RESOLVING TRANSFORMED WAVE DIRECTIONS NEAR COASTAL STRUCTURES

Torstein Pedersen[1], Judah Goldberg[2], Atle Lohrmann[1], Eric Siegel[2],

Numerous wave measurement stations in our coastal communities measure waves in shallow waters, close to structures, where the “incident” waves are transformed by the interaction with these structures. It would be advantageous to parse out incident from transformed waves. We present a technique to separate the incident and reflected waves through an example of incident waves reflecting from a breakwater. Field data was collected with a 1 MHz AWAC. The starting point for this analysis is the full directional spectra, which is a description of the energy as a function of both direction and frequency.

INTRODUCTION

Background

Coastal monitoring of waves and currents is quickly becoming a standard practice for many ports and coastal industrial centers. It not only serves as a resource for all mariners alike, but also provides detailed information about near shore processes that are valuable for planning and management. Unfortunately, coastal waves are very complex, particularly those near structures, and therefore precise wave characteristics can be difficult to measure accurately. This is in contrast to waves measured offshore that typically have unambiguous directional characteristics because there are no structural interferences.

Special attention is required when wave properties (height, period, direction, spread, etc.) are measured in the near shore region where transformations (e.g. reflection, diffraction, refraction) due to abrupt boundaries can redistribute wave energy in directions different from the offshore, incident direction.

Measurement Procedures

Wave measurement instrumentation for coastal waves can be quite varied. One of the more common practices employed for wave measurements is the “triple-point” measurement. This includes any system measuring three wave properties that are directionally orthogonal (x,y,z). Wave buoys and PUV systems (Pressure and horizontal velocity) represent two of the more common triple-point measurements. Such systems are proven for accurately characterizing wave fields that contain one primary direction at a given frequency. Typically, calculated wave directions are based on the first pair of

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[1] Nortek AS, Vangrkoken 2, Rud, Norway, inquiry@nortek.no
[2] NortekUSA, 222 Severn Ave., Annapolis, MD, USA, Judah@nortekusa.com / eric@nortekusa.com

Fourier coefficients, and describe the mean direction at a given frequency. However, this method is not adequate when wave trains from two independent directions are present. One such example of this typically occurs along coastal areas where structures transform incident wave energy and create reflected waves that are measured at the same location leading to a weighted average of the two directions. In this situation one may consider to instead estimate the full directional energy distribution as a function of both direction and frequency. For cases where there are two clear directions of two different wave directions, a solution such as the Maximum Entropy method needs to be employed (Lygre et. al, 1986). In short, the Maximum Entropy method is an optimization procedure that uses the same four Fourier coefficients to determine the full directional energy distribution. This is an improvement over the standard Fourier expansion since it does not contain negative energy in the distribution.

Alternatively, an array of sensors may be used which allows for two wave trains having the same frequency but different propagation direction to be separately resolved. One of the more common ways to do this is to use the Maximum Likelihood Method (MLM). The Nortek AWAC (Acoustic Wave And Current profiler) is one of the array type of measurement instruments, where an array is projected just below the surface. The array is composed of three orbital velocity measurements and a direct measurement of the surface position. The AWAC performs these measurements using a combination of three slanted acoustic beams that are symmetrically positioned about the center and angled 25 degrees from the vertical. A vertical fourth beam is dedicated to Acoustic Surface Tracking (AST) that provides direct measurements of the surface elevation. In the presence of incident and reflected waves, the AWAC shows two clear peaks from waves of the same frequency but different directions.

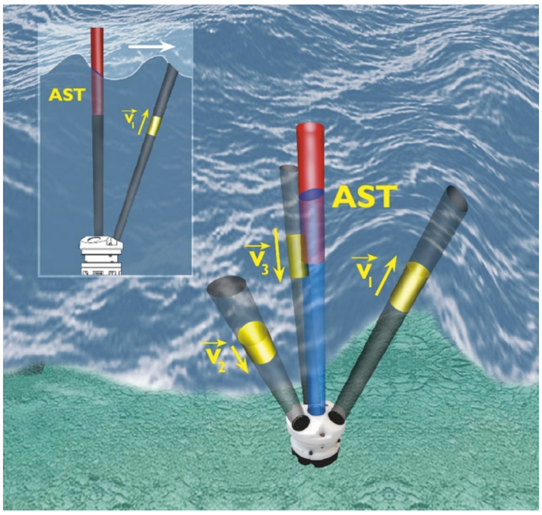

Figure 1 AWAC with three slanted beams to measure orbital velocity and a vertical beam in the center dedicated to Acoustic Surface Tracking.

