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Practical Guidance for Numerical Modeling in FUNWAVE-TVD

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PURPOSE: This technical note describes the physical and numerical considerations for developing an idealized numerical wave-structure interaction modeling study using the fully nonlinear, phase-resolving Boussinesq-type wave model, FUNWAVE-TVD (Shi et al. 2012). The focus of the study is on the range of validity of input wave characteristics and the appropriate numerical domain properties when inserting partially submerged, impermeable (i.e., fully reflective) coastal structures in the domain. These structures include typical designs for breakwaters, groins, jetties, dikes, and levees. In addition to presenting general numerical modeling best practices for FUNWAVE-TVD, the influence of nonlinear wave-wave interactions on regular wave propagation in the numerical domain is discussed. The scope of coastal structures considered in this document is restricted to a single partially submerged, impermeable breakwater, but the setup and the results can be extended to other similar structures without a loss of generality. The intended audience for these materials is novice to intermediate users of the FUNWAVE-TVD wave model, specifically those seeking to implement coastal structures in a numerical domain or to investigate basic wave-structure interaction responses in a surrogate model prior to considering a full-fledged 3-D Navier-Stokes Computational Fluid Dynamics (CFD) model.

From this document, users will gain a fundamental understanding of practical modeling guidelines that will flatten the learning curve of the model and enhance the final product of a wave modeling study. Providing coastal planners and engineers with ease of model access and usability guidance will facilitate rapid screening of design alternatives for efficient and effective decision-making under environmental uncertainty.

BACKGROUND: Numerous coastal structures monitored by the U.S. Army Corps of Engineers (USACE), such as jetties, breakwaters, and groins, are vital for commercial and military navigation along the U.S. coastline. Coastal structures provide stability along adjacent beaches and at inlets, as well as protection from extreme incident wave conditions at harbors and marinas. Wave-structure interactions and general wave-driven processes are very complex and can occur across multiple temporal and spatial scales. Common wave processes of particular interest at or around coastal structures are wave reflection and absorption, run-up and overtopping, and transmission (USACE 2006). Accurate and robust quantification of these processes in mixed coastal domains is a ubiquitous problem in the coastal community.

Operationally accurate and robust computational tools are needed for screening design alternatives and providing a validated assessment of coastal structures. Advancements in high-performance computing (HPC) have made numerical modeling of nonlinear coastal wave processes more practical to apply in shallow-water environments. There is increasing interest among academic, government, and private institutions in using FUNWAVE-TVD for accurately predicting transformation and interaction (e.g., run-up, overtopping, and transmission) of surface waves with permeable coastal structures. FUNWAVE-TVD has been used in a variety of nearshore applications including harbor resonance in Alaska (USACE 2020) and living shoreline assessment in New York (Marrone et. al. 2019). In the last decade, the FUNWAVE-TVD model has received several developmental examples, including the addition of the ship-wake module (Shi et al. 2018), Sediment Transport and Morphology Modules (Tehranirad et al. 2017; Malej et al. 2019), Storm and Meteo-tsunami Module (Woodroff et al. 2018), and parallel input/output (I/O) with profiling and optimization (Lam et al. 2018).

However, results from any numerical model are only as reliable as the input parameters, settings, and conditions provided by the user. A fundamental level of understanding of the model is required by the user to produce accurate predictions of complex physical processes. This knowledge and experience is even more important when considering the use of high-fidelity, nonlinear numerical models like FUNWAVE-TVD.

Most of the guidance and guidelines offered in this document are specific to modeling in FUNWAVE-TVD, though some of these best practices are applicable to other models with similar numerical domain setup (e.g., rectilinear grid) and propagation of physical processes. Additional details for modeling using FUNWAVE-TVD can be found on the comprehensive Wiki page (https://fengyanshi.github.io/build/html/index.html; Shi et al. 2019).

NUMERICAL MODELING BEST PRACTICES: In this section, a set of practical numerical modeling guidelines is presented. To exemplify the application of these guidelines, a range of feasible wave conditions is considered over an idealized, flat bathymetry. This range of wave conditions represents the simulation test bed of the wave modeling study. The guidelines and test bed discussed herein are specific to modeling with FUNWAVE-TVD, though some components may be generalized for application in other numerical models of similar setup.

