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Infra-Gravity Wave Input Toolbox (IGWT): User's Guide

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PURPOSE: This Coastal and Hydraulic Engineering Technical Note (CHETN) is a user's guide for the Infra-Gravity Wave Toolbox (IGWT) developed as an activity of the Coastal Inlets Research Program (CIRP) of the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Predicted infra-gravity (IG) wave input is required in modeling of long-waves affecting harbors. IG waves may also influence navigation, coastal inlets, and coastal structural design projects. The IGWT has been implemented in the Surface-water Modeling System (SMS) of the U.S. Army Corps of Engineers (USACE) to establish a link between CGWAVE and BOUSS-1D numerical wave models.

BACKGROUND: Most harbor structures and harbor layouts are designed for protection against wind-generated (short-period) waves with periods of order 3-20 sec. However, IG waves, also referred to in this note as low-frequency or long-period waves, with periods on order of 30-600 sec, are generated by groups of short-period waves through nonlinear wave-wave interactions. These long-period waves can cause oscillations and resonance problems in harbors. Such low-frequency waves are responsible for harbor downtime, causing oscillation problems to ships that could significantly degrade on-loading and off-loading operations inside ports. IG waves can also damage mooring lines because the natural periods for the horizontal motion of large moored vessels are typically the same order of magnitude. Lastly, IG waves also contribute to the prediction of bedload transport, wave setup and setdown, and wave runup and overtopping in a variety of coastal engineering applications. The presence of these waves and their characteristics in field applications are illustrated in the Example application provided in this CHETN.

Longuet-Higgins and Stewart (1964) provided a physical explanation of the nonlinear mechanism responsible for the generation of IG waves by groups of short waves. Gradients of the radiation stress between groups of large and small waves leads to a setdown of the mean water level below the larger waves and a compensating setup underneath the smaller waves. The variation of the mean water level is commonly referred to as a "bound" long wave since it is phase-locked to the carrier short waves. Analytical expressions to calculate the bound wave for three-wave (triad) interactions are provided in Dean and Sharma (1981). In addition to the long waves that are bound to groups of short-period wind waves, free long waves can also be generated in areas with steep changes in bottom topography and at harbor entrances (e.g., Mei and Benmoussa 1984; Bowers 1977). These long waves would be resonantly amplified inside a harbor if the long wave period were close to one of the natural modes of basin oscillation.

Different approaches can be used to estimate the IG wave energy in shallow water from the deep water wind-wave spectrum. Dean and Sharma's analytical expression (Dean and Sharma 1981) can be used to estimate the bound long-wave from the deep water spectrum or envelope of a wave time series. However, this approach is only valid for water of constant depth and tends to overestimate the IG energy over sloping bottoms. Spectral wind-wave models that include nonlinear triad interactions in shallow water could prove to be the preferred approach in the future since they include variable depth effects from deep to shallow water and are appropriate for modeling waves over large regional-scale project applications. Since Boussinesq-type wave models can represent nonlinear wave-wave interactions extremely well (Nwogu and Demirbilek 2001), one may also use Boussinesq class of wave models to transform deep water wave spectrum from the "deep-water" limit of Boussinesq model ($h/L_0 < 0.5$, where h = water depth, and L_0 = wavelength) to shallower water. This is the approach used in the IGWT described in this technical note.

The USACE has developed a finite-element model, CGWAVE, for predicting wave conditions inside harbors of arbitrary shape (Demirbilek and Panchang 1998). CGWAVE is capable of describing most linear wave transformation processes including shoaling, refraction, diffraction, full or partial reflection and transmission, bottom friction, wave breaking and dissipation, and wave-current interaction. The present version of CGWAVE does not include wave-wave interaction processes, and it is, therefore, necessary for users to provide long-period wave input at the model's open ocean boundary. With the long-period wave input specified, CGWAVE can then represent the previously-mentioned nearshore wave processes occurring during the propagation of waves in waters of arbitrary depth. The model grid and input are generated in the Surface-water Modeling System, SMS (Zundel (2006, Zundel et al. (1998). SMS includes an customized interface for CGWAVE that facilitates the generation of computational grids, specification of input to model, and visualization of model output.

