 sec in 0.4 second intervals.

Similarly, it is illustrative to take the time average of the Shields parameter over a significant period of time, which provides a clearer picture of which processes dominate over the course of the solitary wave passage. In this case we consider that significant bed interaction will take place from slightly after breaking (\( t = 3 \) seconds) to the point at which the wave meets the initial shoreline (\( t = 8 \) seconds). These results are shown in Figure 4.12. Averaged over this interval, the effects of the passing wave are again filtered out, and the regions subject to sediment transport for the longest time are those coincident with eddy impingement points. Further onshore this value is high as well, while between these two zones the average Shields parameter is below the
critical value for a typical sand grain. The passing wave is important instantaneously, but its effects are limited in time, whereas the eddy activity at the bottom has an influence with much longer duration.

The importance of the non-transient motions in the tank (i.e. not directly related to wave motion) points to coherent structure interaction with the bed as an important factor in sediment transport. This can be investigated by calculating the time-averaged TKE levels at the bed over the same interval and comparing the resulting contour plots. Figures 4.12 and 4.13 show that there is indeed high spatial correlation between the regions with higher average turbulence and higher average bed stress. Even when relatively low time-averaged TKE exists, the corresponding time-averaged Shields parameter can be greater than critical for typical sand grains, such as the region around $x = 12$ m, $y = 0.55$ m.

Over the course of the solitary wave event, the coherent structure induced bed stress can be twice as large as the stress resulting from the wave motion. In tank locations not subjected to eddy impingement, the average bed stress yields a Shields parameter of around 0.04. From the instantaneous plots it is evident that the wave induced stress and turbulence induced stress are comparable in magnitude. However, the longer residence time of the turbulent interaction compared to the wave boundary layer effect creates the lower time-averaged $\theta$ values mentioned. The consequence of a wave breaking related phenomenon lasting much longer than the wave influence time could be missed in theoretical models which rely on wave period information to estimate sediment transport.
Figure 4.12: Time-averaged Shields parameter, averaged over $t = 3$ sec to $t = 8$ sec.
Figure 4.13:  Time averaged TKE at the first grid point above the bed in (cm/s)$^2$, averaged over $t = 3$ sec to $t = 8$ sec.
The number of coherent structures generated from a single wave seems to be limited by the energy contained in the wave as it propagates. Looking at the contours of the instantaneous TKE at the tank bed (Figure 4.9) reveals that this simulation is dominated by two strong eddies, both of which can be related to the breakdown of large rollers seen in the $\lambda_2$ contours (Figures 4.6 and 4.7). Immediately landward of the second large eddy, the energy distribution at the bottom is wider, perhaps as a result of less highly focused impingement points. This can be seen in Figure 4.9d, where after a gap between $x = 9$ m and $x = 11$ m, most of the width of the tank is affected by relatively low levels of turbulence, from about $x = 11$ m to $x = 13$ m. These do not have as large an impact in terms of turbulence kinetic energy and bed stress. Although smaller rollers are apparent in the $\lambda_2$ snapshots, looking strictly at the free surface reveals that the wave is at least no longer overturning, generating rollers, and entraining air. This appears to inhibit the amount of energy that is transferred to the bed, as the distribution is sparser and less intense than the upstream zone dominated by the two large eddies.

Even further onshore, the energy at the bottom increases again, after about $x = 13$ m in Figure 4.9d. This region is adjacent to and intersects the run-up and run-down zone. Here, however, it is not hypothesized that turbulent coherent structures are necessarily strong again, but rather that a propagating bore is simply very close to the bottom due to shallow flow depth and thereby easily transfers energy to the bed. The
depth in this zone is typically less than 3 cm, or approximately less than or equal to the local wave height.

This distribution of energy in the wave tank lends itself to a demarcation of zones, in which different bed interaction behavior exist. The deeper zone closer to initial breaking tends to be dominated by the roller-generated coherent structures that have sufficient intensity to interact with the bed (see x = 6~9m in Figures 4.9 – 4.11). These are large packets of energy, around 1/6 the width of the tank. Within this region eddies maintain that size independent of depth. This is seen by comparing the peak TKE regions at the bed to the contour plots generated at different depths previously, as in Figures 4.3 – 4.5. Streamwise spacing between the eddies is approximately 1.5 m. Looking at the time-averaged result, coherent structures are responsible for a large amount of significant turbulent kinetic energy at the bottom. Alternatively, turbulence generated simply by the passing wave is much smaller over the course of the breaking process. This can be seen in Figure 4.13. The bottom distribution of TKE in the depth-limited breaking zone displays a less energetic profile than the deep region offshore. Inside the two eddies in this zone, the local average maxima can be approximately twice as large as the peak values reached in the depth limited zone (~110 (cm/s)^2 compared to ~50 (cm/s)^2).

