Distribution of Extreme Waves Behind a Shoal

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Abstract: In 1989 Vincent and Briggs found that irregular waves with directional spread typical of natural wave systems were not as strongly focused behind a shoal as would be predicted from use of monochromatic waves. These conclusions were based on an analysis of significant wave height alone. Reexamination of the data in terms of H_{max} and $H_{1/100}$ indicated that the largest waves behind the shoal were close to those predicted from the Rayleigh distribution based on the observed significant height.

INTRODUCTION

Vincent and Briggs (1989) investigated the refraction-diffraction pattern of irregular waves propagating over an elliptical shoal on an otherwise horizontal bottom in a laboratory basin. They found that the degree of wave focusing depended strongly upon the amount of directional spread in the directional spectrum. In general, the narrower the directional spread, the greater the focusing effect, with the maximum wave height H_{max} behind the shoal about 2.4 times the incident significant wave height H_i for the case of unidirectional, irregular waves. This is approximately the same magnitude as that for monochromatic waves. However, for irregular waves with narrow (Mitsuyasu $S_{max} = 75$) and broad (approximately Mitsuyasu $S_{max} = 10$) directional spreads, the focusing was much less, with H_{max} behind the shoal typically 1.2–1.5 times H_i. Vincent and Briggs concluded that monochromatic wave theory overestimated the focusing effect of shoals for natural waves of typical directional spreads. Panchang et al. (1990) and Ozkan and Kirby (1993) obtained similar results for nonbreaking conditions using numerical parabolic wave propagation models forced with directional wave spectra.

Vincent and Briggs suggested that the reason for the decreased focusing was that waves of different period and direction were focused at different points behind the shoal. This technical note investigates a concern that within an irregular, directionally spread sea, short groups of relatively long-crested, swell-like waves occur. These waves could possibly be focused by the shoal, yielding a few waves with anomalously high wave heights relative to the significant wave height H_s of the record. These waves might be similar to rogue waves because they would result from a combination of grouping and propagation direction with respect to the shoal, appearing anomalous to the other waves at the time. If this were the case, the analysis based on H_s alone would be misleading for several engineering applications.

EXPERIMENTAL SETUP

The data used in this study were collected as described in Vincent and Briggs (1989), Briggs and Vincent (1993), and Briggs et al. (1995). Fig. 1 shows the relative locations of the shoal, gauges, and wavemaker in the directional spectral wave basin at the Coastal and Hydraulics Laboratory, U.S. Army Engineer Waterways Experiment Station. The elliptical, submerged shoal had a major radius of 4 m (13 ft), a minor radius of 3 m (10 ft), and a height of 30 cm (1.0 ft) at the center. Water depth was 46 cm (1.50 ft). A 6-m- (20-ft-) wide by 15-m- (50-ft-) long measurement area was centrally located over and in the lee of the shoal (Fig. 1). Parallel-wire, resistance gauges were used to measure surface elevation time histories. Wave heights were calculated using the time domain zero-upcrossing method.

In this note, we look at two arrays of perpendicular gauges. The side array was positioned along the left edge of the measurement area, and the center array extended along the shoal center line. Both arrays included five gauges (open circles in Fig. 1), with a spacing between gauges of 3.05 (10 ft). In each array, the gauges are numbered from 1 to 5, from front to back, respectively.

This note uses the four directional spectral types from Vincent and Briggs (1989). These are denoted as narrow directional spread with wide frequency spread (Case N1); narrow directional spread with narrow frequency spread (Case N2); broad directional spread with wide frequency spread (Case B1); and broad directional spread with narrow frequency spread (Case B2).

RESULTS

Three ratios of wave-height focusing were calculated from measured data as a function of position over the shoal. They are defined as follows:

- Significant wave height $H_{1/3}$ at each gauge to the incident significant wave height H_i
- Average of the highest 1% wave height $H_{1/100}$ at each

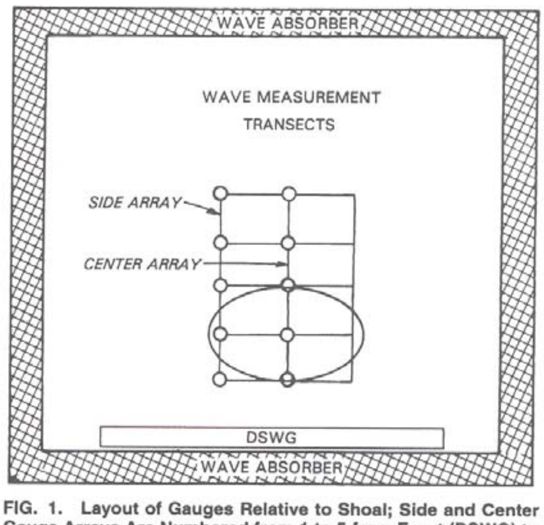

FIG. 1. Layout of Gauges Relative to Shoal; Side and Center Gauge Arrays Are Numbered from 1 to 5 from Front (DSWG) to Back