CGWAVE model is often applied in analysis of Federal harbors for predicting short wave disturbance and identifying harbor resonance periods and long-wave amplification factors. The base model is based on the linear mild-slope equation, and has since been extended to have capabilities for modeling waves over steep slopes to include wave breaking, dissipation, and nonlinear amplitude dispersion mechanisms. Because the original CGWAVE does not include nonlinear wave-wave interaction processes responsible for IG wave generation, it cannot predict the amount of long-period wave energy inside a harbor from an offshore wind-wave spectrum. Thus, users are required to provide long wave input at model's open boundary if long-wave processes were to be represented. In this CHETN, a procedure is described for generating the IG wave input for CGWAVE by using a Boussinesq-type nonlinear wave model.

Design wave data for coastal studies are typically based on the transformation of offshore buoy measurements to the nearshore region. The standard engineering method of transforming waves from an offshore buoy to the nearshore is based on a phase-averaged approach, in which the wave action energy conservation equation is solved for the spatial variation of wave energy spectrum. Useful engineering quantities such as the wave celerity, radiation stress, and energy flux are estimated using linear wave theory. Wave breaking and energy dissipation are approximated with empirical relations. Examples of phase-averaged wave models include STWAVE (Resio 1987; Smith et al. 2001), SWAN (Holthuijsen et al. 2004); and WABED (Demirbilek et al. in preparation, a, b; Lin et al. 2006; Lin and Demirbilek 2005; Mase et al. 2005).

Given their computational efficiency, phase-averaged spectral wave models are widely used for wave estimation in large regional-scale coastal engineering applications. Although these models neglect or approximate some sub-wavelength wave transformation processes such as wave diffraction, reflection, and nonlinear interactions, they are useful and efficient for predicting waves in the nearshore studies. Lin and Demirbilek (2005) describe an application of two spectral models at coastal inlets where wave breaking, diffraction, reflection, and wave-current interaction are important. Frequently used spectral wave models generally do not include nonlinear triad wave interactions in shallow water.

Numerical models based on Boussinesq-type equations may be used to predict IG waves in shallow water (Nwogu 1993; Nwogu and Demirbilek 2001) by transformation of short-period waves. These models solve depth-integrated equations of conservation of mass and momentum and are uniformly valid from deep to shallow-water depths for waves propagating in water of variable depth. Boussinesq models have been shown to accurately simulate short-period wave disturbance in harbors (e.g., Abbott et al. 1978) and the diffraction of bound long waves into harbors (Smallman and Cooper 1989). Boussinesq models can be computationally demanding for harbor studies that require wave information over large domains.

NEED: Nonlinear wave-wave interactions in shallow water are relevant to harbor navigation and inlet studies, sediment transport, and morphological modeling, and in the study of fluid-structure interaction processes (wave setup and setdown, wave runup and overtopping). Because long-period waves contribute to other nearshore processes and IG wave data are not available from deepwater or nearshore coastal data sources, and they cannot be generated with linear spectral models, the CIRP has developed a methodology for estimating these waves. This technical note describes the predictive tool for IG waves implemented in SMS.

APPROACH: The IGWT utilizes a one-dimensional (1-D) version of the BOUSS-2D model that is also available in SMS as part of the Boussinesq wave model suite (Nwogu and Demirbilek 2001; Demirbilek et al. 2005a and 2005b). The 1-D Boussinesq model is used to transform wave spectrum from the "deep-water" limit of the Boussinesq model ($h < L_0/2$, where h = water depth and L_0 = wavelength) to the computational boundary of the CGWAVE model. A constant 1:50 slope is assumed between the offshore and nearshore water depths. For regions with complex offshore topography, it is recommended that the full BOUSS-2D model be run from offshore to nearshore boundaries.

The components of the IGWT interface are described next. The objective was to develop an automated procedure using Boussinesq and CGWAVE models and their SMS-based interfaces for convenient application in planning, operations, and engineering design of harbors and navigation projects. The IGWT links these two wave models inside the SMS without intervention by users. The IGWT is a "proof of concept" product, and places the power of existing model technology into the hands of users. With this first release, it is expected that the IGWT will be refined and its future capabilities expanded into a more robust and comprehensive tool. The example application used in illustration of the IGWT is Barbers Point Harbor, HI, the same harbor described in other CHETNs for the BOUSS-2-D model (Demirbilek et al. 2005a, 2005b).

