20th Australasian Fluid Mechanics Conference
Perth, Australia
5-8 December 2016

Transformation of Waves Over 3D Reef Slopes

X.Z. Ma[1], L.W. Wang[1] and Y.X. Ma[1]

[1]State Key Laboratory of Coastal and Offshore Engineering,
Dalian University of Technology, Dalian 116024, China

Abstract

To better understand the wave transformation process and the associated characteristics over relatively steep reef slopes, we carried out large scale experiments on waves propagating over a three-dimensional reef sloping bottom in a wave basin. The incident waves include wind waves and a combination of wind waves and swell. High resolution of data was obtained by a set of dense wave probes along the cross section of the slope. Numerical simulations were also carried out with a non-hydrostatic free surface model, SWASH, which was well calibrated with the well-known existing published experimental data and the present experimental data. Combining the experimental and numerical data, the nonlinear characteristics (e.g., the Ursell number, the asymmetry, the skewness and the kurtosis) of waves over a 3D reef slope were analyzed. The dissipation of the waves in the surf zone over a relatively steep 3D slope was presented. The effects of swell and the direction between wind waves and swell on the nonlinear characteristics were analyzed as well.

Introduction

The reef is characterized by a steep slope with a transition at the reef crest to a shallow flat attached to the shoreline. Significant transformation of waves (e.g., refraction, diffraction, shoaling and breaking) often occurs while propagating over the reef slope.

Due to the steep slope before the reef, the waves often accompanied with strong nonlinear transformation when propagating to the water near reef. In this paper, we consider four nonlinear characteristics of waves: the Ursell number, the asymmetry, the skewness and the kurtosis. The asymmetry and the skewness show the change in wave surface. This changes have an impact on the transportation of coastal sediment, and the destruction of the coastal structures [1-2]. Doering and Bowen [1] discovered that the changes of the asymmetry and the skewness are based on the variation of Ursell number through the study of different wave data which gathered from natural beach. Peng et al. [3] fitted an empirical formula about the asymmetry and the skewness and the relationship with the Ursell number, based on a physical model test of an embankment under the water with a steep slope. Kurtosis used to represent the distribution patterns of wave height. Sergeeva et al. [4] indicated that the kurtosis would increase with the decreasing of water depth, and the distribution of waves would deviate from a Gaussian distribution.

In Section 2, we present the non-hydrostatic free surface model, SWASH. A physical model experiment of wave transforming over a 3D reef slope was setup in Section 3. The wave conditions in the experiment included wind waves and mixed waves which consist of wind waves and swells. The comparison of the experiment results and the simulation results imitated by SWASH was obtained. And in Section 3, the changes of nonlinear characteristics and the dissipation of the waves in the surf zone are presented.

Numerical Model Description

SWASH (an acronym of Simulating Waves till Shore) is a shallow non-hydrostatic pressure numerical model for wave and current established by Stelling et al. [5], mainly used to simulate waves, flow movement in the coastal region. It is a general-purpose numerical tool for simulating non-hydrostatic, free-surface, rotational flows and transport phenomena in one, two or three dimensions. Detailed information on SWASH is referred to Zijlema et al. [5] and its website. Although SWASH has been very well validated for its accuracy in modelling the surf zone waves, a series verification of has been performed for present simulation with existing published experimental data including waves propagating on a semi-sphere[6] and the well-known experiment of Berkhoff[7]. Generally good agreement has been achieved for the accuracy of this model. But for brevity, the verification results are not presented here. By doing this and many trying computations, we obtain the number of layers in the depth direction, which decides the dispersion property of the non-hydrostatic free surface model. Combining the accuracy and computational efficiency, we use two layers of depth for all the simulation.

Physical Experiment Setup

Physical model experiments were completed in multi-function wave basin of the State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology. The dimension of the multi-function wave basin is about 34 m × 55 m, and the maximum working water depth is 0.7 m. One end of the basin is equipped with a portable multidirectional wave maker; and the wave absorbers are placed around the other sides of the basin. The simulation area is 5500×3000 m^2, and the experimental model scale is 1:100.