In the mid-depth section of the tank, eddies and turbulent events continue to generate, despite their attenuated effect on the bed. This is highlighted by the lower levels of turbulence in the averaged domain downstream of approximately x = 9 m (see x = 9~13 m in Figures 4.9 and 4.11). The major breaking process by this point has largely completed, and the waveform has become more of a propagating bore. Free surface overturning no longer takes place. Instead, water piles up at the leading edge.
of the wave and is pushed forward by the water behind it. This environment is still productive in terms of instantaneous TKE, but the result is a largely dispersed field rather than the tightly focused one further upstream. Around this time in the breaker evolution, the depth has decreased, but not to the point that surface processes necessarily interact with the bottom. Consequently, the bed interaction is much more random and less intense, as turbulent coherent structures individually are formed in less robust configurations, and therefore are dissipated more frequently before they reach the bottom of the tank.

Finally, once the depth becomes less than the wave height (see $x > 14$ m in Figures 4.9 and 4.11), the surface processes directly dictate the behavior of the entire water column. This portion of the tank results exhibits depth-limited breaking only, and the wave decay rate is the same in the model and the laboratory. Here large energy levels are again seen at the bed both instantaneously and in a time-averaged sense, but are mostly unrelated to direct coherent structure impingement.

When turbulence generated by a surface wave reaches the bottom, its duration there is significant comparing to bottom boundary layer process. For example, the first large eddy seen to touch down maintains a presence for the better part of three seconds in which wave crest have already passed. During this time, it evolves in shape to become much more disconnected and disperse, while simultaneously advecting downstream somewhat. This persistence is linked to the maintained presence of a turbulent flow in the water column directly above the bed (see $x \sim 6.8$ m, Figure 4.8h-p, for example). Unless this turbulence above is dissipated via another mechanism, it will continue to move with its downward and shoreward momentum, effectively “supplying” energy at the bottom. The advection of turbulence was also observed in
Ting and Nelson, [2011] for periodic waves. In the field, the turbulence may evolve and decay in a more complex manner, because subsequent flow from periodic waves and return flow offshore would present other mechanisms, aside from viscous dissipation alone, by which turbulent kinetic energy could be damped.

It was shown that large Shields parameter values coincide with this highly turbulent bottom behavior (compare Figures 4.9 and 4.11). This was seen in the time averaged domain (Figures 4.12 and 4.13), in which two dominant locations were noted to coincide directly with high intensity TKE regions, and in the spatially averaged domain, where highly positive deviating values of Shields parameter exist. As expected, the Shields parameter values are large instantaneously beneath the wave, but these effects are seen to be transient when averaged over, and less durable than the large Shields values resulting from the highly turbulent flow fields.

The implications of sediment transport based on the present simulation results would obviously also change when applied to a periodic wave simulation or field conditions. However, the critical role played by the breaking-wave-induce turbulent coherent structures in enhancing bottom stress and sediment transport is expected to be qualitatively similar. It is probable that these highly turbulent events may be able to suspend sediment very high in the water column. Again, it is noted that the sediment transport ramifications presented in this investigation are tenuous. There are scaling issues involved in modeling a laboratory wave tank and making conclusions about field-scale responses. In addition, real sediment would have a non-uniform distribution and would modify the turbulent flow experienced at the bed.

It has been remarked on in the literature and in this paper previously that while the existence of multiple turbulent coherent structures beneath a breaking wave is well
known, their measurement is a hurdle which point sensors cannot easily overcome, due to the indeterminate nature of their spatial and temporal generation points. In this numerical study one coherent structure was captured using a point sensor. However, instantaneous contour plots reveal that these point sensors missed even more intense events that occurred nearby. Inspection of the bottom TKE levels indicates, also, that the eddy detected using time series data probably was not strong enough to reach the bottom, as the bed at that point in the tank at t \sim 4.3 \text{ seconds} is almost completely unperturbed.

Based on the theoretical groundwork for turbulent coherent structure formation, especially that of Watanabe, [2005], it should be expected that structures are formed constantly as a wave breaks, resulting in a large population beneath the crest. This generation is mainly attributable to the highly rotational flow that takes place under a curling wave surface. Accompanying this fluid state is a vorticity field, which is interconnected in complex ways. The evidence suggests that the presence of these formations in the upper water column is simply a characteristic of any breaking wave (as seen in the \lambda_2 contours in Figure 4.7). Because of their ubiquity there, turbulent coherent structures are responsible for a great deal of momentum transfer and bubble transport.