DESCRIPTION: The IGWT is a calculator inside the CGWAVE interface in SMS. This calculator allows users to input wave conditions from a deepwater buoy location or user-defined site, and then accesses several utilities including BOUSS-1D to estimate the generation of long-wave energies affecting nearshore projects. The IGWT thereby generates input wave conditions at the offshore boundary of the CGWAVE domain. The features of the IGWT are described next.

Users can access the toolbox through the CGWAVE Model Control dialog. The left side of Figure 1 shows this dialog with the IG wave button being selected. After this button is pushed, another dialog appears (Figure 1, right side). Users would then enter the wave parameters at the deepwater buoy (or site) into the dialog. The input parameters, in order from the top of the dialog down, are the following:

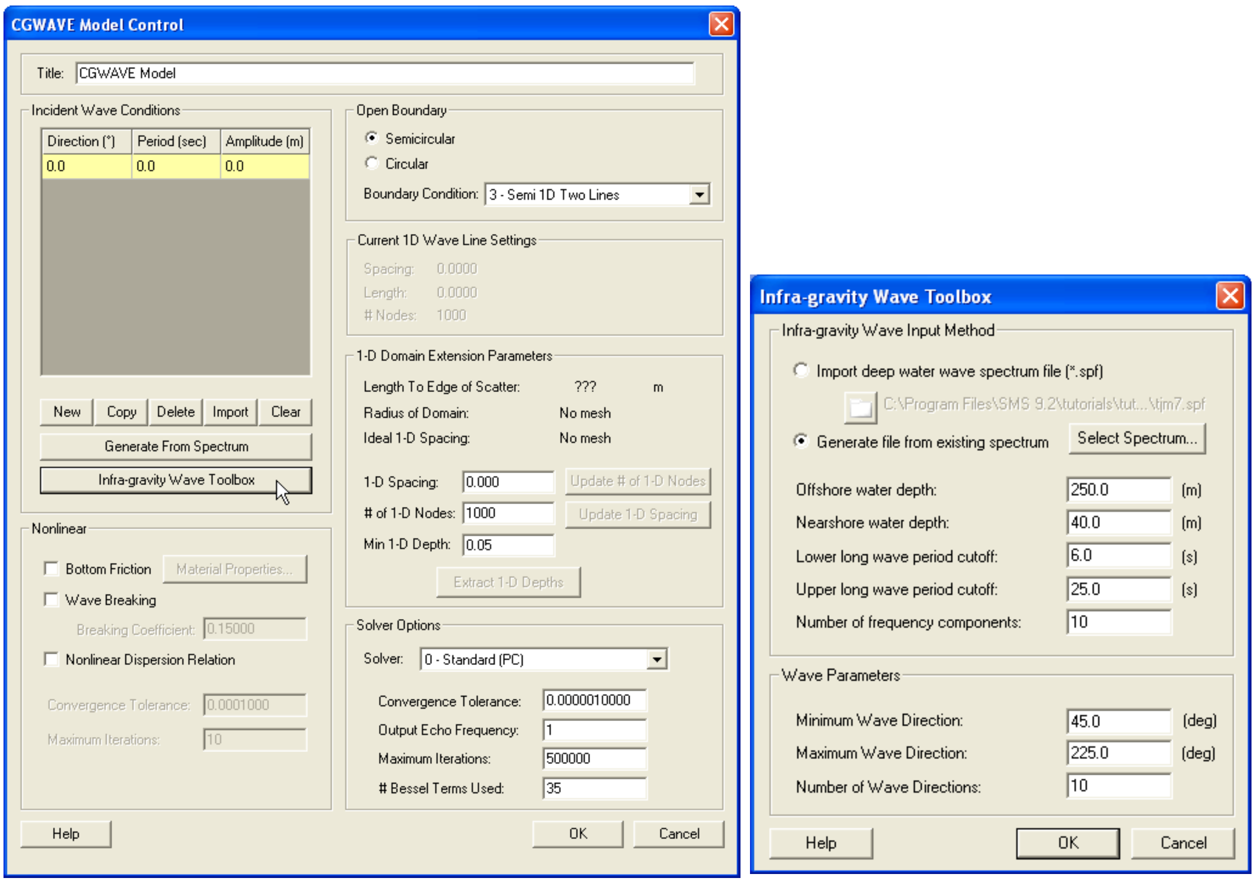

Figure 1. CGWAVE model control and long wave input dialogs.