Figure 1 shows the plan view and cross section of the reef bathymetry.

There are two types of irregular waves studied in the present experiments. One type was generated unidirectionally from the spectra with single peak, while the other was generated from the spectra with double peaks either unidirectionally or with an angle between the direction of two spectral peaks. The wave parameters used in the experiments are shown in tables 1 and 2, where d_0 is the water depth near the wave maker; H_s is the significant wave height; T_p is the spectral peak period and θ is the incident wave angle between the wave crest line and the wave maker. The single-peak wave cases are denoted with SPW02 and SPW02. The double-peak wave cases are denoted with DPW02 through DPW03. All the incident waves are computed with JONSWAP spectrum, and the waves with double spectral peaks are generated by superposing two JONSWAP spectra.

Cases	**d_0 (m)**	**H_s (m)**	**T_p (s)**	**θ (°)**
SPW01	0.40	0.03	1.00	0.00
SPW02	0.40	0.03	1.00	22.50

Table 1 The parameters of waves with a single-peak spectrum.

The wave surface was measured by wave resistance wave gages. And the data acquisition was recorded using type-2000 data collection system. Each case was repeated two times, and the average value was taken as the final result. The sampling frequency was 50Hz and the sampling duration guaranteed at least 100 waves were recorded.

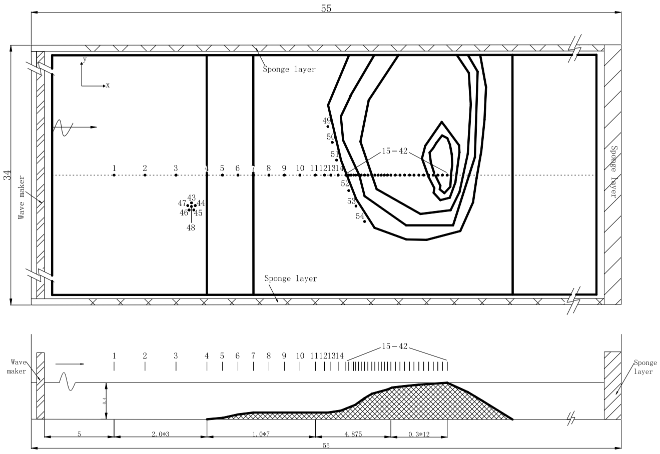

Figure 1: Experimental setup of wave basin and placement of the gages.

Cases	**d_0 (m)**	**H_{s1} (m)**	**H_{s2} (m)**	**T_{p1} (s)**	**T_{p2} (s)**	**θ_1 (°)**	**θ_2 (°)**
DPW01	0.40	0.02	0.015	2.22	0.91	0.0	0.0
DPW02	0.40	0.02	0.015	2.22	0.91	0.0	11.25
DPW03	0.40	0.02	0.015	2.22	0.91	-11.25	11.25

Table 2 The parameters of waves with double-peak spectrum.

Nonlinear Characteristics Parameters

When waves propagate from the deep water to the water near reefs, the nonlinear characteristic of wave will changed because of the transform of topography. In this paper, we consider four nonlinear characteristic parameters, i.e., the Ursell number, the asymmetry, the skewness and the kurtosis.

The Ursell number is a parameter to measure the strength of nonlinear characterization of waves. It is defined by the local wave mean period, which reads

$$U_r = \frac{H_s L_m^2}{h^3} \tag{1}$$

where h is the depth, H_s is the significant wave height, L_m is the local mean wavelength and is determined by the linear dispersion relationship using the local mean period.

