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Making Waves at CERC

Michael J. Briggs

Coastal Engineering Research Center
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199, U.S.A.

ABSTRACT

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This paper describes a unique wavemaker for the generation of naturally occurring shallow water waves in laboratory experiments. The main feature of this wavemaker is its ability to simulate waves of many different periods and directions at one time. This combination of multiple waves is more representative of the sea and swell waves that occur naturally in lakes and oceans. Recent research involving wave shoaling over a submerged mound, stability of a harbor entrance jetty, and wave transformation in a harbor is presented to illustrate the versatility of this wavemaker.

ADDITIONAL INDEX WORDS: *Coastal engineering, physical model testing, wavemakers, directional wave spectra, wave transformation/propagation, wave shoaling and refraction, jetty stability, harbor resonance.*

INTRODUCTION

The mission of the U.S. Army Engineer Waterways Experiment Station's (WES's) Coastal Engineering Research Center (CERC) is to better understand the effects of waves, currents, tides, and water levels on beaches, tidal inlets, harbors, and coastal structures. Combinations of field, laboratory, and numerical model studies are used to insure optimal coastal designs. Laboratory modeling is an important component of the CERC mission. Laboratory facilities are used for testing and optimizing various proposed designs and improving our understanding of the physics of coastal processes. Often, physical models are required to provide data sets for improving the capability of numerical models to accurately model the processes occurring in nature.

Historically, monochromatic (regular) or unidirectional spectral (irregular) waves have been used to test hydraulic models of coastal projects. However, real ocean waves are short-crested, having directional spreading, which spreads or diffuses wave energy over many directions about a central angle of wave approach. Based on over 1,000 samples of ambient and storm conditions off the North Carolina coast measured with a linear gage array, LONG (1989) and LONG and OLTMAN-SHAY (1989) found a complete absence of unidirectional waves. In fact, typical directional spreading was 20° to 40°. SAND *et al.* (1983) measured diffracted wave energy in the lee of an entrance breakwater for unidirectional and directional irregular waves. They found larger waves for the directional cases. KIRKEGAARD *et al.* (1980) measured motions of a moored vessel near an open jetty, and found differences in response between unidirectional and directional irregular cases. During harbor modeling tests, BOWERS (1987) observed significantly reduced long period energy in the harbor when directional spreading was present. Thus, it appears that the inclusion of directional spreading can have a significant effect on the design of coastal facilities and breakwaters.

Before 1984, it was not possible to simulate wave directional spreading effects in a laboratory experiment at CERC. The capability to simulate different angles of wave approach in a wave basin involved physically relocating the wavemaker or rotating the model between tests. The directional spectral wave generator (DSWG), gives CERC the capability to accurately simulate these naturally occurring directional seas in a laboratory environment. The DSWG also can generate monochromatic, cnoidal, impulsive, tsunami waves, and wave groups.

Since 1986, CERC has conducted research studies with the DSWG involving wave diffraction in the lee of a breakwater, shoaling and refraction of waves as they pass over a submerged mound, propagation and transformation of impulsive waves on a horizontal sea floor and in a harbor,

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stability of a harbor entrance jetty subjected to waves, and nonlinear evolution of waves as they propagate shoreward on a beach. Ongoing research includes wave-current interaction in inlet and harbor entrances, wave transformation in harbors and its effects on harbor resonance and navigability, and prediction of tsunami runup.

This paper presents a description of the DSWG and how it works. Three example case studies are described which illustrate the versatility of this wavemaker and the importance of directional effects. The first case study describes the effect that a submerged mound of dredged material has on wave heights in the lee of the mound. The second case study discusses the stability of the north entrance jetty at Yaquina Bay, Oregon. The last example deals with harbor resonance in the Barbers Point, Oahu, Hawaii, harbor and marina.

WAVE GENERATION SYSTEM

Wavemaker Design

The DSWG is an electronically controlled, electromechanical system, designed and built by MTS Systems Corporation, Minneapolis, Minnesota. It is 27.4 m long and consists of 60 paddles, each 46 cm wide and 76 cm high (Figure 1). The four portable modules, of 15 paddles each, allow all or part of the DSWG to be moved to other model basins. Each of the 61 paddle joints is independently driven by a ¾-HP closed-loop dc servomotor operating in piston mode. A belt drive converts rotary motion to a ±15-cm displacement. Paddles are connected in a continuous chain with flexible polyethylene seals between the paddles and spacer plates to produce a smoother, cleaner wave form without spurious waves from the ends of the paddles (OUTLAW, 1984). Articulated joints allow for foreshortening when adjacent paddles are at different displacements. Angles between paddles can be continuously varied within the range of 0° to 180° using the "snake principle" to produce waves at angles approaching ±85° from the normal to the DSWG.

Typical Wave Parameters

Model scales are typically in the range of 1:25 to 1:100 (*i.e.*, 1 model length unit to 100 prototype length units) and are undistorted (*i.e.*, horizontal and vertical scales are the same). Froude scaling is used to preserve the dynamic similarity between model and prototype gravitational and inertial forces. Model water depths can be as deep as 50 cm. Wave heights up to 8–9 m (22 cm in the model) can be simulated, depending on the model scale and the water depth. Sea and swell wave periods from 5 to 20 sec (0.7 to 4 sec in the model) are routinely generated. Longer wave periods for tsunami and harbor resonance studies can also be reproduced.

Data Acquisition System

Digital and analog circuits which comprise the DSWG control console are located in a nearby climate-controlled room. This console, also built by MTS, supplies digital wave board control signals for input to 61 Preston digital-to-analog (D/A) signal converters. Mini-computers (a) perform D/A conversion for the 61 paddles at run time, (b) monitor paddle displacement and feedback, (c) calibrate wave gages, (d) digitize data, (e) update the control signals, and (f) analyze collected data (BRIGGS AND HAMPTON, 1987). A CRAY Y-MP supercomputer, located at WES, is used to create control signals and do more advanced analysis of the data. All computers communicate with one another through a fiber-optic network.