- **Input wave spectra:** This radio group allows users to specify the frequency versus energy density spectrum at the deepwater site. This spectrum can be defined in two ways. If the spectrum is available from the buoy or has been generated, users may provide the data in BOUSS-2D Type 2 time series or ".spf" file. The format of this file is illustrated in Figure 2. Alternatively, users may select one of the full directional spectra types defined in the SMS, and the system will generate the ".spf" file for that spectrum.

- **Offshore water depth**: This parameter refers to the depth (m) at the deepwater buoy (or site). The input value of this depth will be checked and, if necessary, adjusted automatically to the deepwater limit of the Boussinesq model. This action ensures the proper usage of Boussinesq model within its range of applicability.

- **Nearshore water depth**: Because the largest bound waves are generated close to the point of breaking, this parameter refers to the depth (m) at the predominant breaking location. This value can be approximated as twice the incident significant wave height.

```
# BOUSS2D Type 2 Time Series File
#
:NDataSets              2
:DataDescription(1)     Frequency
:DataUnits(1)           Hertz
:DataDescription(2)     Spectral Density
:DataUnits(2)           m**2/Hz
#
#
:NFrequencies           1201
#
:EndHeader
 .00000    .000
 .00042    .000
 .00083    .000
 .00125    .000
 .00167    .000
 .00208    .000
…
…
…
```

Figure 2. BOUSS2D type 2 time series file format.

- **Minimum/maximum long wave period**: This input parameter refers to the minimum and maximum cutoff periods for the IG wave spectrum. Typical values are from 30 to 600 sec.

- **Number of components**: This parameter refers to the number of frequency components the user would like the IGWT to generate between the specified lower and upper cutoff periods.

- **Maximum oblique angle**: Angle information is used only in the CGWAVE input, and the IGWT will generate wave components without direction. If a single angle is desired, all components will be shore-normal. If multiple directions are specified, all components will be repeated in the CGWAVE input for multiple directions centered about the shore-normal and with a direction variation of this value on either side.

- **Number of angles**: This parameter refers to the number of directions to be generated. Emphasizing again that the 1-D Boussinesq model generates low-frequency (long-wave) components without direction. Users can specify any given wave directions for long-wave components in their CGWAVE run. The default direction is shore-normal.

Once these parameters are entered, the IGWT accesses four utilities:

- A preprocessor that checks the validity of the inputs and generates specific parameters for the other three utilities.
- A nonlinear, 1-D Boussinesq model simulation that generates a nearshore time series of the water surface.
- A spectral analysis engine that processes the times series generated in the previous step.
- A utility to output a spectrum representing the long wave effects at the nearshore site (point).

EXAMPLE: Illustrated here is an application of the IGWT for Barbers Point, HI. Nwogu and Demirbilek (2001) provide details of measured and predicted IG waves at the Barbers Point Harbor, HI. Figure 3 shows location of nearshore gauges outside and inside harbor. Figures 4 and 5 show measured and predicted wave spectra from BOUSS-2D model at these gauges. It can be seen from these figures that the IG waves are present both in field data and numerical model results. However, both the shape and frequency content of the measured and computed spectra are changing as waves move from deep to shallow-water depths. It is evident in Figures 4 and 5 that a greater amount of wave energy appears to be moving into lower frequencies as water depth decreases. Figure 5 shows evidence of wave groups both in the measured and predicted time-series and also the resulting long-period waves occurring inside the harbor.

For this example, wave data from NOAA Buoy 51003, located approximately 205 n.m. southwest of Honolulu, are accessed to generate long-wave effects at the offshore edge of CGWAVE computational domain. The model domain includes Barbers Point Harbor located on the southwest corner of the island of Oahu. The extent of CGWAVE mesh (computational domain) around the harbor at Barbers Point, relative position of the buoy, and the domain, along with an inset of the domain depths, are shown in Figure 6.