The subsequent discussion will highlight the possibilities and limitations of such a directional energy analysis. A case study from Malaga, Spain, where data was collected in front of a breakwater (and clearly shows incident and reflected wave energies) will be presented in order to discuss the possibility of separating incident and reflected wave energies using the full directional solution. We chose to use the SUV (discussed below) with the Maximum Entropy method simply because there are fewer model assumptions than with the Maximum Likelihood Method (MLM). The results are evaluated for “geometric integrity” as well as the possibility of using the results to estimate reflection coefficient.

The Processing Procedure

The processing technique used for the AWAC data is the SUV method. A full explanation of the technique is described in Pedersen et al. 2005. In simple terms, the processing approach is most similar to a standard triple-point type of measurement that uses two measures of the horizontal orbital velocity, but instead of using pressure as the third measure (such as the PUV technique), the vertical AST measurement is used. The standard processing of the SUV method provides the first two pairs of Fourier coefficients, which are commonly used with the Maximum Entropy Methods to provide a description of the full energy distribution in terms of frequency and direction. An example is presented in Figure 2.

Admittedly, all methods attempting to reproduce the full directional spectra fall short in one respect or another. To what degree this occurs is a matter of debate. It is not our intention to steer this in either direction however for our purposes here we simply wish to investigate what possibilities exist with using the full directional spectra.

There are two procedures that we perform on the full directional spectra in order to evaluate the accuracy of both directional estimates and the distribution of energy.

The first procedure identifies the angle that bisects the incident and reflected waves. This direction should always be the same and is independent of the incident wave direction. It may be easier to view this as the mean direction of the incident and reflected wave directions. This bisect angle should also be the angle that the breakwater runs (Figure 4). This provides a first level check that the peak energy in the full directional spectra is reasonable, and more importantly, accurate.