Asymmetry (A) is a parameter which used to describe the degree of asymmetry of wave profile with regard to the vertical axis. It defined as:

$$A = \frac{\left\langle \mathrm{H}(\eta - \bar{\eta})^3 \right\rangle}{\left\langle (\eta - \bar{\eta})^2 \right\rangle^{3/2}} \tag{2}$$

The parameter of asymmetry of a wave profile relative to the horizontal axis is called wave skewness, *S*. It is defined as follow:

$$S = \frac{\left\langle (\eta - \bar{\eta})^3 \right\rangle}{\left\langle (\eta - \bar{\eta})^2 \right\rangle^{3/2}} \qquad (3)$$

Kurtosis (*K*) used to describe the distribution patterns of probability density function of wave height. It essentially is a fourth-order moment of wave surface elevation. The kurtosis is defined as follow:

$$K = \frac{\left\langle (\eta - \bar{\eta})^4 \right\rangle}{\left\langle (\eta - \bar{\eta})^2 \right\rangle^{2}} \qquad (4)$$

where H() represents Hilbert transform; η is surface elevation; $\bar{\eta}$ is mean value of η and 〈〉 means averaging.

Results and Discussions

Waves with single spectral peak

Figure 3 and Figure 4 show the variations of the Ursell number, the asymmetry, the skewness, and the kurtosis for the waves with single spectral peak propagating over the reef slope. As can be seen in these figures, the numerical results for nonlinear characteristic parameters are in good agreement with data from the physical experiments.

The value of Ursell number tends to be zero before the reef slope, and it increases rapidly in the reef slope. It means, in nearby reef, the magnitude of wave's nonlinearity has increased, and waves will deform due to the impact of nonlinear effects.

The wave deformations will lead to the changes of wave surface on the vertical axis and the horizontal axis, it denotes the variation of the asymmetry and the skewness. When waves spread to the reef slope, the value of the asymmetry increase negatively and that manifests that the wave crest lines tilted backwards. As waves spread to the reef flat, the value of asymmetry then increased to zero.

In the reef slope, the value of the skewness is increased positively. The deformation of waves has happened: the wave crests become sharp and the wave troughs become flat. With waves propagating through the reef slope, the terrain become flat, and the value of skewness will be gradually reduced.

Before waves propagate to the reef slope, kurtosis is maintained nearby a constant value, however, in the reef slope, the value of kurtosis become larger. That means the distribution of wave height turns steeper comparing with Gaussian distribution.

Comparison of Figure 4 and Figure 5, it is denoted that the effect of the direction of waves on the nonlinear parameters is insignificant.

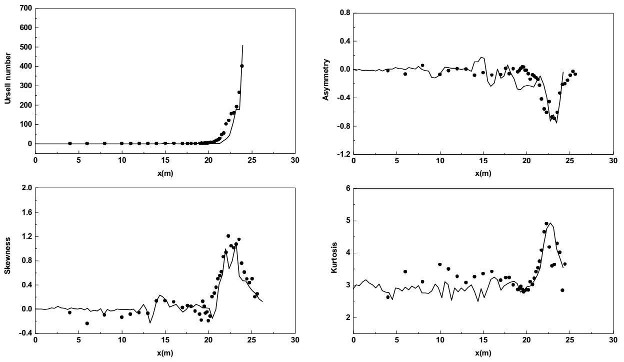

Figure 2 The variation of nonlinear characteristic parameters of case SPW01

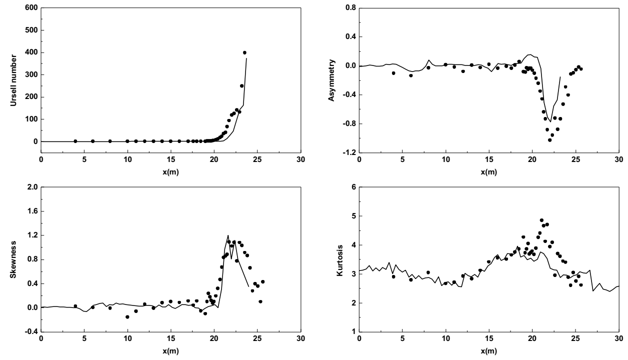

Figure 3 The variation of nonlinear characteristic parameters of case SPW02

Waves with double spectral peaks

Figure 5 shows the nonlinear characteristic parameters of mixed wave of wind wave and swell in different cases. From Figure 6, each nonlinear parameter of mixed wave has the similar trends with the wind wave.