By selecting the Spectral Energy command from the CGWAVE menu (as shown in Figure 7), the user could define or read a wave spectrum at the deepwater buoy (site). In this case, the spectrum was generated for a peak wave period of 10 sec and amplitude of 2.5 m. The resulting spectrum is shown in Figure 7. In most applications, the peak period may vary from 6-16 sec, and is typically in the 8-12.5 sec range.

The long waves are then calculated by selecting the Model Control command in the CGWAVE menu, selecting the spectrum and entering the parameters as shown in Figure 1. The wave conditions are computed and filled into the CGWAVE Model Control dialog. These conditions are included in the CGWAVE input file (*.cgi). The user is now ready to perform CGWAVE modeling for the study site.

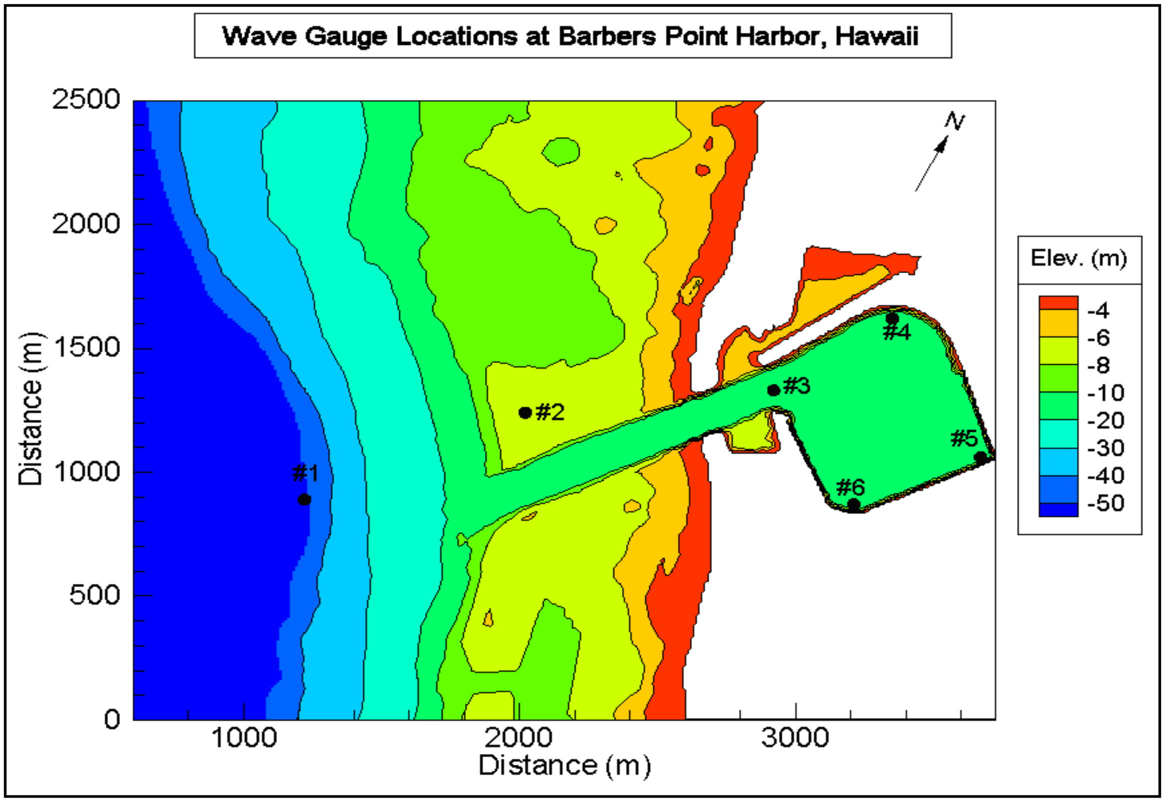

Figure 3. Location of field gauges at Barbers Point Harbor, HI.