Control Signal Generation

Irregular waves are simulated as the product of a target frequency spectrum and a directional spreading function. The frequency spectrum may be input in one of two ways. It can be calculated according to the empirical formula for a depth-limited TMA (named for the Texel, MARSEN and ARSLOE data sets) (BOUWS *et al.*, 1985) spectral form or input as discrete spectral lines from a numerical simulation or field observation. Any number of frequencies can be used and the spectrum can be multimodal (*i.e.*, contain multiple peaks). The shallow-water TMA spectrum is a function of five parameters: peak spectral frequency f_p, constant α, peak enhancement factor γ, right and left spectral width parameters σ_a and σ_b, and water depth h. The TMA spectrum reduces to the JONSWAP (Joint North Sea Wave Project) spectrum in deeper water.

The directional spreading function may be either an empirical wrapped normal (BRIGGS *et al.*, 1987) or input as discrete values at even increments within 360°. Values of the spreading function between 181° and 359° are usually set to zero to prevent the simulation of incoming or reflected waves.

Realizations of the desired time series for the

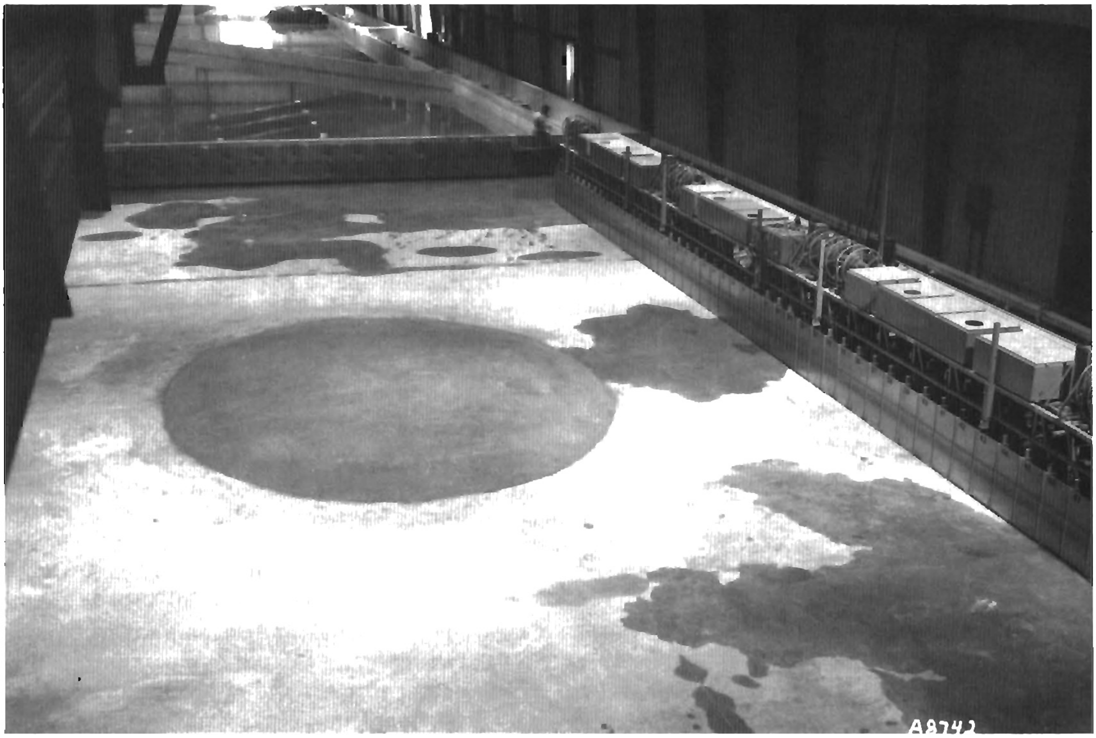

Figure 1. Directional spectral wave generator and submerged mound.

specified directional wave spectrum are simulated in the frequency domain using a deterministic amplitude, random phase model and then Fourier transformed to the time domain (BORGMAN, 1990). These random wave realizations then are multiplied by a dimensionless wavemaker frequency function to obtain the desired stroke time series for the DSWG.

The three-dimensional, height-to-stroke transfer function (SAND, 1979) is based on theoretical, ideal hydromechanical aspects of wave generation. Because of leakage around and under the DSWG, electronic and mechanical losses, and basin response characteristics, the desired wave spectrum is not always faithfully reproduced. Thus, a correction factor or response amplitude operator (RAO) transfer function is calculated based on measurements from an initial calibration run for each control signal. The RAO is the ratio of measured spectrum to desired or target spectrum for each gage. An average of selected gages is used to correct the control signals in the frequency domain. One iteration is usually sufficient to correct the control signals for each wave condition.

SUBMERGED MOUND STUDY

The Corps regularly spends millions of dollars on dredging and dredged material disposal. Prior to placing a submerged mound, it is important to determine the stability of the mound and its effects on the wave climate. Waves passing over a submerged mound are refracted and diffracted by the change in depth. Refraction and diffraction of waves passing over complicated bathymetry has long been an important consideration in Corps design. Although the complexity of natural sea states has been recognized, most engineering analyses of this phenomenon have been based on simplification of the sea state to a monochromatic wave with the assumption that this is a conservative representation. The propagation problem is solved either empirically with physical models or numerically by linear and nonlinear models. Although monochromatic numerical models have been fairly successful, spectral models are still in

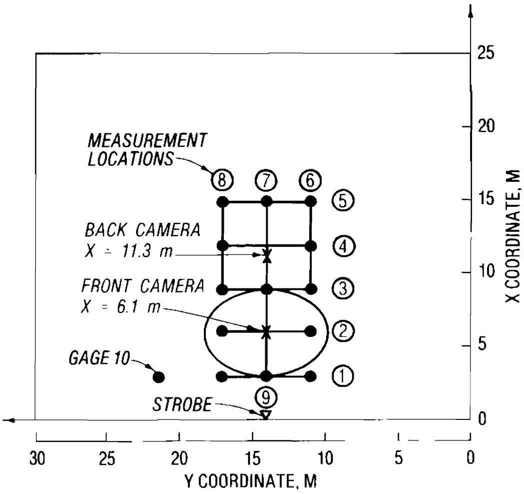

Figure 2. Locations of submerged mound and measurement transects.