What the simulation results do indicate, though, is that this abundance of turbulent kinetic energy focuses eventually, and that this focusing is an important, if not the determining, feature in the fate of eddies. In the tank regions near the break point these tightly focused eddies were the only ones which eventually interacted with the bed. The first eddy to reach the bed, for example, centered near y = 0.4 \text{ m}, whereas the subsequent eddy to touch down was at y = 0.3 \text{ m}. However, in the upper parts of
the water column, TKE is generally distributed equally across the width of the tank. In each roller generated in this simulation, the energy preferentially locates in the coherent structure, although this is difficult to distinguish except near the bed. The first two eddies are located near the center of the tank, however subsequent smaller turbulent events at the bed are more indiscriminate in their spacing, suggesting that the location at which a turbulent coherent structure is formed is more or less random.

From this simulation, where the tank width is six times the typical eddy length scale, multiple eddies generated from the same roller were not observed. It is conceivable that this could occur, however, if the tank width were increased, for example.

In terms of the computational issues related to this type of study, a few points bear mentioning. First, it was noted that to ensure the most accurate free surface tracking possible using this particular VOF scheme, the grid size ratio (i.e. the grid spacing in the x-direction versus the grid spacing in the z-direction) must be held close to unity throughout the domain. If this $\Delta z/\Delta x$ quantity becomes too small or large, non-physical behavior occurs, such as detachment of the free surface near the wave breaking interface. Additionally, this grid ratio has implications for the LES model, because the filter grid size becomes much different than the actual grid used in the simulation. Maintaining a well-behaved grid ratio throughout the domain, however, constrains the resolution possible in the simulation, since one cannot simply choose to focus on resolving only one dimension very well. Therefore, each increase in grid number in one direction results in a nearly cubic increase for the entire domain, since the other two dimensions must increase proportionally.
Related to resolution is the energy resolved by the LES model. It was noted in preliminary studies of this case using coarser resolution that less turbulent kinetic energy was measured. As the grid was refined, the energy increased, which agrees with the interpolated spectral investigation performed previously. Additionally, the turbulent fluctuations become noisier as the resolution increases. Large eddy simulation is dependent on grid size, and as this the grid size becomes smaller, the resolved energy at a given length scale becomes greater. This inhibits the type of grid independence testing which is possible with other turbulence models, where a particular grid size is identified for which the turbulence levels will not vary significantly with further resolution. Therefore, the best possible LES will effectively be a direct numerical simulation. However, as the results indicate, subgrid-scale modeling can perform well in this capacity for the present, and still yield interesting and useful results.
Chapter 6

CONCLUSIONS AND FUTURE WORK

The OpenFOAM library of Navier-Stokes equations was utilized to simulate a series of solitary wave laboratory studies. Agreement with the experimental data from Zelt, [1991], Synolakis, [1987], and Ting, [2006], and established theory were in general favorable, although some wave generation issues experienced when the wave height to water depth ratio becomes very large. Still, the predicted offshore wave profiles, run-up profiles, and turbulent velocity, turbulent kinetic energy, and Reynolds stress values were found to be satisfactory. Further investigation of the Ting, [2006] dataset and simulation results revealed detailed generation and evolution of turbulent coherent structures, especially the oblique descending eddies.

Oblique descending eddies and turbulent coherent structures in general are well documented phenomena in the literature. This is true with regards to their existence (for example, Nadaoka, [1989]), generation mechanism (Watanabe, [2005]), and effects (Cox and Kobayashi, [2000], etc.), all of which have corroborated throughout this numerical investigation. TKE, vorticity, and $\lambda_2$ contours showed that in the case of spilling breakers, coherent structures are the result of the breakdown of two-dimensional surface rollers that form around air voids. Excessive shearing in the upper water column near the wave leads to this phenomenon, which is evidenced by the growing vorticity field in all three directions near the free surface. Once the roller detaches from the wave surface, its momentum decays and it settles relatively near its generation point while the wave continues to propagate. Its deconstruction into small
three-dimensional structures occurs largely in a narrowly confined area, with a region of relatively quiescent fluid surrounding it. Two large structures generated in this fashion were computed in the numerical simulation, their spatial separation being a function of the time elapsed between subsequent wave turnovers.

The model results in the present study leave open a number of questions. For instance, the ultimate fate of sediment suspended by turbulent coherent structures needs to be further investigated and understood in order for a functional parameterization to be formulated. As was seen in Ting and Nelson, [2011], when a coherent structure descends to the bed it induces a large upward velocity fluctuation region in around it, which could suspend sediment, and possibly deliver it to much higher in the water column. Also, the swash zone is obviously of great importance in the overall sediment transport in the nearshore. While this study captured the preliminary stages of run-up onto a beach, studies such as Sumer, et al., [2011] indicate that the bed stress induced during the run-down is significant as well, though it is difficult to measure in the field. Numerical modeling could elucidate this phenomenon more clearly.