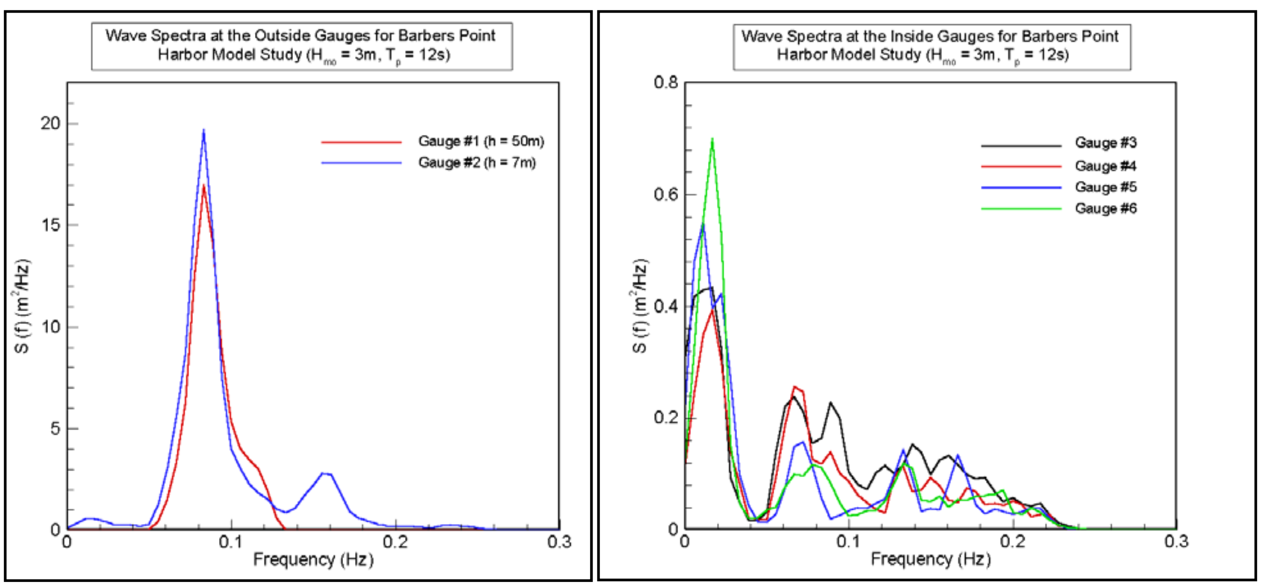

Figure 4. Measured wave spectra of outside and inside gauges at Barbers Point Harbor, HI.

