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Correcting wave reflection estimates in the coastal zone

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ABSTRACT

The impact of random noise on an existing two-dimensional method for separating incident and reflected wave spectra using an array of wave gauges is investigated using simulated time series with known wave amplitudes, reflection coefficients, and signal-to-noise ratios. Both the incident and reflected spectra are overestimated by a quantity that can exceed 100% for signal-to-noise ratios less than 1. Consequently, estimated reflection coefficients are also overestimated with larger errors occurring when the known reflection is low. Coherence decreases systematically with increasing noise and this trend is used to develop a mathematical function to correct for the observed bias and provide 95% confidence intervals for incident and reflected spectra and reflection coefficients. The correction technique is shown to be very effective in reducing error by up to ~90%. Field data from a natural beach are used to demonstrate the application of these results; corrected values suggest that reflection coefficients are frequently overestimated by over 50%.

1. Introduction

Wave reflection is an important process influencing the hydro- and sediment dynamics in front of natural coastlines and man-made coastal structures. Therefore, understanding and accurately predicting the magnitude of wave reflection is essential for estimating potential storm damage, modelling shoreline change, and assessing the reflection performance of marine structures.

Several methods exist to decompose a two-dimensional wave signal propagating over a horizontal bed into its incident and reflected components using cross-shore arrays of spatially separated wave gauges. These methods utilise the phase difference between pairs of wave gauges to provide information on the propagation of the incident and reflected waves. Early methods to calculate wave reflection typically use an array of only two wave gauges (e.g., [6,12]); however, these techniques suffer from singularities at a discrete number of critical frequencies where the distance between the two wave gauges is equal to an integer number of half the corresponding wavelength. To overcome this limitation and estimate wave reflection over a wider frequency range, several newer techniques have been developed that use the wave records from three or more wave gauges (e.g., [2,5,11]), thus providing a range of wave gauge pairs and separation distances for use in the analysis.

An alternative method of calculating wave reflection is to use a co-located wave gauge and velocity sensor (e.g., [8,15]), where the direction of wave propagation is estimated using information on the slope of the sea surface provided by the cross-shore current. These methods have the advantage of estimating wave reflection at a singular cross-shore location, whereas the wave reflection estimate from an array method is the average value for the spatial extent of the array, which may be quite large. Additionally, methods that use a co-located wave gauge and velocity sensor are not affected by variations in the bathymetry. However, it is critically important to have the wave gauge and velocity sensor located at the same horizontal location as even a small spatial separation can have important effects on the resulting wave reflection estimates [10]. In many cases, array methods remain the preferred approach as wave gauges are typically less intrusive to deploy in the field than current sensors and far more economical if wave reflection estimates are required at several cross-shore locations [9].

Most array methods used to separate incident and reflected waves are designed for two-dimensional waves propagating over a horizontal bed and do not account for the effects of sloping bathymetry such as that of a natural beach. Therefore, depending on the wave conditions and bed slope, errors in the analysis are likely when used in such conditions. Baldock and Simmonds [1] demonstrated that relatively simple modifications are required to adapt the separation method of Frigaard and Brorsen [4] to account for shore-normal linear waves propagating over a bed with arbitrary bathymetry. Their analysis showed that neglecting the shoaling effects of waves can lead to large errors in the estimated reflection coefficient (the ratio of reflected to incident wave energy) in cases of low wave reflection. Furthermore,

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accounting for bathymetry variations was found to be crucial to avoid significant errors (up to 90%) in estimating the incident and reflected wave amplitudes.

An additional source of error that may impact wave reflection estimates, present in both laboratory and field data, is that of noise. Potential sources of signal noise include water surface variability that is unrelated to wave motion, proximity to standing wave nodes, and electronic noise. Using simulated time series of surface elevation and velocity with known true reflection coefficients and added uncorrelated noise, Huntley et al. [10] show that the presence of noise in the data can introduce a significant positive bias to the reflection coefficients estimated from co-located wave gauge and velocity sensor methods. In an attempt to overcome this, Tatavarti et al. [17] developed a method using principal component analysis to separate the elevation and velocity time series into orthogonal eigenvector combinations, thus allowing the correlated parts of the two time series to be separated from undesired noise. This technique was validated by Huntley et al. [10] who also demonstrate that the bias in reflection coefficients estimated using other co-located wave gauge and velocity sensor methods can be corrected for by using the estimated reflection coefficient itself and the coherence between the estimated incident and reflected waves. A similar investigation into the effect of noise on wave reflection estimates using array methods is currently lacking.

The aim of this paper is to use simulated time series of water surface elevation to investigate the impact of noise on wave reflection estimates using the array method of Gaillard et al. [5]. A mathematical function is developed to provide a correction for the observed bias in incident and reflected spectra and corresponding reflection coefficients. This function is applied to field data to demonstrate its value. The results presented in this paper are principally applicable to the array method of Gaillard et al. [5] which was chosen for its relatively simple approach that directly returns incident and reflected spectra from which to assess the noise impact. However, the procedure outlined in the following section could equally be used to assess the impact of noise on other two-dimensional array methods.