Each reduced-order or asymptotic numerical model serves a specific purpose: to solve a set or series of complex equations that cannot be solved analytically in a closed form. As a result, each model has its practical limitations with respect to its physics (e.g., physical processes resolved) and the numerical methods used to propagate them. In practice, it is important to understand the bounds of these physical limitations for the specific model and to provide realistic and appropriate input parameters for the model to simulate. If inputs passed to the model are outside the scope of its purpose, or range of validity, the outputs from the model may not accurately represent the physical processes expected from the model, and results can be misleading. In addition, the numerical domain should be constructed such that information can be passed from one point of the grid to the next (e.g., equations are solved and propagated through the domain) in an efficient, effective, and stable manner.

Three fundamental numerical modeling best practices are presented to address the aforementioned considerations when modeling with FUNWAVE-TVD. These practices include the following:

1. Valid range of wave climates
2. Spatial resolution requirements with respect to input wave parameters
3. Spatial resolution requirements with respect to stability

This list is not comprehensive of all practices a user must consider when initiating a wave modeling study. However, these considerations provide a strong foundation for orienting novice and intermediate users toward robust and efficient numerical modeling practices. Should these practices be violated or ignored, there may be consequences in the numerical stability during the simulation or in the integrity of the numerical modeling results upon its completion. The effects of some of these consequences on the integrity of results are presented later in this document.

Valid range of wave climates. Consider an idealized simulation test bed for a regular (i.e., monochromatic) wave climate with a range of input wave periods T (in seconds) and water depths h (in meters) over a flat bathymetry. The test bed incorporates a range from 2 to 16 seconds at an interval of 1 second for wave period, and from 1 to 20 meters at an interval of 1 meter for water depth. These values represent feasible wave and water depth conditions that have been observed or measured across the U.S. contiguous and Alaskan coastlines. All possible combinations of (T, h) wave climate pairs yielded 257 unique simulations.

In FUNWAVE-TVD, a regular wave simulation is defined using the internal, regular wavemaker native to the model (Shi et al. 2019). This wavemaker requires the wave period, water depth, and wave amplitude as user-defined input. The wavelength associated with these input parameters governs the scope over which the model is valid and dictates the appropriate level of spatial resolution to use in the domain. This relationship is, in part, based on the underlying Boussinesq theory that is accurate to the second order in kh, where k is the wavenumber and can be rewritten as $2\pi/\lambda$ (λ is the main/peak wavelength) and h is the undisturbed water depth. It is recommended to calculate this parameter with your specific wave conditions before beginning any simulation.

The wavelength λ (in meters) in shallow-water theory is primarily a function of the incident wave period (T) and water depth (h), where $\lambda = T\sqrt{gh}$, with g as the gravitational constant 9.81 m/s^2. However, for each unique combination of (T, h) in the simulation test bed, the associated wavelength λ was computed by iteratively solving the linear dispersion relation in intermediate water, $\omega = \sqrt{gk * \tanh(kh)}$, where ω is the wave frequency ($2\pi/T$). Figure 1 displays the full range of possible wave period and water depth combinations, with the associated wavelength shown as contours. For more details about water wave mechanics, see Dean and Dalrymple (1991).

