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Laboratory measurements of an equilibrium-range constant for wind waves at extremely high wind speeds

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ABSTRACT

When improving wave models, it is important to determine the equilibrium-range constant for the wind-wave spectrum and find the dominant velocity parameter that well represents the equilibrium-range constant both at normal and extremely high wind speeds. Eight dominant velocity parameters were evaluated using laboratory experiments in two wind-wave tanks. One tank, installed at Kyoto University, is used for generating mechanically-generated large wind-waves. This tank has a maximum 10-m wind speed (U_{10}) of 67 m/s and is equipped with a programmable irregular wave generator for the loop-type wave-generation method, which was originally developed in our previous study. The other tank, installed at Kyusyu University, is used for generating pure large wind-waves, and has a total length of 54 m. The results show that at extremely high wind speeds the equilibrium-range constants for mechanically-generated large wind-waves agree with those of pure small wind-waves. In addition, comparison of the correlation coefficients of the eight dominant velocity parameters with the equilibrium-range constant reveals that three dominant velocity parameters of $(u^{*2}C_P)^{1/3}$, $(U_{10}{}^2C_P)^{1/3}$, and $U_{LS/2}$ (u^*: friction velocity; C_P: phase velocity; $U_{LS/2}$: wind velocity at half the height of wavelength over the ocean) well correlate with the equilibrium-range constant at both normal and extremely high wind speeds.

1. Introduction

The precise prediction of the development and propagation of ocean waves is important because ocean waves have a significant influence on transportation by ships, shore erosion, and water sports. In addition, since air–sea momentum, heat, and mass transfer at high wind speeds are strongly affected by distinctive wave breaking (Takagaki et al., 2012; Iwano et al., 2013; Komori et al., 2018), it is essential to understand the shape of wind waves at high wind speeds.

The shape of wind waves is generally defined by the wind-wave spectrum $S(f)$, where f is the frequency. In an effort to clarify the wave-generation and wave-development mechanisms, and to improve the precision of wave development and propagation prediction, researchers have conducted field observations and laboratory experiments, and have also proposed several wind-wave spectral

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models for normal wind speeds (e.g., Phillips, 1958; Pierson and Moskowitz, 1964; Hasselmann et al., 1973; Toba, 1973). The wind-wave spectral model includes an equilibrium-range constant, where the equilibrium-range constant determines the energy level of the wind-wave spectrum. When developing the wind-wave spectral model it is important, therefore, to clarify the effects of wind and fetch on the equilibrium-range constant. In fact, at normal wind speeds these empirical models have been proposed (e.g., Hasselmann et al., 1973; Donelan et al., 1985).

Conventional wind-wave spectrum models, which use wave data at normal wind speeds, are not appropriate for representing the shape of wind waves at extremely high wind speeds, because of intensive wave breaking (Donelan et al., 2004; Takagaki et al., 2012, 2016a, 2016b; Donelan, 2018). Takagaki et al. (2012) investigated the wind-wave spectrum at high wind speeds, and found that strong breaking of wind waves occurs at extremely high wind speeds, which deforms the wind-wave spectrum and causes the drag coefficient (C_D) saturation. Takagaki et al. (2016a, 2016b) then estimated the equilibrium-range constant and peak enhancement factor for the wind-wave spectrum at normal and extremely high wind speeds, and foundthat the equilibrium-range constant has a strong relationship with the inverse wave age. Donelan (2018) repeated the modelling of the relationship between C_D and the equilibrium-range constant at extremely high wind speeds by applying the *Jeffreys*'s sheltering model. However, their analyses for the equilibrium-range constant were conducted using a single dominant velocity parameter (U_{10}), and their laboratory studies were on pure small wind waves (e.g. significant wave height of 0.063 m and wind speed of 41.2 m/s, Takagaki et al. (2016a)), under fetches less than 10 m. Therefore, no study has yet clarified whether the dominant velocity parameter (U_{10}) best represents the equilibrium-range constant, or whether equilibrium-range constants obtained in such small wind waves with short fetches are applicable to large wind waves with long fetches. Recently, to overcome the size limitation of the laboratory tanks, which inhibit the production of large wind waves, in a previous study we developed an original large wind-wave generation-method using a programmable irregular-wave generator, which we titled the loop-type wave-generation method (LTWGM) (Takagaki et al., 2017).