2. Methodology

The water surface elevation η at two cross-shore locations, x_1 and x_2, separated by Δx, is given by linear wave theory as

$$\eta(x_1,\ t)=a_i\cos(\omega t-kx_1+\phi_i)+a_r\cos(\omega t+kx_1+\phi_r) \tag{1}$$

$$\eta(x_2,\ t)=a_i\cos(\omega t-kx_1-k\Delta x+\phi_i)+a_r\cos(\omega t+kx_1+k\Delta x+\phi_r) \tag{2}$$

where t is time, a is wave amplitude, ω is wave angular frequency ($2\pi f$, where f is frequency), k is wavenumber ($2\pi/L$, where L is wavelength), ϕ is phase, and subscript i and r denote incident and reflected waves, respectively. The signs of the terms are for an onshore-directed x–axis. Eqs. (1) and (2) show that between cross-shore locations x_1 and x_2, the incident and reflected waves are phase shifted by $-k\Delta x$ and $k\Delta x$, respectively. Eqs. (1) and (2) are used to generate simultaneous time series of water surface elevation at three cross-shore locations on a horizontal bed.

For the purpose of the simulations, wave amplitudes a_i and a_r are independent of frequency and all waves travel at the shallow water wave speed. A range of simulations were performed with incident wave amplitudes between 1 and 10 m, known reflection coefficients between 0 and 1, and with normally distributed, random noise added to the time series at known signal-to-noise ratios (SNR). While the use of constant wave amplitudes and reflection coefficients across all frequencies is not representative of real field data, each frequency provides an independent estimate of the incident and reflected spectra for any particular SNR, wave amplitude and true reflection coefficient. This allows mean values of error, and confidence intervals on these estimates, to be calculated for particular frequency ranges. By running a range of simulations with different wave amplitudes and noise levels, errors and corresponding confidence intervals can be predicted for each frequency bin in a measured spectrum.

Synthetic time series were generated with 4096 data points and a sampling frequency of 4 Hz. Smooth spectral estimates were computed using a 50% overlapping Hanning window, giving a frequency resolution of 0.0039 Hz and 12 degrees of freedom [13]. The spectra are then separated into incident S_i and reflected S_r components using the first order formulae of Gaillard et al. [5] as

$$S_i(f)=\frac{\overline{S}-\overline{C}+\overline{Q}}{2S_a} \tag{3}$$

$$S_r(f)=\frac{\overline{S}-\overline{C}-\overline{Q}}{2S_a} \tag{4}$$

where

$$\overline{S}=S_1+S_2+S_3 \tag{5}$$

$$\overline{C}=C_{21}\cos(k\,\Delta x_{21})+C_{31}\cos(k\Delta x_{31})+C_{32}\cos(k\,\Delta x_{32}) \tag{6}$$

$$\overline{Q}=Q_{21}\sin(k\Delta x_{21})+Q_{31}\sin(k\,\Delta x_{31})+Q_{32}\sin(k\,\Delta x_{32}) \tag{7}$$

and

$$S_a=\sin(k\,\Delta x_{21})+\sin(k\,\Delta x_{31})+\sin(k\,\Delta x_{32}) \tag{8}$$

where S, C and Q represent the auto-, co-, and quadrature-spectra respectively, Δx is sensor spacing, and subscript numbers denote sensor location (S) or sensor pair (C, Q, Δx). Co- and quadrature-spectra are calculated as the real and imaginary parts of the cross-spectrum, respectively. The incident and reflected spectra are then used to estimate reflection coefficients R by

$$R(f)=\sqrt{\frac{S_r}{S_i}} \tag{9}$$

The purpose of using an array method with three wave gauges is to avoid singularities occurring at a discrete number of critical frequencies. However, gauge triplets must be chosen intelligently with spatial separations that mitigate the coincidence of critical frequencies, otherwise these frequencies will suffer similar effects to those from using a two gauge array. This paper will focus on the frequency range 0.01–0.33 Hz. The low frequency cut-off of 0.01 Hz was chosen to avoid any adverse effects radiating from the singularity that always occurs at 0 Hz, regardless of whether two of three wave gauges are used. The high frequency cut-off of 0.33 Hz was chosen as it coincides with the upper limit of the frequency range commonly used to define 'short' waves (e.g., [14]). Furthermore, wave reflection from natural coastlines has been found to be negligible at higher frequencies, particularly on dissipative beaches. The use of this frequency range allows for spectral estimates at 82 discrete frequencies. To avoid the influence of singularities across the entire frequency range of interest, three different array set-ups are used in the simulations to satisfy frequency ranges 0.01–0.05 Hz, 0.05–0.20 Hz, and 0.20–0.33 Hz, respectively. The full range of simulations was performed for each array set-up and spectral estimates for the corresponding three frequency ranges were concatenated providing the full spectrum of interest for each combination of simulation parameters.

3. Results

For each simulation scenario, an assessment is made of the accuracy to which the incident and reflected spectra, and corresponding reflection coefficients, are reproduced by the decomposition method of Gaillard et al. [5]. Mean coherence between the three synthetic time series is calculated to investigate the extent to which coherence can be used as a proxy for SNR. By averaging the coherence between the three pairs of time series, fluctuations due to standing wave nodes and antinodes are removed. Throughout this section, target values for incident and reflected spectra and reflection coefficients (i.e.,