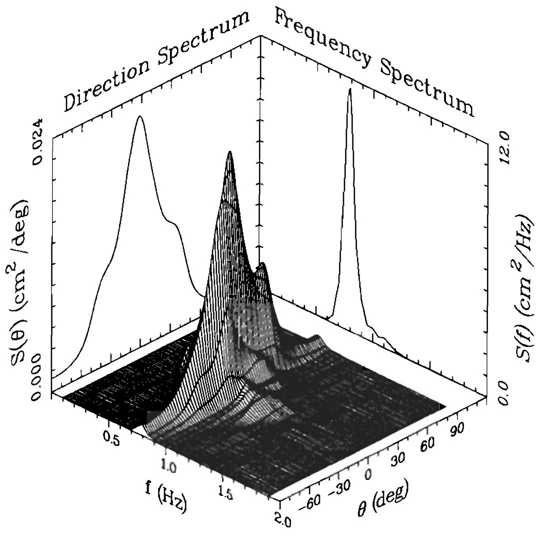

Figure 3. Directional wave spectra with narrow frequency and wide directional spread.

the development stage. The DSWG was used in a laboratory experiment to generate realistic sea states for evaluating the monochromatic assumption and creating an extensive database for use in expanding the capabilities of existing numerical models.

Physical Model

A submerged mound with an elliptical shape (Vincent and Briggs, 1989) was constructed in the model basin (see Figure 1). It had a major radius of 4 m and a minor radius of 3 m at the base with a height of 30.5 cm at the center. The water depth was 45.7 cm, giving a depth of submersion of 15.2 cm at the center. Water surface elevation time histories were measured using an array of nine resistance gages, which were moved to cover a 6-m by 15-m area (Figure 2). They were spaced 76 cm apart in an aluminum frame that minimized the amount of interference from support legs. This gage frame was moved between tests to nine transects or locations, five parallel to the DSWG and four perpendicular. The same test conditions were repeated at each gage transect. Two overhead cameras were used to record the wave transformation in the vicinity of the submerged mound.

Wave Conditions

The DSWG was used to generate monochromatic and directional irregular waves with equivalent wave periods and heights. The monochromatic wave period was equal to the spectral peak period. The monochromatic wave height was equal to 0.707 times the zero-moment wave height (Thompson and Vincent, 1985). Irregular waves with both narrow and broad frequency and directional spreading were created. Figure 3 shows an example of the directional wave case with narrow frequency spreading and wide directional spreading. The rear vertical panels illustrate the integrated direction spectrum and frequency spectrum. The frequency spectrum is obtained by summing the directional spectrum over all directions for each frequency and multiplying by the direction increment. Similarly, the directional spectrum is the sum over all frequencies for constant direction, multiplied by the frequency increment.

Wave Height Amplification

Figure 4 illustrates the wave height amplification in the lee of the submerged mound for monochromatic waves. The waves are traveling across the mound (see outline of mound at the bottom of the picture) toward the top of the picture. For these waves the elliptical mound acts as a lens to focus wave energy, creating larger wave heights in the lee of the mound. The test results indicate that monochromatic waves deviate by as much as