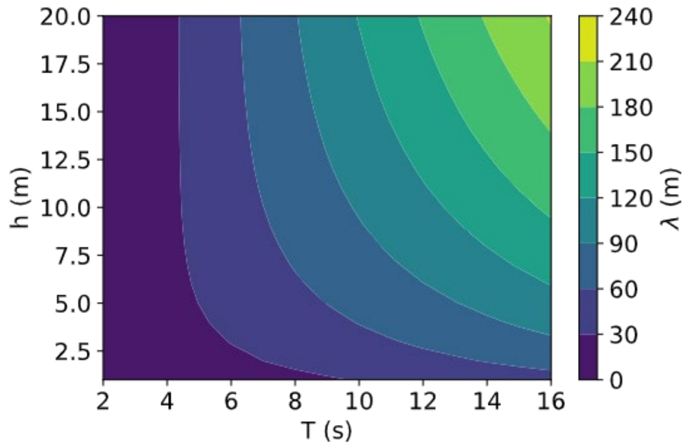
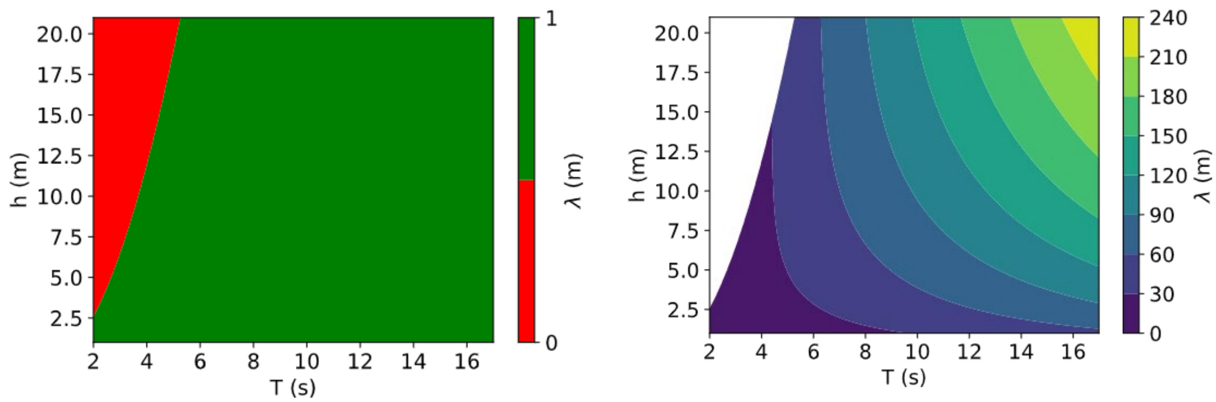


Figure 1. Full range of possible input wave period (*T*) in seconds and water depth (*h*) in meters considered for the simulation test bed; contours represent possible wavelengths (λ) in meters corresponding to (*T*,*h*) pairs; wavelength determined by iteratively solving the linear dispersion relation (Dean and Dalrymple 1991).

In FUNWAVE-TVD, the range of validity for the model (i.e., the scope of its purpose) is specifically for shallow to intermediate water depths, where we commonly say that waves feel the bottom. In deeper physical coastal environments, these regimes are of finite depth, where waves are fully dispersive and waves of different wave lengths (or frequencies) travel at different speeds. Numerically, FUNWAVE-TVD is weakly dispersive (accurate to second order in kh), whereby waves in deeper water cannot be resolved. This shallow-to-intermediate water depth regime—referred to as "waves feeling the bottom"—condition is met when the input wavelength λ is greater than twice the undisturbed water depth h (Eq. 1):

$$\lambda > 2h \quad (1)$$

Implementing this condition on the range of possible input wave parameters in the simulation test bed produces Figure 2*a*. In this figure, areas shaded in green are (T, h) pairs that produce wavelengths λ that meet the above condition. Areas in red are pairs that fail to meet this condition. As a result, the possible range of wavelengths λ in the simulation test bed that can be entertained in the FUNWAVE-TVD model is visualized in Figure 2*b*. Therefore, when conceptualizing a wave modeling study, users should be sure to compute the wavelength λ associated with the intended input wave period (T) and water depth (h) to ensure the wave conditions meet the criteria of finite depth and are within the range of validity of the model. It is also worth noting that for modeling irregular waves (e.g., TMA spectrum), the peak wavelength (i.e., most energetic) or the shortest wavelength (i.e., largest frequency = shortest period) should meet the above criterion in terms of resolving the waves of interest. Users may otherwise cross-reference their input wave conditions for regular waves with Figure 2*b* on the FUNWAVE-TVD Wiki page (Shi et al. 2019).



(*a*) (*b*)

Figure 2. Graphical representation of (*a*) the valid range of possible input wave period (*T*) and water depth (*h*) that produce waves with wavelengths greater than twice the water depth (λ > 2*h*), where areas in green meet the criteria and areas in red do not, and (*b*) the wavelengths that do not meet the criteria removed from Figure 1 wavelength contours.

Spatial resolution requirements. At this stage, the idealized simulation test bed is restricted to the appropriate range of validity for the model. The next considerations are specific to developing the structure of the numerical domain. The choice of spatial resolution (e.g., number of grid points or discretization of the numerical domain) is a critical component for all numerical modeling applications and can largely influence the model output. If the spatial resolution is low, the accuracy of the numerical solution decreases, as does the computational expense of the model; the inverse is true if the spatial resolution is high. It is important to select an appropriate spatial resolution that meets accuracy needs within available computational resources.