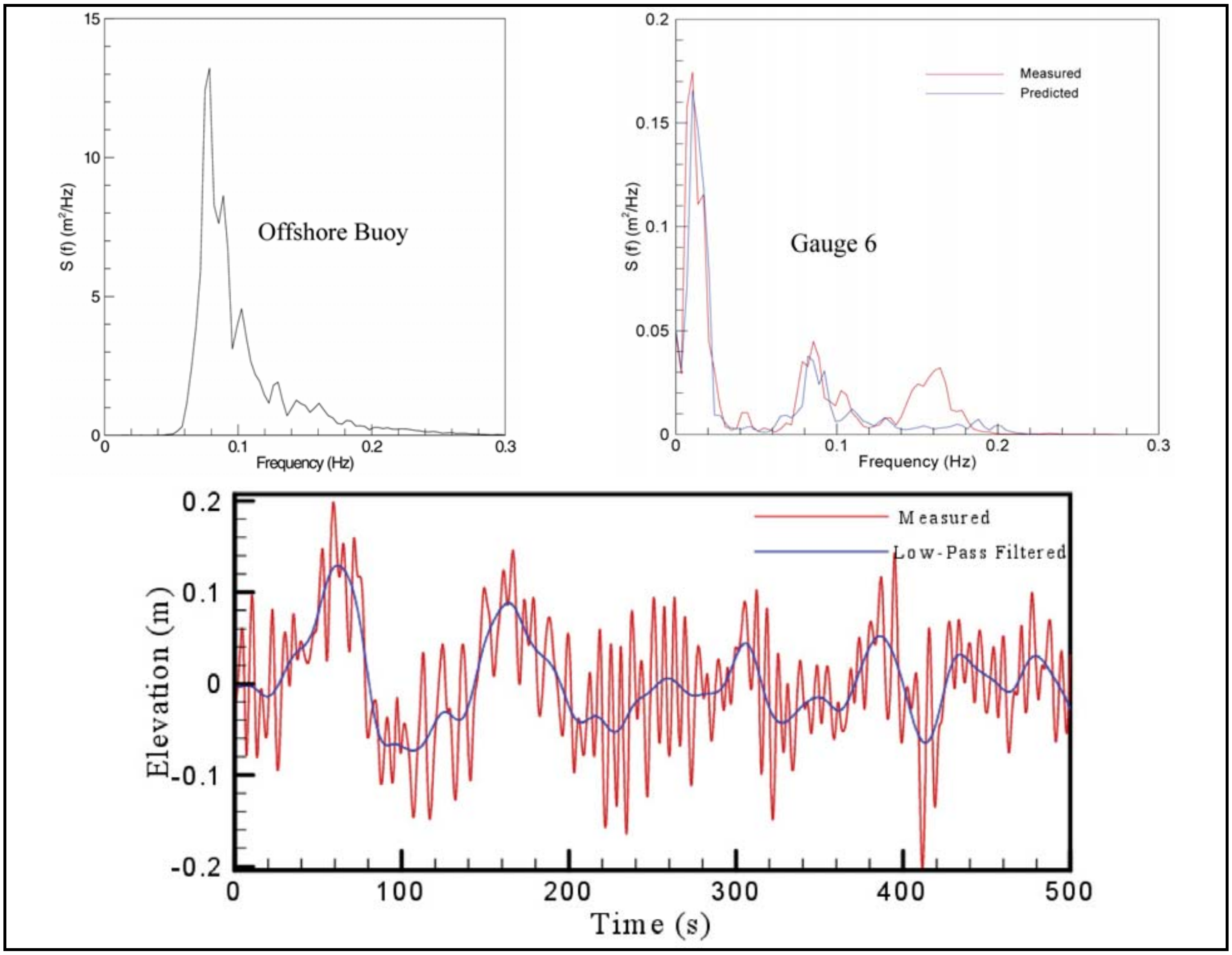

Figure 5. Comparison of measured and predicted wave spectra and time series data at Gauge 6.

It should be pointed out that the generation of the IG wave input is not conditioned upon having an existing CGWAVE mesh read into SMS. If a user wishes to access the IGWT independently of a specific finite element mesh (i.e., wants to create such wave input for a future CGWAVE mesh that may be constructed at a later date), then the user should start SMS, and choose CGWAVE to be the current model. Because this application does not depend on a mesh (i.e., there is no CGWAVE input file for SMS to work with), it would be necessary to first create a single point that will serve as a dummy mesh node. Doing so will activate the CGWAVE model control dialogs, allowing user to construct IG wave input for a nonexisting CGWAVE mesh file. After creating a single mesh node, the user can access the model control dialog, and from there the IGWT. The output from the utilities appears in the spreadsheet format on the left side of the CGWAVE Model Control dialog. Users can save this output by cutting and pasting it to a spreadsheet for later use in their CGWAVE project applications. This saved information is part of the required input to CGWAVE as described in Demirbilek and Panchang (1998).