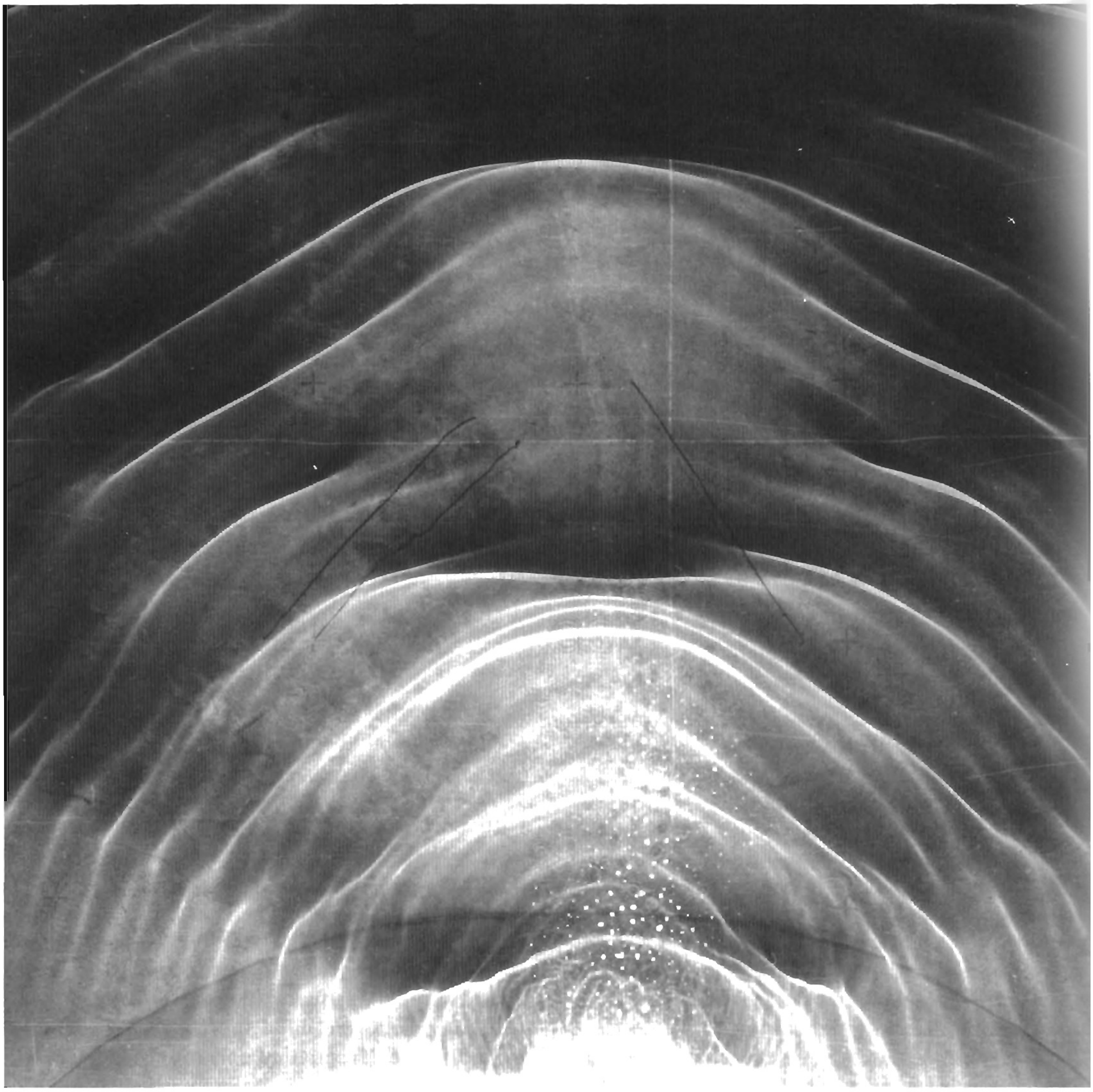

Figure 4. Wave height amplification in the lee of a submerged mound for monochromatic waves.

50% to over 100% from irregular waves with typical spectral shapes and directional spreads. Figure 5 shows a comparison of the normalized wave heights along transect 4 for monochromatic, unidirectional, and directional irregular waves. Investigation of the cause of the difference included relative amounts of frequency and directional spreading in the spectrum, wave steepness effects, and wave breaking. Results indicated that monochromatic waves provide a poor approximation of irregular wave conditions if there is directional spread or high wave steepness. Thus, monochromatic waves should be used with caution when estimating the wave environment in the lee of a submerged mound.

YAQUINA BAY ENTRANCE JETTY STUDY

Yaquina Bay is an estuary located on the Oregon coast, approximately 203 km south of the mouth of the Columbia River. Two rubble-mound

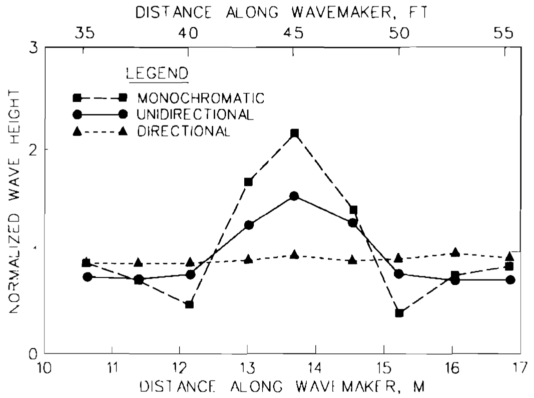

Figure 5. Normalized wave heights in lee of the submerged mound.

jetties protect the 12-m-deep, 122-m-wide entrance channel. This channel passes through an offshore basaltic reef, which lies approximately 1 km seaward of the channel entrance and extends northward for 31 km.

The north jetty has been plagued with a history of unusually rapid deterioration when compared with similar North Pacific jetties. Since authorization of the jetty system in 1880, the north jetty has undergone extension or rehabilitation a total of seven times, the most recent in 1988 following damage in the period 1979 to 1980. Probable damage hypotheses are (a) wave breaking on the jetty, (b) wave-current interaction due to the presence of an offshore reef, (c) scour leading to armor unit slumping, (d) foundation failure, or (e) some combination of the above. The proximity of the reef to the end of the north jetty appears to be an important factor in modifying waves and currents at this location, especially since little or no damage has occurred to the south jetty, which has similar construction characteristics and wave exposure.

Physical Model

A physical model of the north jetty as it existed in 1979 was constructed to test the first hypothesis (Carver and Briggs, 1991). The 1:45 scale model included the entrance channel, rubble-mound jetties, and nearshore bathymetric contours.

Wave heights were measured at 10 different locations using capacitance wave gages (Figure 6). Gages 1 to 8 were used in a calibration phase to insure accurate reproduction of the target wave conditions. The last two gages were located on either side of the north jetty head to measure wave transformation. Gages 2 to 8 comprised a linear array patterned after the larger linear array design of Oltman-Shay at CERC's Field Research Facility (Crowson *et al.*, 1988). The unit lag spacing of 61 cm was selected to optimize the frequency and directional resolution of the array for the 13-m prototype contour.

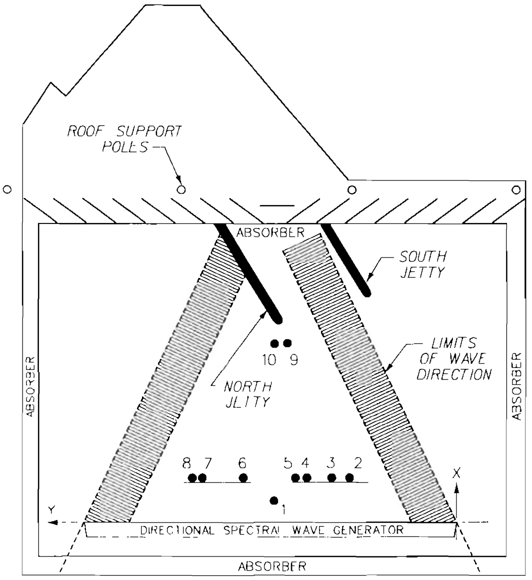

Figure 6. Experimental setup for Yaquina Bay, Oregon.