In FUNWAVE-TVD, the spatial resolution variables are DX (x-direction) and DY (y-direction) over the rectilinear grid. For one-dimensional (1-D) applications, DX is the primary resolution variable, whereas two-dimensional (2-D) applications require careful consideration of both DX and DY. In this study, guidelines specific to the spatial resolution of 1-D simulations are discussed, though they can be applied to 2-D simulations as well.

There are two fundamental considerations for defining spatial resolution in the numerical domain when modeling in FUNWAVE-TVD. The first consideration is a function of the input wavelength (λ) of the waves to be resolved. For general numerical wave modeling applications, the numerical domain should have at least 60 grid points per wavelength to adequately resolve the physical processes in space. This condition is met with the following relationship (Eq. 2):

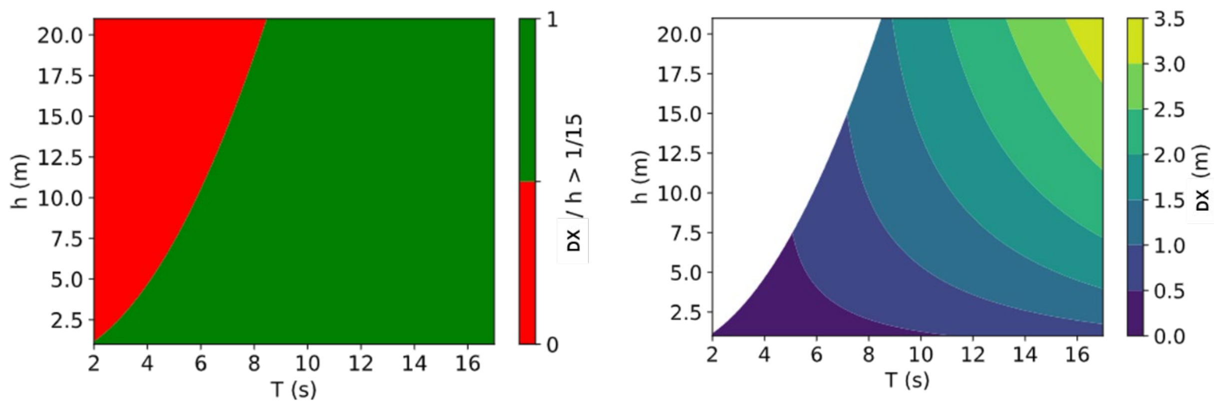
$$DX < \frac{\lambda}{60} \quad (2)$$

A physical process of particular interest to the practitioner is the propagation of total wave energy through the domain. The sensitivity of monochromatic wave energy propagation to changes in spatial resolution is discussed in the next section. For the idealized simulation test bed considered here, a spatial resolution of 70 points per wavelength was implemented.

The second consideration for spatial resolution is a function of the water depth *h*. For general numerical stability, the ratio of spatial resolution to the water depth should be greater than the ratio of 1 over 15 (Eq. 3). This condition stems from dozens of trial and error attempts at stabilizing the model by the FUNWAVE-TVD modeling community and is suspected to be related to wave characteristics or the nonlinear Courant-Friedrichs-Lewy (CFL) condition. No direct investigation or discussion of the root cause of this instability has been completed at the time of this publication.

$$\frac{DX}{h} > \frac{1}{15} \tag{3}$$

Implementing this condition on the valid range of wave conditions in the idealized simulation test bed produces Figure 3*a*. In this figure, areas in green meet the *DX*/*h* condition, and areas in red do not. Combining the limitations of validity (Figure 2*a*) and spatial resolution (Figure 3*a*) produces Figure 3*b*, with contours representing the variation in spatial resolution equivalent to 70 points per wavelength. At this stage, only the (*T*, *h*) pairs that meet the above conditions should be considered in a monochromatic wave modeling study. Of the 257 unique combinations of input wave period and water depth, only 216 combinations are reasonably applicable in FUNWAVE-TVD.



(*a*) (*b*)

Figure 3. Graphical representation of (*a*) the appropriate range of possible input wave period (*T*) and water depth (*h*) that meet the stability criteria for spatial resolution (*DX* / *h* > 1 / 15), where areas in green meet the criteria and areas in red do not, and (*b*) the contours of valid spatial resolution (*DX*) for the corresponding (*T*, *h*) input wave parameters limited to the range of validity (Figure 2*b*).