In this study, we aim to find which dominant velocity parameter can best represents the equilibrium-range constant for the wind-wave spectrum, for both pure small wind-waves and mechanically-generated large wind-waves, at normal and extremely high wind speeds, by using our original wind-wave generation method.

2. Experiments

2.1. Equipment and measurement methods

A high-speed wind-wave tank (HSWWT) (c.f., Takagaki et al., 2012; Iwano et al., 2013; Krall and Jähne, 2014; Komori et al., 2018) with a 15.0 m long, 0.8 m wide, and 1.6 m high glass test section was used for the experiments (Fig. 1a). Wind waves were generated in a water tank filled with filtered tap water at U_{10} = 7–68 m/s and F = 6.5 m and at U_{10} = 19.3, 32, and 42 m/s and F = 17–42.5 m, where F is the fetch. Large waves were mechanically generated at F = 17–42.5 m with a programmable piston-type irregular wave generator, constructed using a wave-generating board, servomotor (Mitsubishi Electric HC-SFS-352), function generator (NF circuit WF1973), wave gauge, data recorder, and computer (Takagaki et al., 2017, 2018). The wave-generating board was an acrylic plate with a height, width, and thickness of 0.72, 0.78, and 0.02 m, respectively. The center of the board stroke was set to x = -0.5 m at the entrance slope. The maximum stroke was 0.4 m.

A laser Doppler anemometer (Dantec Dynamics LDA) and phase Doppler anemometer (Dantec Dynamics PDA) were used to measure the wind velocity fluctuation (Takagaki et al., 2012). A high-power multi-line argon-ion (Ar^+) laser (Lexel model 95-7; the laser wavelenghts are 488.0 and 514.5 nm) with a power of 3 W was used. The Ar^+ laser beam was shot through the sidewall (glass) of the tank. Scattering particles with a diameter of ~1 μm were produced by a fog generator (Dantec Dynamics F2010 Plus) and were fed into the air flow over the waves. The sampling frequency and time were 500–5000 Hz and 240 s, respectively. As an example, the wind speeds were measured by LDA at z = 0.05–0.55 m with the vertical unequal intervals of 5–50 mm at U_{10} = 19.3 m/s and F = 17 m. The air friction velocity (u^*) was estimated to be $u^* = (-< u'v' >)^{1/2}$ using an eddy correlation method, where u' and v' are the streamwise and vertical air velocity fluctuations, respectively. Here, the shear stress at the interface (τ) was estimated by extrapolating the measured values of the Reynolds stress $-\rho < u'v' >$ to the mean surface of z = 0 m. The wind velocity profile across the rough boundary under neutral stratification is expressed using a logarithmic profile:

$$U(z)/u^* = \ln(z/z_0)/\kappa, \quad (1)$$

where $U(z)$ is the wind speed at an elevation of z, κ (= 0.4) is the von Karman constant, and z_0 is the roughness length. The C_D is generally used to express the magnitude of momentum transfer at the sea surface as:

$$\tau = \rho u^{*2} = \rho C_D {U_{10}}^2, \quad (2)$$

where τ is the sea surface wind shear stress, ρ is the density of air, and u^* is the air friction velocity. Based on Eqs. (1) and (2), C_D displays one-to-one correspondence with the roughness length (z_0) under neutral stratification:

$$\kappa {C_D}^{-1/2} = \ln(z_{10}/z_0), \quad (3)$$

where z_{10} = 10 m. Therefore, we evaluated z_0, C_D, and U_{10} using Eqs. (1)–(3).

The water level fluctuations were measured using resistance-type wave gauges (Kenek CHT4-HR60BNC). The resistance wire was placed in the water and the electrical resistance at the instantaneous water level was recorded at 500 Hz for 600 s using a digital recorder (Sony EX-UT10). The energy of the wind waves (E) was estimated by integrating the spectrum of the water level fluctuations