Wave Conditions

Meteorological and buoy records were scanned to identify the worst storms during the 1979–1980 storm season. A numerical model (Hughes and Jensen, 1986) was used to refract and shoal these storms from the deep ocean to a shallow water depth of 16.5 m, corresponding to the depth of the DSWG in the model. Buildup and decay of each storm was represented by several 12-hr segments including both low- and high-water levels (*i.e.*, storm surge and diurnal tide). These storms had peak wave periods of 10 to 17 sec and significant wave heights of 1 to 5 m. Figure 7a–c illustrates target and measured model (scaled to prototype) directional spectra for high- and low-water levels, respectively, for the December 25, 1979 storm. The linear array was used in the directional spectral calculations. The 3-D directional spectra have units of m^2-sec/deg. The right rear panel is

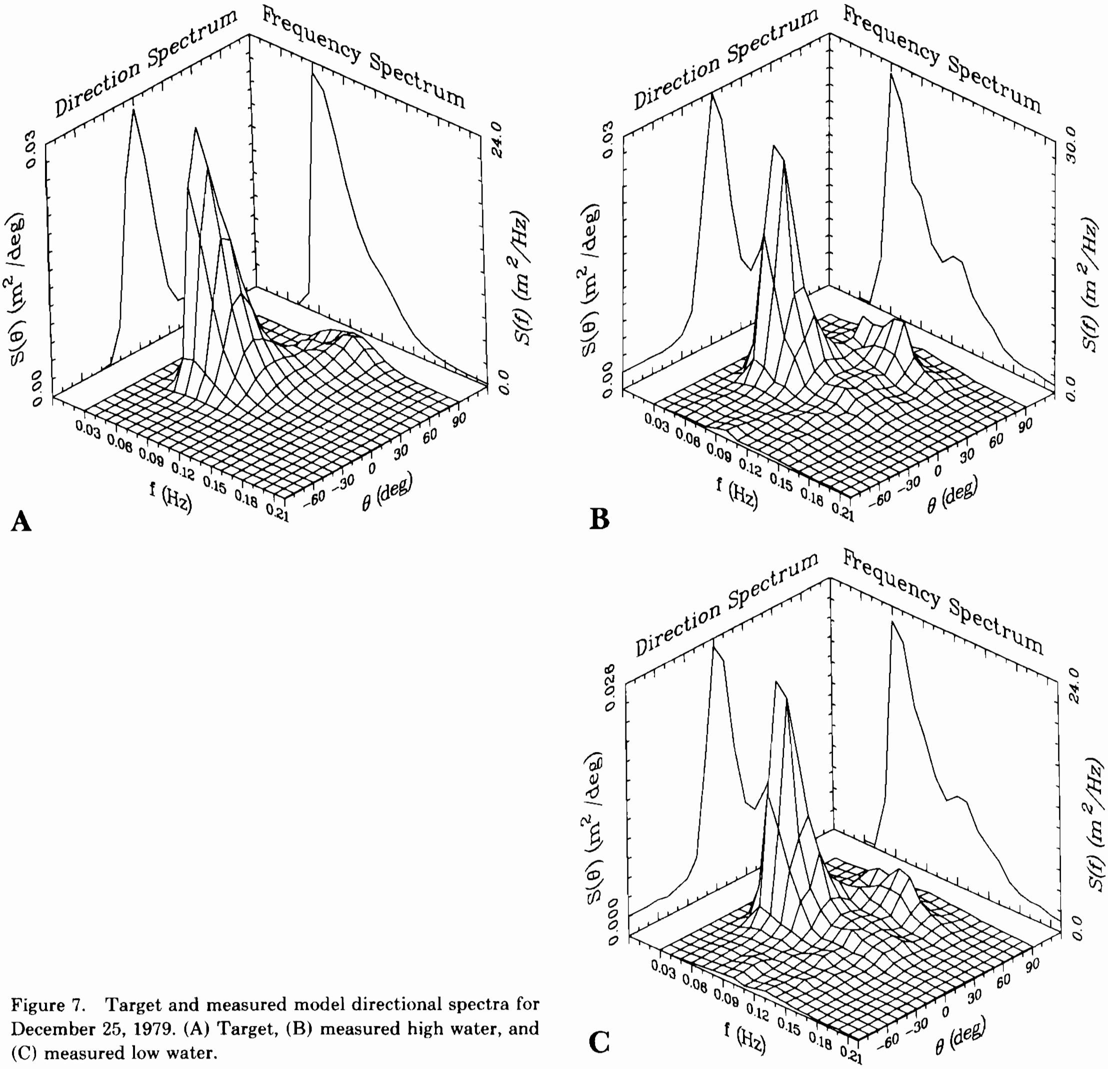

Figure 7. Target and measured model directional spectra for December 25, 1979. (A) Target, (B) measured high water, and (C) measured low water.

the frequency spectrum and the left rear panel is the directional spectrum. In general, the agreement is very good to excellent.

Stability Results

Although isolated stones rocked and were dislodged, stability tests with these storm events failed to produce any significant damage to the north jetty (Figure 8). Based on this limited physical model test series, it was concluded that armor instability due to wave attack alone is probably not the primary failure mechanism at the Yaquina Bay north jetty. Therefore, it can be assumed that some other factor(s) (possibly current action, foundation stability, scour, *etc.*) caused or, at least, contributed to the prototype failure.

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Figure 8. North jetty after stability tests.


YAQUINA BAY JETTY
STABILITY STUDY
AFTER TESTING

Figure 9. Barbers Point Harbor, Oahu, Hawaii.