Additional considerations. There are a few additional guidelines specific to modeling with FUNWAVE-TVD that are worth mentioning here. The FUNWAVE-TVD model uses an internal wavemaker (Shi et al. 2019) to generate waves in the numerical domain. Users should carefully consider the location of the internal wavemaker relative to the west (in local FUNWAVE grid layout terms) boundary absorbing sponger layer, as well as the width of the absorbing sponge layer. The appropriate distance between the wavemaker and boundary sponge layer should generally be at least half of the input wavelength of the generated wave. In addition to the appropriate (or default) selection of sponge absorption parameters, this distance allows adequate space for the symmetric internal wave maker to produce a symmetric wave train without severe interference from the sponge layer. A combination of sponge layers (e.g., direct and frictional) should also be considered at the west boundary to meet the absorption needs of individual simulations. The boundary sponge layer parameters may need adjusting to satisfy modeling requirements and goals.

Additionally, the width of the boundary sponge layer should also be at least half of the wavelength. This width provides a more sufficient distance over which the sponge can absorb the wave generated by the wavemaker with minimal reflections from the west boundary of the domain. The effect of the sponge layer is vital, especially for longer period waves, and those waves closer to the infragravity (IG) wave band ($T > 20$ seconds) will be difficult to absorb all together.

More details about installation, setup, and execution of FUNWAVE-TVD can be found on the Wiki, including the setup and expected outcomes from example simulations (Shi et al. 2019).

NONLINEAR EFFECTS ON WAVE PROPAGATION: The FUNWAVE-TVD model is a nonlinear, weakly dispersive Boussinesq numerical wave model. As a result, nonlinear effects on wave propagation through the numerical domain are expected to occur, even for regular (i.e., monochromatic) wave conditions. The onset of nonlinear effects is usually governed by the magnitude of the characteristic nonlinear parameter ratio (e.g., wave height versus water depth ratio being small makes the model more linear) of the modeling setup. In general, nonlinearities can cause changes in the shape of regular waves, such as the basic transfer of wave energy from the peak harmonic into higher and lower order harmonics in the frequency domain and the loss of wave energy over the numerical domain (i.e., numerical dissipation). Lesser understood about these effects in the model is when nonlinearities might manifest in the domain and by how much the input wave characteristics are altered over the simulation time and space. When extrapolating a numerical domain into a real physical setup (e.g., variable bathymetry), this situation becomes even more uncertain. This section aims to quantify and elucidate what the user should expect in their wave simulations, in part, due to nonlinear effects on wave propagation.

The nonlinear effects on propagation can be observed in both the time and frequency domains. In the time domain, an idealized linear monochromatic wave is represented as a sinusoid (Figure 4, top), where the peaks and troughs are of equal amplitude and bandwidth. The nonlinear wave-wave interaction among different linear wave components (i.e., free waves) in shallow water produces additional waves (e.g., free and bound waves) in the domain, with frequencies equivalent to multiples of the peak or input frequency. The presence of these higher order harmonics creates what is known as a Stokes wave (Rahman 1996), where the periodic wave has sharp peaks and flatter troughs (Figure 4, middle). If given enough simulation or wave propagation time, the wave will also develop skewness and asymmetry of the wave front, producing a sawtooth shape (Figure 4, bottom; Wei and Kirby 1999). The sawtooth effect is a direct consequence of the fully nonlinear Boussinesq equations in FUNWAVE-TVD.