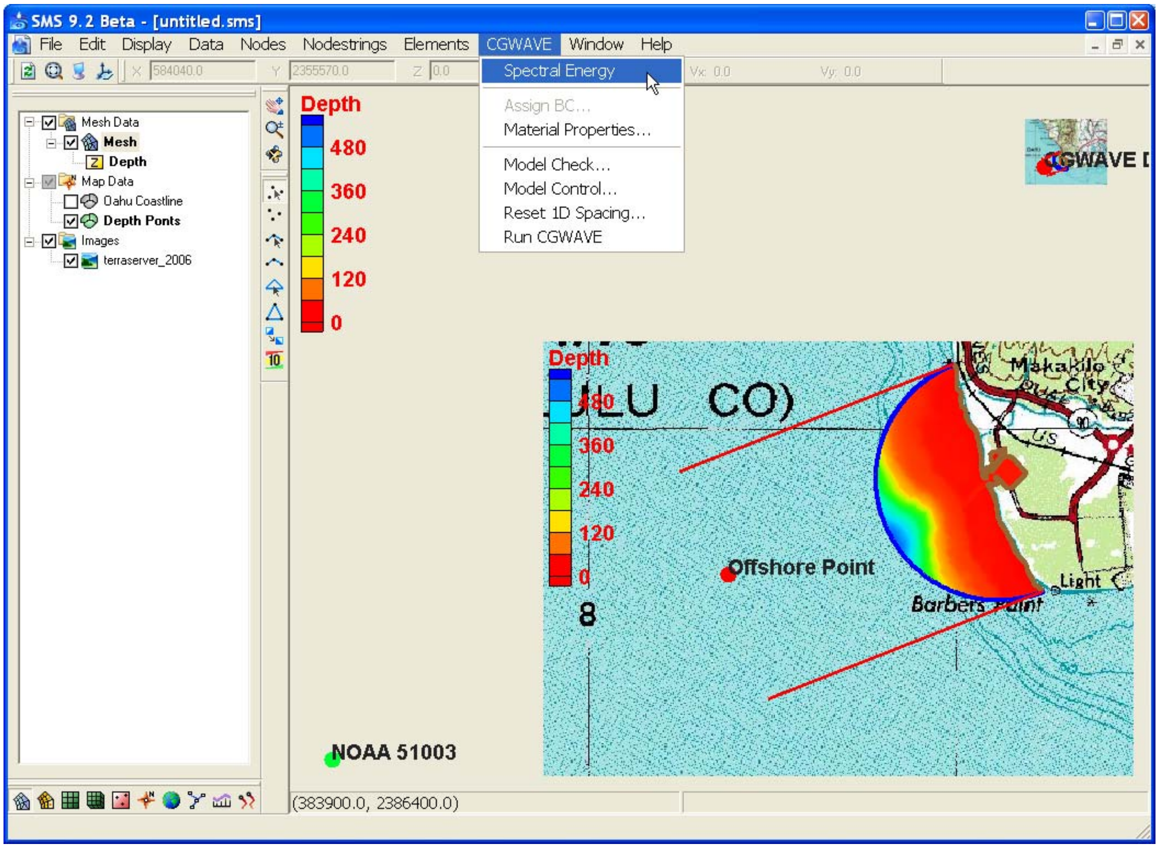

Figure 6. Outline of island of Oahu with respect to NOAA buoy 51003.

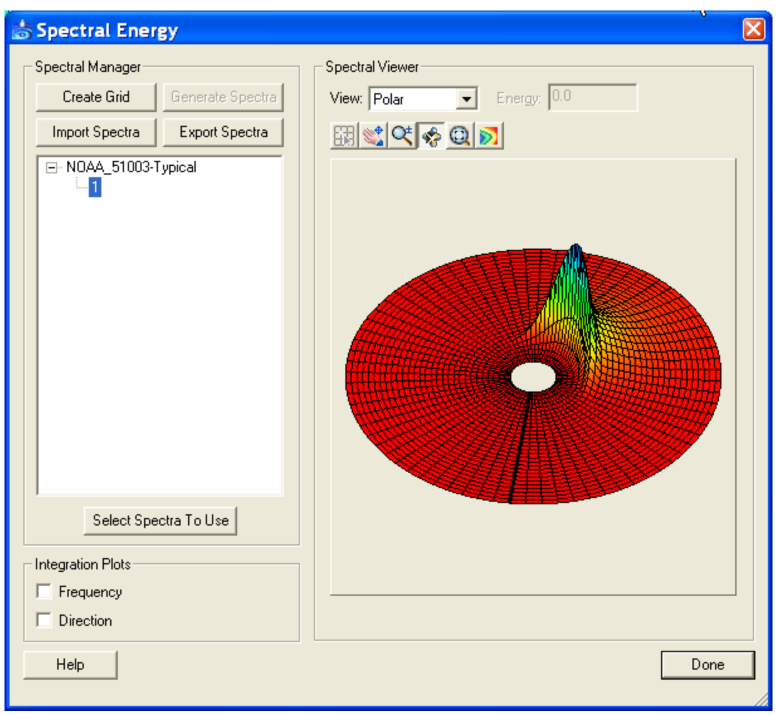

Figure 7. Spectrum at NOAA Buoy 51003.

ADDITIONAL INFORMATION: Questions relative to this CHETN may be addressed to Dr. Zeki Demirbilek at 601-634-2834 or e-mail: Zeki.Demirbilek@erdc.usace.army.mil of the Harbors, Entrances, and Structures Branch, Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center. Questions about the Coastal Inlets Research Program can be directed to the Program Manager, Dr. Nicholas C. Kraus (Nicholas.C.Kraus@erdc.usace.army.mil). This CHETN should be cited as:

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