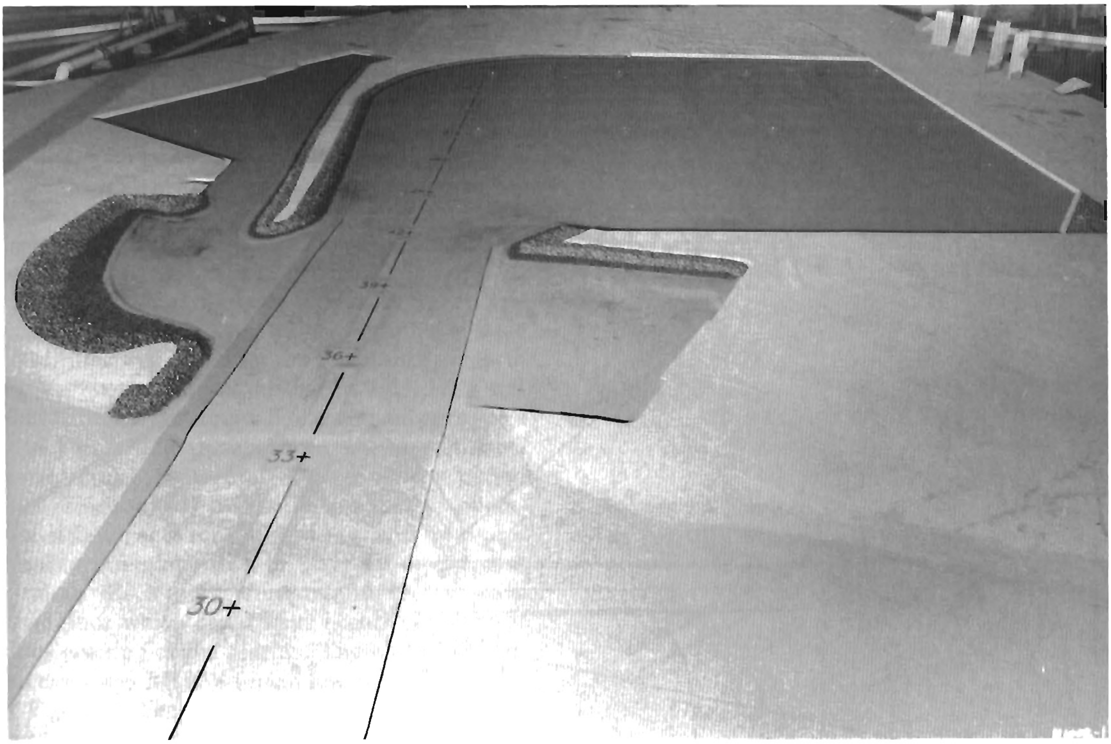

Figure 10. Barbers Point Harbor physical model.

BARBERS POINT HARBOR STUDY

Barbers Point, Hawaii, is located on the southwest coastline of Oahu and consists of a deep-draft harbor, barge basin, resort marina, and entrance channel (Figure 9). The main harbor is 11.6 m deep and has an area of 0.37 sq km. The barge basin is 67 m by 396 m and is 7 m deep. The West Beach marina, opened in July 1989, has a depth of 4.5 m and was designed to accommodate 350 to 500 small boats. The entrance channel is 137 m wide, 1,300 m long, and 13 m deep.

As waves travel into harbors from deep water, nonlinear processes transfer energy from the wind wave frequencies to long waves with periods of the order of several minutes and wavelengths much longer than wind waves. If the periods of these long waves correspond to resonant periods of the harbor, they will excite harbor oscillations which can produce dangerous navigation and mooring conditions. The lowest frequency (*i.e.*, longest period) mode is known as the Helmholtz or pumping mode because the water appears to move up and down in unison throughout the harbor or marina. Higher modes (*i.e.*, higher frequency) are characterized by an increasing number of nodes and antinodes within the harbor. Water can oscillate or seiche in different directions for the different modes. Energy sources that produce harbor resonance are tsunamis, atmospheric pressure disturbances, and locally generated or free infragravity waves forced by wave groups. The nonlinear processes that transform wind wave energy to infragravity waves (waves with periods in the range of 25 to 200 sec on Pacific coasts) is the mechanism described in this paper.

On February 8, 1988, a Coast Guard vessel was in the process of entering a drydock when they both sustained damage due to harbor seiching under relatively calm conditions outside the harbor (NODA, 1988). Numerical and physical models are being used to predict the harbor response to long period wave energy for different wave conditions outside the harbor. The ultimate goal is to install a real-time warning system for ships wishing to enter the harbor if wave conditions would make entrance and mooring conditions hazardous.