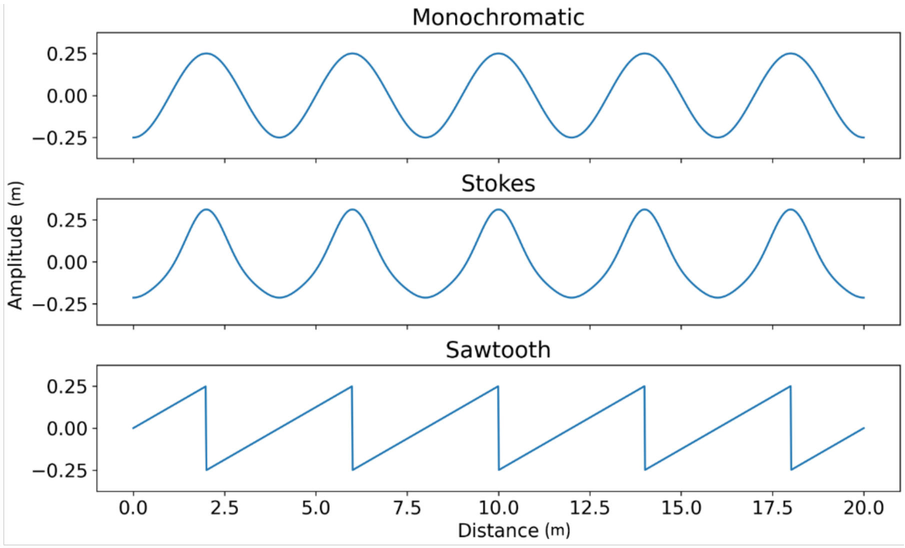


Figure 4. Example of different wave shapes over a domain of length 20 m with amplitude 0.25 m, wavenumber k = 1.571, and wavelength λ = 4 m; (top) an idealized monochromatic wave train, (middle) a Stokes wave train, and (bottom) a sawtooth wave train.

The energy density associated with each frequency band in the periodic wave can be observed by transforming from the physical to frequency domain via the fast Fourier transform (Nussbaumer 1981). Initially, as the wave is created, all of the energy in a monochromatic wave is in the peak (i.e., input) frequency. In an idealized linear model, all of the energy would exist only at the peak frequency through the domain. The moment numerical dissipation and nonlinearity initiates in the model, the total energy begins to leak or transfer to other harmonics or can be lost from numerical scheme dissipation. This energy transfer is a characteristic result—albeit possibly a spurious one—of the limitations in existing numerical methods (e.g., aliasing in the finite discretization). The higher harmonics are represented as smaller peaks in the frequency domain and occur at multiples of the input frequency (Figure 5). These additional peaks in a regular (i.e., monochromatic) wave simulation and changes in the spectral shape or energy distribution in irregular wave simulations are indications of nonlinearities in the simulation. Energy transfer is expected to occur toward lower frequencies as well, corresponding to longer period waves. This effect is a signature of generating IG waves in the simulation.

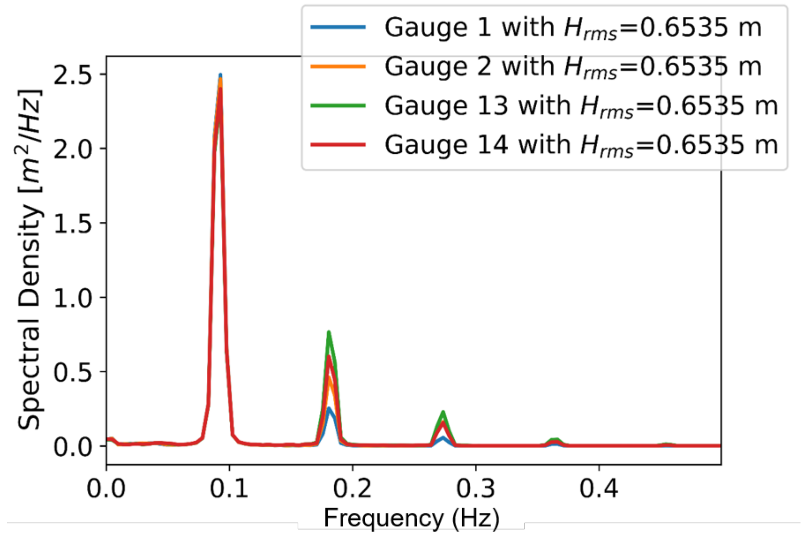


Figure 5. Example of power spectral density distribution across the peak frequency f = 0.09 Hz (T = 11 s) at four internal stations in the numerical domain; higher order harmonics are observed at 2, 3, and 4 times the peak frequency (f = 0.18 Hz, 0.27 Hz, and 0.36 Hz); gauges 1, 2, 13, and 14 are located 20 m, 40 m, 260 m and 280 m east of the wavemaker, respectively; results from monochromatic wave simulation with period T = 11 s, water depth h = 6 m, wavelength λ = 81.6 m, wave height H = 0.6 m, and DX = 70 pts/λ.