As the waves propagate from deep water to the reef slope, the nonlinear characteristics are enhanced, same like wind wave. The value of Ursell number increases rapidly. The asymmetry drops down to negative value rapidly, and then rises to a value close to zero. The value of skewness and kurtosis increase in the reef slope, and reduce at the reef flat. The distribution of wave height is steeper than Gaussian distribution.

Comparison of these three conditions of mixed waves in Figure 6, the value of nonlinear parameters between these three kinds of wave conditions are similar. It manifests that the direction of waves has little effect on the nonlinear characteristic. The trend of nonlinear characteristics of mixed waves do not occur great changes, when wind waves and swells combined with each other with a little angle or no angle.

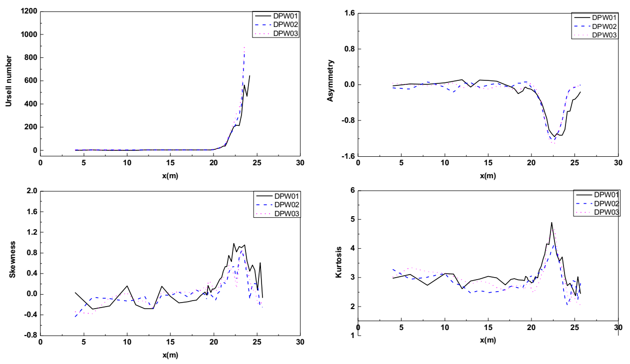

Figure 4 The variation of nonlinear characteristic parameters of waves with double spectral peaks.

Conclusions

This paper investigates the variation of nonlinear characteristic parameters when waves transformed over a 3D reef slope by physical model test and numerical model SWASH. The conclusions are made by numerical analysis of this two model data.

As the waters near the reef slope become shallow sharply, the nonlinear characteristic of waves are obviously enhanced. Whether it is a wind wave or a mixed wave of wind wave and swell, the change trends of each nonlinear characteristic parameter (e.g., the Ursell number, the asymmetry, the skewness and the kurtosis) are similar. The value of Ursell number increased rapidly with the strengthening of nonlinear characteristic of waves. Over the reef slope, waves occurred serious deformation. As the wave crest lines tilted backwards, the asymmetry increases negatively. And in the wake of the wave peak became sharp, the skewness increases positively. In addition, the effect of wave direction on nonlinear characteristic parameters is inconspicuous, regardless of the waves with single or double spectral peaks.

Acknowledgments

This work was financially supported by the High-Tech Ship Research Projects Sponsored by the Ministry of Industry and Information Technology (MIIT) of China.

References

[1] Doering J C, Bowen A J. Parametrization of orbital velocity asymmetries of shoaling and breaking waves using bispectral analysis. *Coastal Engineering*, 1995, 26(1): 15-33.

[2] Nielsen P, Callaghan D P. Shear stress and sediment transport calculations for sheet flow under waves. *Coastal Engineering*, 2003, 47(3): 347-354.

[3] Peng Z, Zou Q, Reeve D Wang B. Parameterisation and transformation of wave asymmetries over a low-crested breakwater. *Coastal engineering*, 2009, 56(11): 1123-1132.

[4] Sergeeva A, Pelinovsky E, Talipova T. Nonlinear random wave field in shallow water: variable Korteweg-de Vries framework. *Natural Hazards and Earth System Sciences*, 2011, 11(2): 323-330.

[5] Zijlema M, Stelling G, Smit P. SWASH: An operational public domain code for simulating wave fields and rapidly varied flows in coastal waters. *Coastal Engineering*, 2011, 58(10): 992-1012.

[6] Chawla A, Ozkanhaller H T, Kirby J T. Spectral Model for Wave Transformation and Breaking Over Irregular Bathymetry. Journal of Waterway Port Coastal and Ocean Engineering-ASCE, 1998, 124(4): 189-198.

[7] Berkhoff J C. Computation of combined refraction - diffraction. *Proceedings of the 13th Coastal Engineering Conference*, 1972: 471–490.