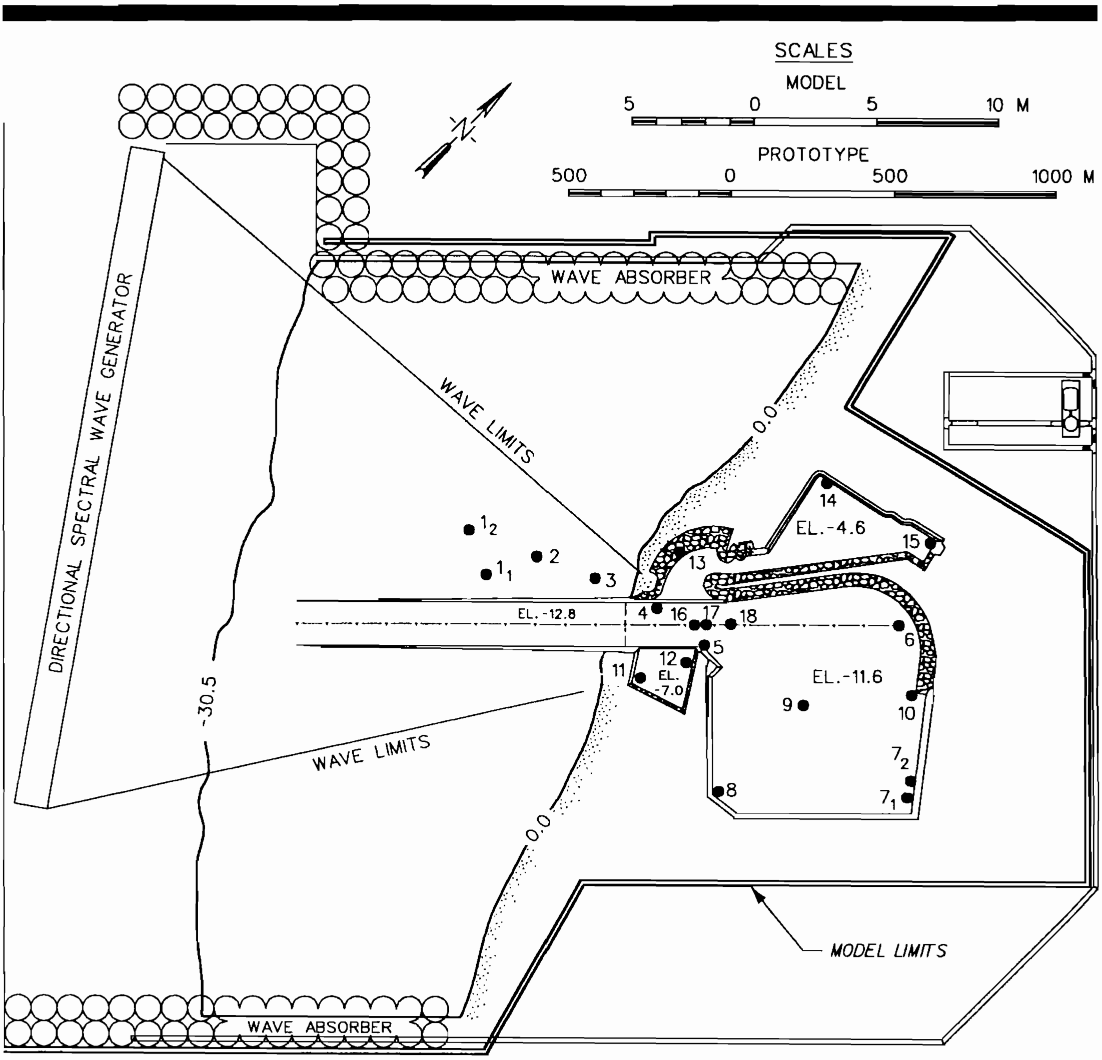

Figure 11. Experimental setup for Barbers Point Harbor and marina.

Model Design

The three-dimensional physical model consists of the main harbor, barge basin, marina, entrance channel, and offshore contours to the 30-m contour (Figure 10). Total area of the model is over 1,020 m². A model-to-prototype scale of 1:75 (undistorted) was selected to allow proper modeling of significant harbor features, typical storm waves, longshore currents, and a remote-controlled "design" ship. The model basin sides and rear were lined with wave absorbers and one side was open to an adjacent basin to minimize reflections and cross-basin oscillations.

Capacitance wave gages were used to measure water surface elevations at the gage locations shown in Figure 11. The first nine positions correspond to field locations. Gages 1 and 2 represent the two different positions of an S_{xy} gage (*i.e.*, slope array of four gages) used to measure incident directional wave spectra. In the main harbor, sensors were located in the North, South, and East corners. Two sensors were located in the entrance channel, one at the channel entrance and the other at the channel mid-point. The other gage positions were added to better quantify the harbor response. Also, two 7-gage linear arrays (not shown) were used to measure incident directional spectra. One linear array was oriented parallel to the 100-ft contour and the other was aligned along the bathymetric contour at the second location of the S_{xy} gage.

Wave Climate

Eight prototype wave conditions, measured between 1986 and 1990, were simulated in the physical model. Simulated wave periods, significant wave heights, and directions range from 6 to 20 sec, 2 to 3 m, and S30W to West with directional spreading up to 10°, respectively. Selection of wave conditions was based on (a) preference given to time after the marina opened in July, 1989 and installation of the second S_{xy} directional gage (gage 2 in Figure 11), (b) obtaining the largest wave heights, (c) a representative range of wave period and direction, (d) maximum number of operational field gages for comparisons, and (e) reproducible directions due to physical model constraints. Each case is representative of wave conditions which could have occurred before or after opening of the marina. The water level for all cases was MLLW (mean lower low water).

Figure 12 shows the incident directional spectra for the prototype (S_{xy}) and physical model (linear array) for March 3, 1989. The right rear panel is the frequency spectrum and the left rear panel is the directional spectrum. The agreement between the two is excellent.

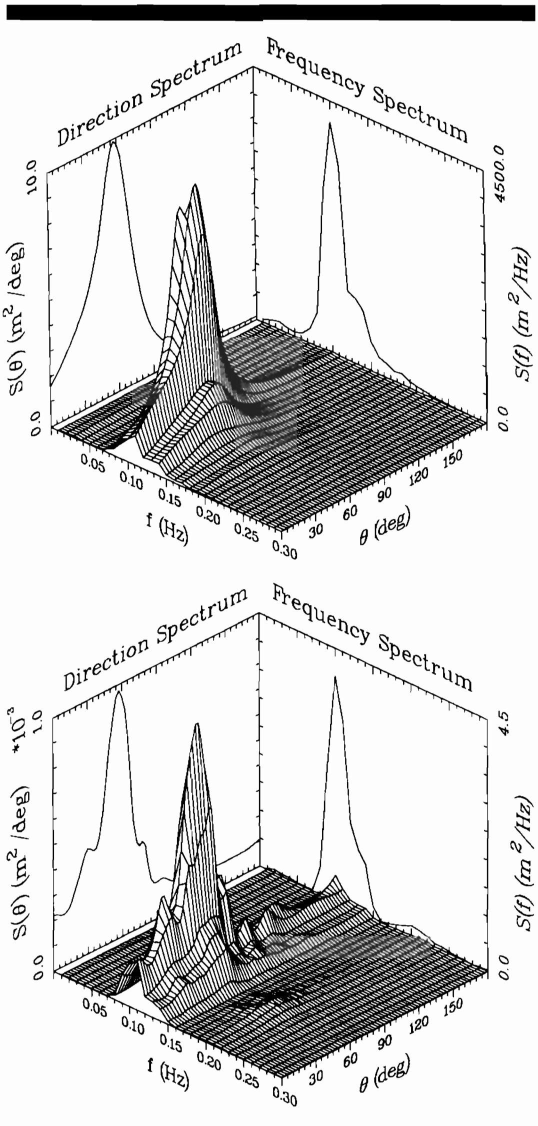

Figure 12. Prototype and model directional spectra for March 3, 1989.