In addition to energy transfer, the total wave energy is expected to decrease due to numerical dissipation over the domain. Numerical energy dissipation is a result of using a discrete numerical method to represent a continuous process or equation, where approximations of the continuous equation/solution are computed at discrete locations (e.g., DX). Depending on the input wave characteristics and domain structure, wave energy can be lost more or less quickly. With a loss in wave energy over space, the target wave height will also decrease over the length of the domain. This spurious effect is an important consideration when evaluating or quantifying the wave responses at or around coastal structures when a specific wave condition is expected to occur. If the input wave height is not the same wave height that interacts with the structure, there will be some error in the response statistics.

The largest contributing factor to changes in energy loss could be the spatial resolution of the numerical domain, if chosen poorly. All valid simulations within the idealized test bed for monochromatic waves over a flat bathymetry were executed with three different spatial resolutions: (1) DX equivalent to 70 points per wavelength (base case), (2) DX equivalent to 135 points per wavelength (DX × 2 case), and (3) DX equivalent to 35 points per wavelength (DX / 2 case). An example of the total wave energy dissipation and reduction in root-mean-square wave height H_{rms} for one of these simulations is shown in Figure 6. For monochromatic waves, it is more appropriate to compute the root-mean-square wave height rather than the significant wave height as the latter is more applicable for irregular (spectral) waves.

The total wave energy can be measured along the domain at internal gauges (i.e., stations) in FUNWAVE-TVD. The resulting time series at each station can be converted to a power spectral density in the frequency domain. The sum or the integral of the spectral density (E_0) represents the total wave energy at that station location. Monitoring the change in spectral density at each gauge provides a measure of total wave energy loss along the domain. Normalizing the spectral density by the first gauge nearest the wavemaker produces a ratio of wave energy dissipation between 0 and 1. Similarly, the H_{rms} can be computed at each gauge by taking the square root of eight times the spectral density, $H_{rms} = \sqrt{8E_0}$. It is worth noting that due to the scalar factor and the square root between the energy density versus root-mean-squared wave height calculation, a reduction of, for example, 70% in wave energy density would result in the 45% reduction in wave height. Hence, it is important to distinguish between those quantities when analyzing the corresponding wave (energy vs. height) reduction.

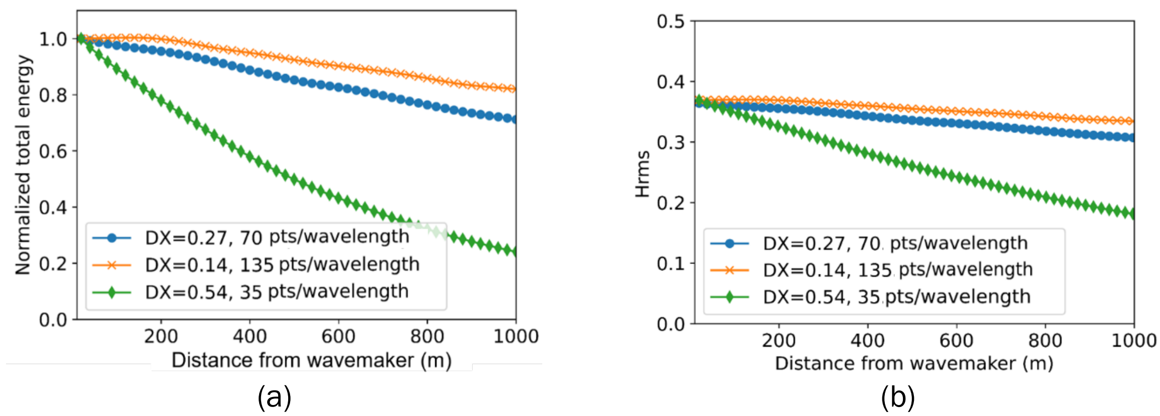


Figure 6. Example of (*a*) total wave energy dissipation and (*b*) reduction in root-mean-square wave height H_{rms} over the numerical domain with three spatial resolution scenarios, DX = 70 points per wavelength (base case; blue circles), DX = 135 points per wavelength (DX/2 case; orange crosses), and DX = 35 points per wavelength (DX × 2 case; green diamonds); monochromatic wave simulation with period T = 4 s, water depth h = 3 m, wavelength λ = 18.9 m, and wave height H = 0.4 m.

