DIRECTIONAL SPECTRA OF INFRAGRAVITY WAVES DURING STORMY CONDITIONS

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INTRODUCTION

Both magnitude and directions of infragravity (IG) waves are essential information for accurate hindcast/prediction of coastal hazard due to stormy waves (e.g., coastal inundation and beach erosion). However, conventional reconstruction methods of directional spectra relying on linear wave theory are not applicable to IG waves which are composed of free (linear) and bound (nonlinear) components. This study proposes a novel method to reconstruct directional spectra of IG waves and presents diverse wave directions of free IG waves during stormy conditions.

PROPOSED METHOD

A governing equation of the new method is derived from weakly nonlinear wave theory by Hasselmann (1962). It is showed that a cross-spectrum among m-th and n-th wave signals, Φ_{mn} , is given as a summation of contributions from free and bound IG waves (Φ_{mn}^F and Φ_{mn}^B):

$$\Phi_{mn}(f) = \Phi_{mn}^F(f) + \Phi_{mn}^B(f)$$

$$\Phi_{mn}^F(f) = \int H_m^{(1)^*} H_n^{(1)} \exp[i\boldsymbol{k}\cdot(\boldsymbol{x_n}-\boldsymbol{x_m})]\, S_{IG}^F(f,\theta)d\theta$$

$$\Phi_{mn}^B(f) = 2\int\int\int H_{m,f}^{(2)^*} H_{n,f}^{(2)} \exp[i\Delta\boldsymbol{k}\cdot(\boldsymbol{x_n}-\boldsymbol{x_m})] \times S_{SS}(f_1,\theta_1)S_{SS}(f_2,\theta_2)\Omega^2\, df_1 d\theta_1 d\theta_2.$$

In these equations, Φ_{mn}^B can be estimated from measured directional spectra of incident sea and swells $S_{SS}(f,\theta)$ with a nonlinear coupling coefficient Ω and transfer functions $H_{n,f}^{(2)}$ based on the weakly nonlinear wave theory. Based on this equation, the present method computes directional spectra of free IG waves $S_{IG}^F(f,\theta)$ from Φ_{mn}^F estimated as $\Phi_{mn} - \Phi_{mn}^B$.

FIELD APPLICATION

The method was applied to field data (water level and water velocity) during stormy conditions at NOWPHAS observatories in Japan. The observatories are located at depths of 20-25 m and are close to breakwaters protecting harbors (Figure 1). At first, estimated power spectral densities of free IG waves were compared with an empirical formula proposed by Ardhuin et al. (2014). At both observatories, the empirical formula successfully represented the observed power spectral densities (Figure 2). On the other hand, observed directional distributions of free IG waves showed different peak wave directions. At 207 (Figure 3), we confirmed that seaward propagating free IG waves are dominant at the observatory ($\theta' \sim 90°$). The peak angle of free IG waves was well explained by specular reflection of incident bound IG waves at the shoreline. On the other hand, seaward propagating free IG waves seemed to be minor and alongshore propagating components ($\theta' \sim \pm 180°$) are dominant at 106 (Figure 4). The alongshore propagating components seemed to be generated by the reflection from the breakwater, which is located at the east of the observatory.

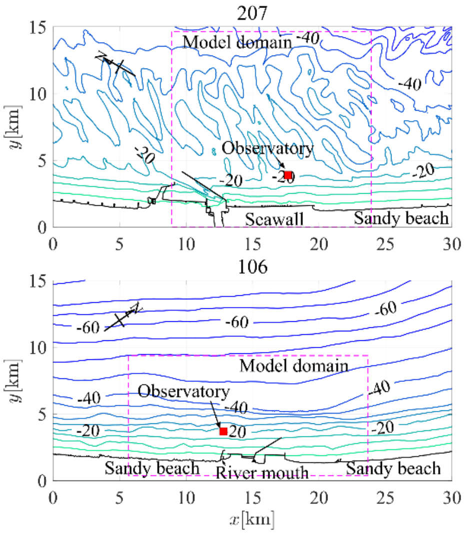

Figure 1 - Bathymetry map at 207 (Lower) and 106 (lower). Edited from Matsuba et al. (2022).

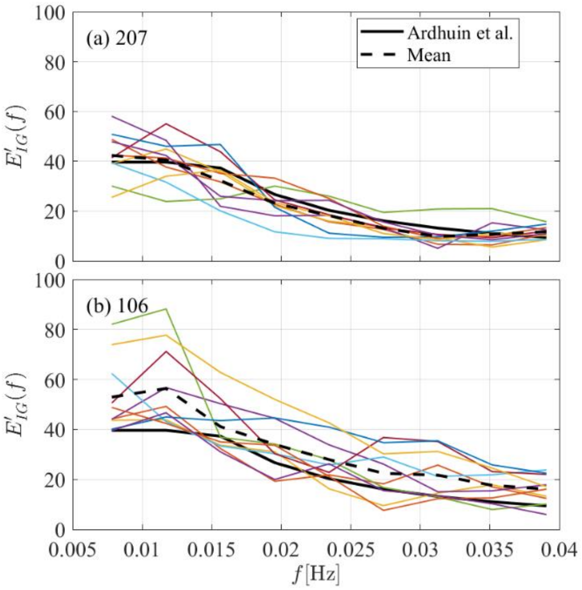

Figure 2 - Measured power spectral density of free IG waves and a comparison with an empirical formula by Ardhuin et al. (2014). From Matsuba et al. (2022).