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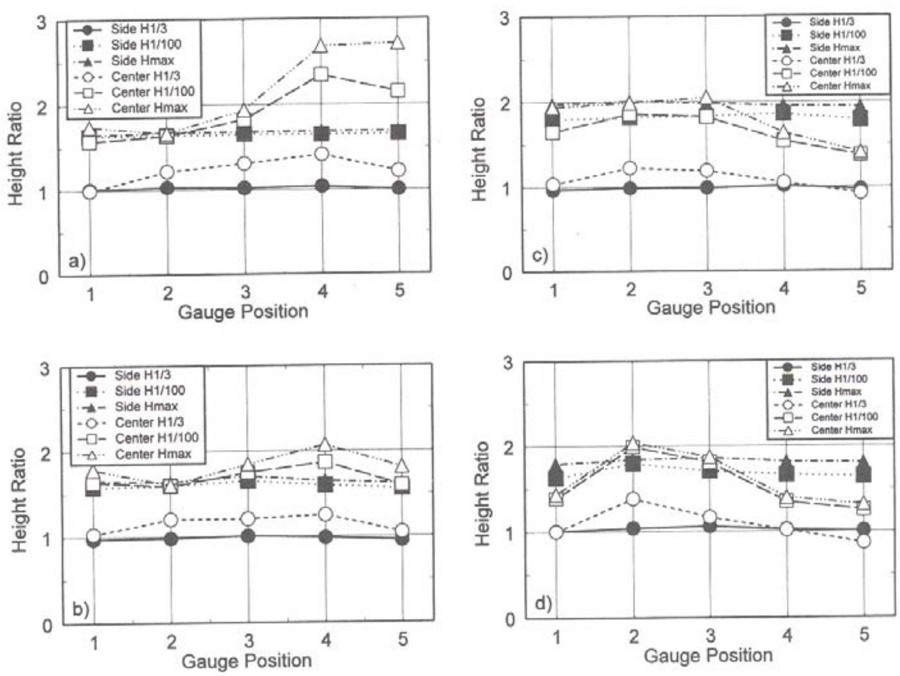

FIG. 2. Plots of Ratio of $H_{1/3}/H_i$, $H_{1/100}/H_i$, and H_{max}/H_i for Four Spectral Cases along Side and Center Gauge Arrays: (a) Case N1, Narrow Directional and Wide Frequency Spreading; (b) Case N2, Narrow Directional and Narrow Frequency Spreading; (c) Case B1, Broad Directional and Wide Frequency Spreading; (d) Case B2, Directional and Narrow Frequency Spreading

TABLE 1. Maximum Wave Height Focusing

	$H_{1/3}$		$H_{1/100}$		H_{max}	
Case (1)	Side (2)	Center (3)	Side (4)	Center (5)	Side (6)	Center (7)
N1	1	1.4	1.5	2.5	1.52	2.7
N2	1	1.2	1.5	1.75	1.52	2.0
B1	1	1.2	1.85	1.8	1.95	2.0
B2	1	1.35	1.80	2.0	1.90	2.1

gauge to H_i

- Maximum significant wave height H_{max} at each gauge to H_i

The value for H_i was estimated by averaging measured data from the first two gauges in the side and center arrays closest to the wavemaker. These ratios are plotted in Fig. 2 for the side and center arrays. Note that the center array included the region of maximum wave amplification. Table 1 lists the maximum wave height focusing value obtained for each of these three ratios for each gauge array and wave case.

Fig. 2 indicates that the most significant differences in these wave height ratios occur as a function of directional spread. For the narrow directional spread cases (N1 and N2), the three ratios are larger by up to 40% in the last three center array gauges behind the shoal (Gauges 3, 4, and 5) than the similar ratios in the side array. For the broad directional spread cases (B1 and B2), the ratios $H_{1/100}/H_i$ and H_{max}/H_i are somewhat lower with the ratio on the center array of gauges typically 10–25% lower than the side array. The focusing for the narrow cases is somewhat further behind the shoal than the broader cases.

The motivation for this note is the concern that focusing by the shoal might create a few rogue waves (waves whose height would be unexpectantly higher given the traditional Rayleigh assumption of wave heights). The critical question is not whether the waves in Fig. 2 are high, but whether they are inconsistent with a Rayleigh distribution, given the local, gauge-specific $H_{1/3}$. If the waves are Rayleigh distributed, $H_{1/100}/H_{1/3}$ should be 1.74. We estimated $H_{max}/H_{1/3}$ by $H_{1/200}/H_{1/3}$, since 200–250 waves were typically in a record. We found that this ratio was equal to 1.9.

In Fig. 3, the ratios of $H_{max}/H_{1/3}$ (i.e., $H_{1/200}/H_{1/3}$) and $H_{1/100}/H_{1/3}$ are plotted for the same gauge array positions, as in Fig. 2. In all four plots, the ratios for $H_{max}/H_{1/3}$ and $H_{1/100}/H_{1/3}$ are nearly horizontal for the side array, lying between 1.4 and 1.7. Along the center array, the plots of $H_{1/100}/H_{1/3}$ and $H_{max}/H_{1/3}$ are almost horizontal; but in the narrow spread cases (N1 and N2), the ratios tend to be higher behind the shoal (Gauges 4 and 5) than near the shoal (Gauges 2 and 3). In the broad spectral cases (B1 and B2), the ratios are slightly lower behind the shoal. With the exception of case N1, the $H_{1/100}/H_{1/3}$ values along the center line are 1.4–1.5 and $H_{max}/H_{1/3}$ values along the center line are 1.8 or less. For the N1 case, the values are only slightly larger.