Long-Period Harbor Resonance

Transfer function estimates can be used to identify the resonant modes in a harbor and the relationship between incident conditions outside the harbor (the input) to conditions inside the harbor (the output). In this study, transfer function estimates were calculated for all gages in the harbor using incident conditions from the S_{xy} gage. The transfer function estimates were based on autospectral and cross-spectral analysis of the gage data. Figure 13 shows the transfer function estimates from the field and physical model results for the gage in the south corner of the harbor with the marina open during the period October 1989 to March 1990. OKIHIRO's analysis (1991) of the field data identified the resonant modes listed below which would affect ship response because half their wavelength is on the order of a ship's length.

Mode Number:	Frequency, Hz:	Period, sec:
1	0.00769	130
2	0.00915	110
3	0.01196	84
4	0.01660	60
5	0.01733	58

The agreement is very good for most of these modes. In general, the longer the time series record, the better the resolution of these long period modes in the physical model, and the greater the number of degrees of freedom υ of the transfer

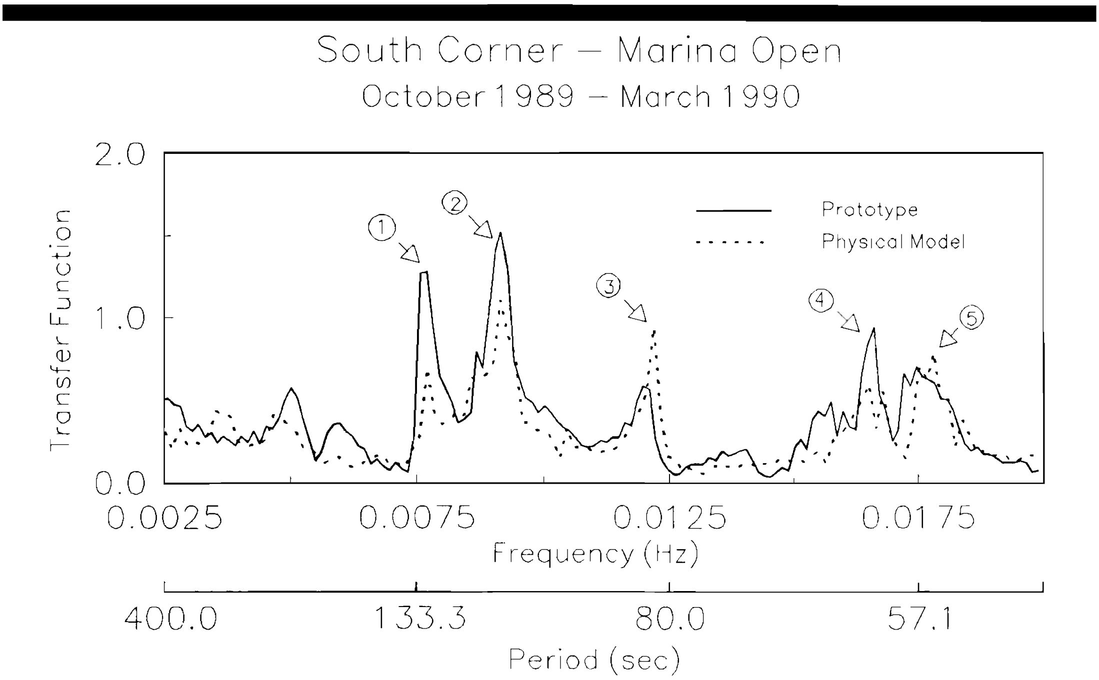

Figure 13. Field and physical model transfer functions for south gage.

function estimates. Typical degrees of freedom for the field estimates was 116 to 234, but only 48 for the physical model, which may explain many of the observed differences.

CONCLUSIONS

This paper has described the directional spectral wave generator at CERC as a unique resource for generating realistic wave conditions in the laboratory. Several recent laboratory experimental studies have been described which demonstrate the versatility of the DSWG and the importance of simulating directional wave spectra in coastal physical models. This computer-controlled tool will continue to advance our understanding of the physics in the nearshore coastal processes, while providing a viable design alternative for situations too complex for analysis using present numerical models.

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□ RÉSUMÉ □

On décrit un générateur de houle pour reproduire expérimentalement les conditions naturelles existant en eau peu profonde. Les principales caractéristiques de ce générateur est son aptitude à simuler des vagures de nombreuses périodes et directions différentes en même temps. Cette combinaison d'ondes multiples est plus représentative de la houle qui se produit naturellement sur les lacs et les océans. On présente une récente recherche sur un remblai immergé, sur la stabilité de l'entrée d'un port, et sur la transformation de la houle dans celui-ci, qui illustre la souplesse de ce générateur.—*Catherine Bousquet-Bressolier, Géomorphologie E.P.H.E., Montrouge, France.*

□ RESUMEN □

Este trabajo describe un generador de olas para la formación natural, en laboratorio, de olas en aguas poco profundas. La principal característica de este generador de olas es que permite la simulación de olas de diversos períodos y direcciones, simultáneamente. Estas combinaciones de olas múltiples es más representativa de las olas de viento y del mar de leva que se manifiestan en los lagos y en los océanos. A fin de ilustrar la versatilidad de este generador, se presentan investigaciones recientes que relacionan las olas en aguas someras sobre una defensa sumergida, la estabilidad de un espigón de entrada a un puerto, y la transformación de las olas en el interior de un puerto.—*Néstor W. Lanfredi, CIC-UNLP. La Plata, Argentina.*