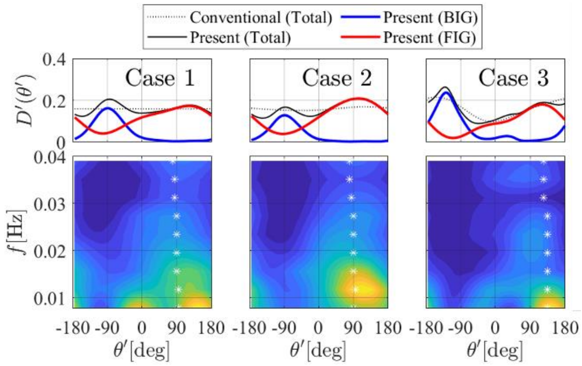

Figure 3 – Directional distributions of IG waves (Upper) and reconstructed directional spectra of free IG waves at 207. From Matsuba et al. (2022).

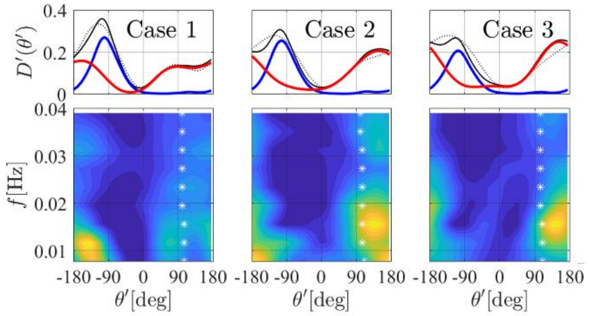

Figure 4 – Directional distributions of IG waves (Upper) and reconstructed directional spectra of free IG waves at 106. From Matsuba et al. (2022).

NUMERICAL SIMULATIONS

To discuss the observed directions of free IG waves, nearshore wave fields were computed by using XBeach (Roelvink et al., 2009). Directional wavenumber spectra were computed from the modeled water levels around the observatories. The modeled directional distributions agreed with the observation by the proposed method (Figure 5). Computations excluding the breakwaters revealed that alongshore propagating IG waves reflected at the breakwaters locally increased IG wave heights by about 20% in nearshore areas (Figure 6). In conclusion, the results showed that intensity and directions of IG waves are highly affected by regional topography and coastal structures because they control dominant directions of reflected free IG wave.

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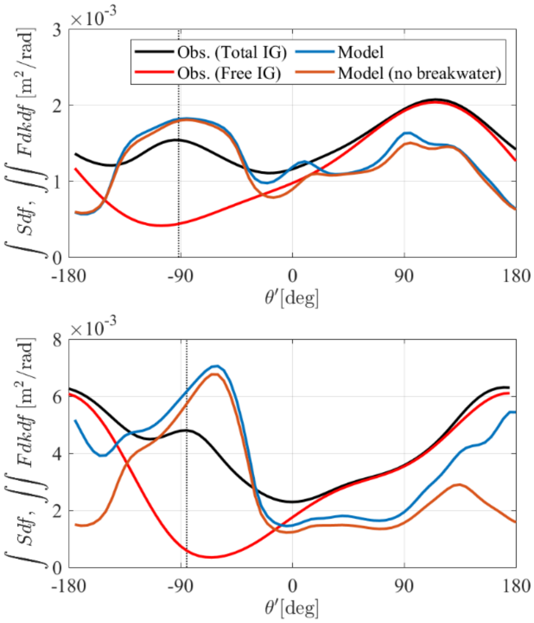

Figure 5 – Observed and modeled directional distributions of IG waves in a representative case at 207(Upper) and 106(Lower). Edited from Matsuba et al. (2022).

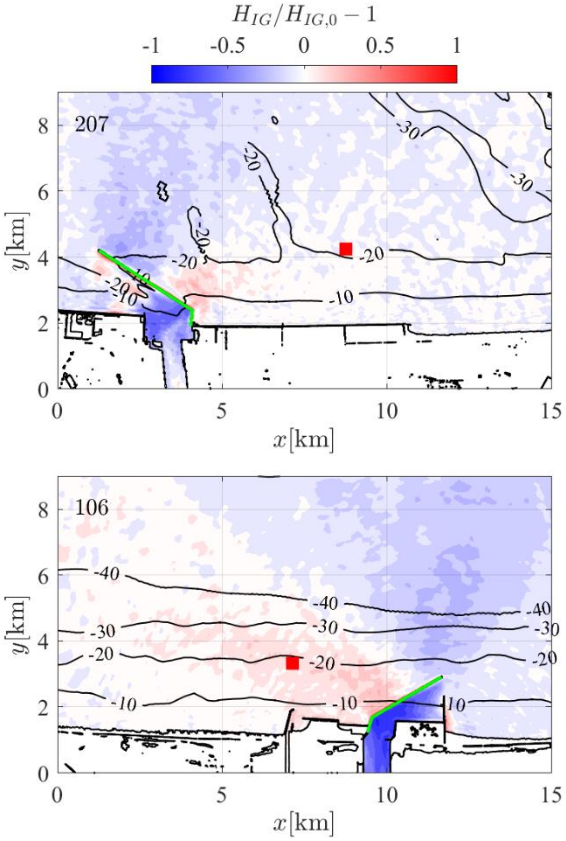

Figure 6 – Relative increase (red) or decrease (blue) of IG wave heights owing to the presence of breakwaters shown in green. Edited from Matsuba et al. (2022).