In addition to coherent structures arising in well-defined locations relative to the width of the wave tank, the high-energy rollers also occupy restricted areas of the tank relative to previously generated rollers and the propagating wave. The spacing between two subsequent events is related to the turnover time of the wave face. This behavior may have dependence on the subgrid closure scheme employed, though. For example, use of the standard Smagorinsky closure method has shown that the turbulent flow field behind a breaking wave is much more dispersed and uniform, i.e. the broken wave leaves a continuous trail of TKE behind it. It was shown in the
preceding sections that the LES closure method employed indeed has appreciable
effects on the results. Due to time constraints, a complete comparison among those
tested was not possible. Contour plots similar to those used in Chapter 4 could present
the differences among the LES closure models in a more physical sense. In general,
further investigation in this direction is warranted.

Wave breaking in a real surf zone encompasses behavior from incipient
breakers to surging breakers, varying in degrees typically quantified by the surf-
similarity parameter. As the front edge of the wave sees an increase or decrease in
energy relative to a spilling breaker, it is expected that the surface roller behavior will
vary accordingly. A stronger breaking mechanism would be anticipated to be
responsible for the generation of more turbulence than a weaker. Oblique descending
eddy have been documented as being much more prevalent in plunging breakers, for
example. The plunging breaker in this study identified two definitive coherent
structures which impinged on the bed, but a stronger breaker could conceivably
produce more. This dependency on wave condition also presents an open question to
investigate in the future.

The periodic nature of real ocean waves obviously presents a more
complicated picture than a single solitary wave shoaling and breaking. Thus,
investigation is warranted of how periodic waves are different than solitary waves
with respect to how coherent structures are generated and dissipated, and how they
behave near the bed. Looking at a train of waves and identifying the turbulent eddies
may also shed light on where they are generated with respect to the center of the wave
crest and why. The solitary wave eddies were seen slightly to the left of the center of
the wave crest and almost directly behind it, before many smaller eddies were deposited more randomly. It remains to be seen what governs this behavior.

In general, it would be beneficial to study turbulent coherent structure behavior in a larger setting. Tsunamis generate these phenomena in coastal areas populated with structures. They also have immense impacts during inundation and retreat, which go beyond sediment transport. Simply being able to quantify the stress generated during these processes would allow for a more thorough understanding of tsunami preparations with regards to inland and coastal structures which are threatened by excessive wave forcing, coherent structure stress, and the resulting sediment transport which could induce severe scour. Smaller scale studies such as the present one can begin to understand these phenomena, especially as the available data increases through additional tests. Ideally, as computational capacity increases, a single model will be able to resolve large-scale events like tsunami waves, sediment transport for a typical ocean bed, and the small-scale turbulent fluctuations that dramatically affect all physical behavior.
REFERENCES


Nadaoka, K., Kondoh, T., (1982). Laboratory measurements of velocity field structure in the surf zone by LDV. *Coastal Engineering Japan*, 25, pp 125-145


Appendix

LETTER OF PERMISSION FOR USE OF TING, [2006] DATA

Jacob Sangermano
Breaking Wave Turbulence with Tom Hsu
4 messages
Jacob Sangermano  Tue, Apr 23, 2013 at 12:53 PM
To: Francis.Ting@sdstate.edu

Hello Dr. Ting,

My name is Jacob Sangermano, and I am one of Tom Hsu's graduate students at the University of Delaware. He may have mentioned me to you in a previous e-mail. I have been working with him on modeling breaking wave turbulence which utilized some of the data from your 2006 paper in Coastal Engineering. We have obtained encouraging results thanks to your allowing us to use that data and I am about to complete my Master's thesis which includes many of those model-data comparisons. However, before I complete and submit it to the University, I wanted to make sure that I have your permission to publish some of your data as part of the paper, to ensure proper copyright guidelines are followed and that you are properly credited in the work. I would be happy to provide you with a copy of the manuscript once it is finished. Thank you again for your help with this investigation, and I hope that you will be pleased with the results we collected.

Regards,

Jacob Sangermano, E.I.T.
Graduate Research Assistant
University of Delaware, '13
Civil and Environmental Engineering

Ting, Francis  Tue, Apr 23, 2013 at 1:46 PM
To: Jacob Sangermano

Jacob,

Are these the data from my 2006 or 2008 paper in Coastal Engineering or both? Thanks.

Francis Ting
Dr. Ting,

Thank you for getting back to me so quickly. Only the data from the 2006 paper was used in my thesis.
Thanks,

Jacob

Ting, Francis <Francis.Ting@sdstate.edu> Tue, Apr 23, 2013 at 7:48 PM
To: Jacob Sangermano <jacob.j.s.1787@gmail.com>

Jacob,

You can use the data from my 2006 paper in Coastal Engineering in your thesis. You may also need to get permission from the publisher if you are using some of the figures in the paper.
Best wishes,

Francis Ting