DISCUSSION: The transfer of wave energy to higher harmonics (Figure 5) should be expected in every wave simulation governed by nonlinear equations of motion for both regular and irregular cases. In the example shown in Figure 5 for a regular wave simulation of period T = 11 s, in a water depth of h = 6 m with wavelength λ = 81.6 m and wave height H = 0.6 m, energy is observed to shift out of the peak frequency (f = 0.09 Hz) as close as 20 m away from the wavemaker (gauge 1). Most of the energy (99%) is still in the peak frequency at this location. Farther from the wavemaker, the percentage of total energy that remains in the peak frequency decreased to 98%, 96%, and 97% for gauges 2, 13, and 14, which are 40 m, 260 m, and 280 m away from the wavemaker, respectively. The variability in the magnitude of this energy transfer away from the peak frequency is ultimately a function of the input wave conditions, spatial resolution, and bathymetric features in the numerical domain (e.g., flat versus variable slope). If a specific percent of initial energy is expected by the practitioner to interact with a coastal structure, the location of the structure relative to the wavemaker will contribute to the magnitude of the energy distribution around the peak frequency.

Over the length of the numerical domain, the total energy (spectral density) is expected to decrease due to numerical dissipation, and is governed, in part, by the spatial resolution of the domain and type and order of the applied numerical methods. In the example presented in Figure 6*a*, the total energy is observed to decrease by 20% 1000 m away from the wavemaker for the DX = 70 points per wavelength condition (blue circles). Increasing the spatial resolution by double (DX × 2; orange crosses) limited the total energy loss to only 10% at the same distance. When the spatial resolution is cut in half (DX/2, green diamonds), 80% of the initial energy in the wave simulation is lost around

1000 m in the domain. Similarly, the reduction in H_{rms} (Figure 6*b*) for the DX/2 condition is nearly half the initial value nearest to the wavemaker (0.35 m to 0.2 m). In practice, it is important to balance spatial resolution requirements with available computational resources. A tolerable level of energy loss and reduction in H_{rms} should also be considered by the practitioner when selecting a spatial resolution for their domain.

This document presents and discusses specific examples of energy transfer and dissipation for a limited set of monochromatic wave simulations and is not intended to be comprehensive. A more detailed analysis of the range of energy loss to be expected across several input wave conditions for regular and irregular waves will be available in the form of a technical report at a later date. That report will additionally include the evaluation of wave reflection, run-up, and overtopping response with several impermeable, partially submerged breakwater designs. In the interim, related materials and guidance will be made available on the FUNWAVE-TVD Wiki (Shi et al. 2019).

SUMMARY: The guidelines and examples presented in this document are the foundation on which coastal engineering practitioners can begin to formulate numerical wave modeling studies using Boussinesq-type models to investigate wave responses (e.g., run-up, overtopping, and reflection) with impermeable coastal structure designs in the shallow-water environment. The effects of nonlinearity and numerical dissipation on monochromatic wave simulations in the FUNWAVE-TVD model can significantly impact the expected wave response at or around any features (e.g., coastal structures) in the numerical domain. It is essential for the practitioner to understand that limitations in numerical methods (e.g., discrete approximations of a continuous physical process) exist, as well as how and when these effects will change or alter the output. Rapid screening using Boussinesq-type wave models will ultimately save time, money, and resources for planners and programs tasked with executing new construction as well as maintenance and rehabilitation of existing infrastructure. USACE District Engineers will have access to this guidance via the comprehensive FUNWAVE Wiki (Shi et al. 2019) for planning and feasibility studies that require advanced wave modeling for new or existing structures. In addition, FUNWAVE-TVD is fully parallelized and is accessible on the Department of Defense HPC environment for registered users with a Common Access Card. Under the ERDC Hydro Tool Kit, the FUNWAVE-TVD HPC Portal Application offers a user-friendly interface to set up, run, and post-process numerical wave simulations in a platform-independent remote cloud environment.

ADDITIONAL INFORMATION: This technical note is a product of the Inlet Engineering Tools work unit of the Coastal Inlets Research Program being conducted jointly at the U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory and Coastal and Hydraulics Laboratory. Questions about this technical note can be addressed to Ms. Marissa J. Torres (Marissa.J.Torres@usace.army.mil). For information about the Coastal Inlets Research Program, please contact the program manager, Ms. Tanya Beck (Tanya.M.Beck@usace.army.mil). This technical note should be cited as follows:

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