Since the values for $H_{1/100}/H_{1/3}$ are generally less than 1.7 and for $H_{max}/H_{1/3}$ are less than 1.9 (excepting case N1), we conclude that the largest waves in our experiment are consistent with (or no larger than) what would be estimated from a Rayleigh distribution for $H_{1/3}$ at the gauge. The exception for case N1 represents two waves in the nearly 10,000 waves recorded.

CONCLUSIONS

Examination of the wave heights in the data originally compiled by Vincent and Briggs (1989) indicates that the extreme waves behave similarly to the H_s results presented in the original paper. The amount of directional spread appears to be the important controlling factor. Approximately 10,000 waves

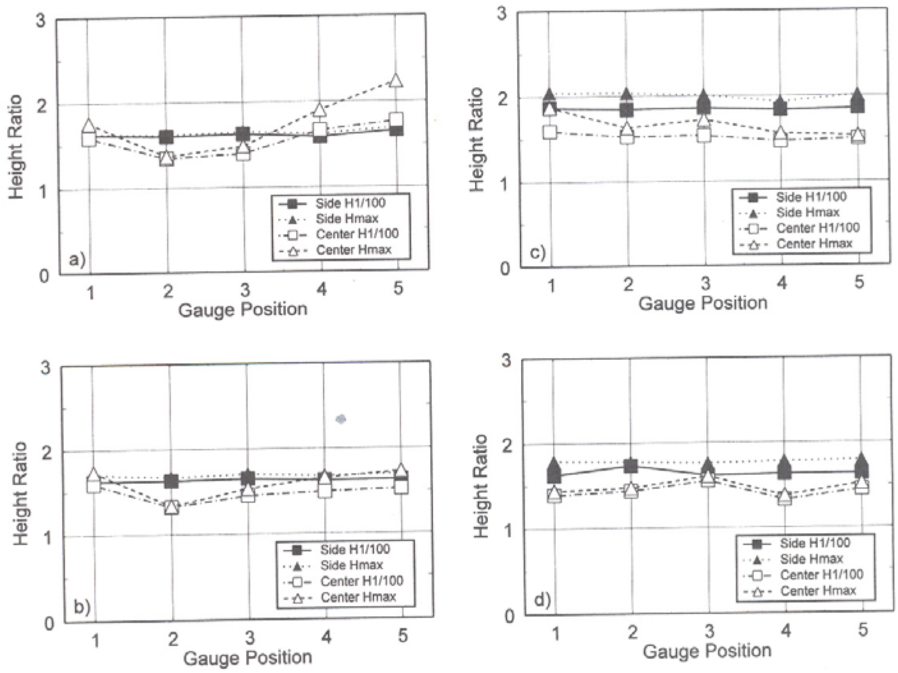

FIG. 3. Plots of Ratio of $H_{1/100}/H_{1/3}$ and $H_{max}/H_{1/3}$ for Four Spectral Cases along Side and Center Gauge Arrays: (a) Case N1, Narrow Directional and Wide Frequency Spreading; (b) N2, Narrow Directional and Narrow Frequency Spreading; (c) Case B1, Directional and Wide Frequency Spreading; (d) Case B2, Broad Directional and Narrow Frequency Spreading

were analyzed, and only in one case (N1) were any waves found that appeared mildly anomalous. The conclusion is that differences of only 10–15% from that expected from a Rayleigh distribution do not support a concern that groups of a few waves are consistently focused behind the shoal producing unexpectedly large waves. The data set analyzed consisted of wave conditions with a few waves that broke over the shoal, which would be typical of many design conditions in nature. If strong breaking occurs over the shoal, there is not much amplification at all behind the shoal (Vincent and Briggs 1989).

SUMMARY

We reexamined the data of Vincent and Briggs (1989) to establish how the extreme waves in the wave-height distribution vary as irregular waves propagate over a shoal. The degree of directional spreading is found to be an important factor, with the narrower spread producing larger $H_{1/100}$ and H_{max} than the broad-spread case. However, the Rayleigh distribution appeared to be a generally good (within 10–15%) estimator of the larger waves.

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APPENDIX I. REFERENCES

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APPENDIX II. NOTATION

The following symbols are used in this paper:

H_i = incident significant wave height;
H_{max} = maximum zero-upcrossing wave height;
H_s = significant wave height;
$H_{1/3}$ = zero-upcrossing significant wave height;
$H_{1/100}$ = average of highest 1% wave heights using zero-upcrossing method;
$H_{1/200}$ = average of highest 0.5% wave heights using zero-upcrossing method; and
S_{max} = Mitsuyasu directional spread parameter, 75 for narrow-banded swell with long decay distance, and 10 for broad-banded wind waves.

Subscript

i = incident.