$$\theta_{mean} = (\theta_{Incident} + \theta_{Re\,flected})/2 \tag{1}$$

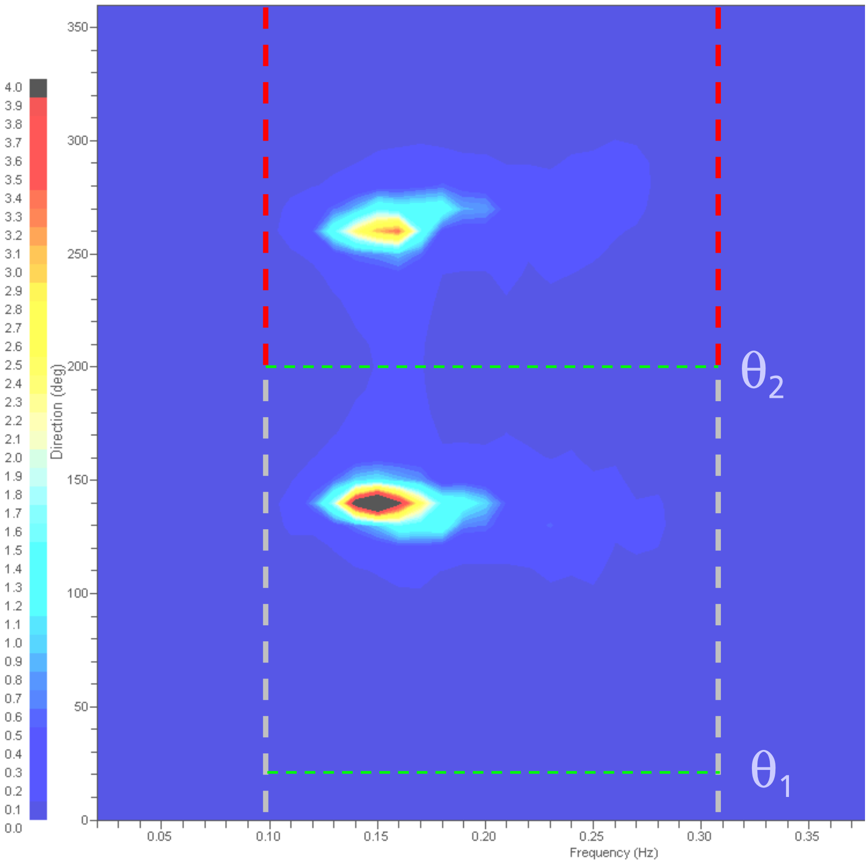

Figure 2. Example of a full directional spectrum. This shows an incident wave event at 140 degrees and a small reflected wave event at 260 degrees. The vertical axis is the direction and the horizontal axis is wave frequency.

The second way of evaluating or quantifying the reflected wave energy is to estimate the reflection coefficient, K_R (more formally described as $K_R = \sqrt{E_R / E_I}$, or the relative energy of the reflected and incident waves). For the data collected at the Malaga breakwater the reflection coefficient was estimated over a large frequency band in order to reduce randomness often seen with estimates based on single frequencies.

$$E_R = \sum_{freq} \sum_{\theta 2}^{\theta 1} FullDirSpec \qquad (2)$$

$$E_I = \sum_{freq} \sum_{\theta 1}^{\theta 2} FullDirSpec \tag{3}$$

$$K_R = \sqrt{\frac{E_R}{E_I}} \tag{4}$$

MALAGA BREAKWATER ANALYSIS

Test Description

The procedure for evaluating reflection from breakwaters has been applied to a data set collected from an AWAC deployed in front of a breakwater in Malaga, Spain (Figures 3 and 4). The AWAC was deployed at a depth of 22 meters, and configured to measure waves once an hour for an approximate duration of 17 minutes (2 Hz, 2048 samples). The data was collected from April 4 – June 3, 2003.

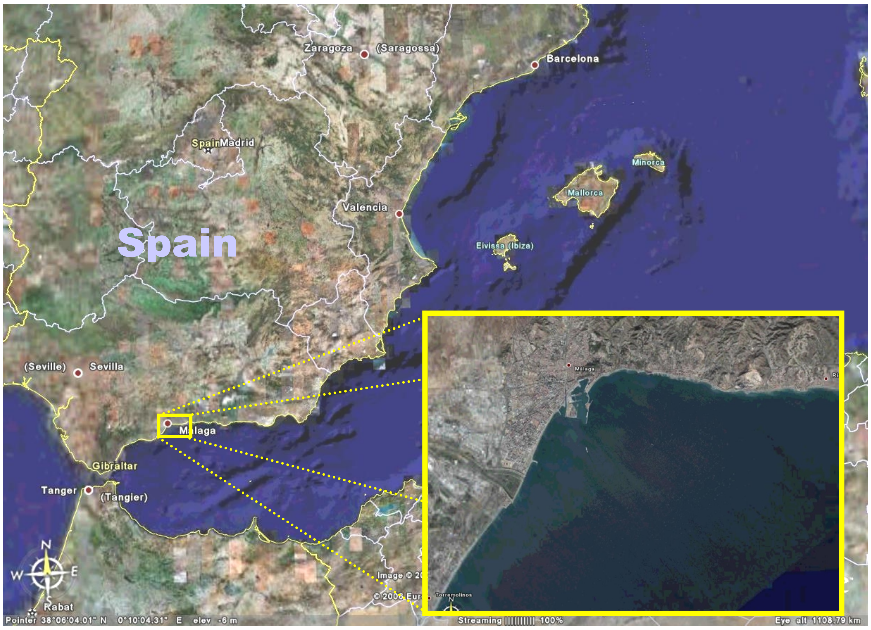

Figure 3. Malaga, Spain is indicated by the boxed in region. The inset image shows the location of the breakwater up near the “corner” of the coastline. The location is exposed to waves between the east and south.

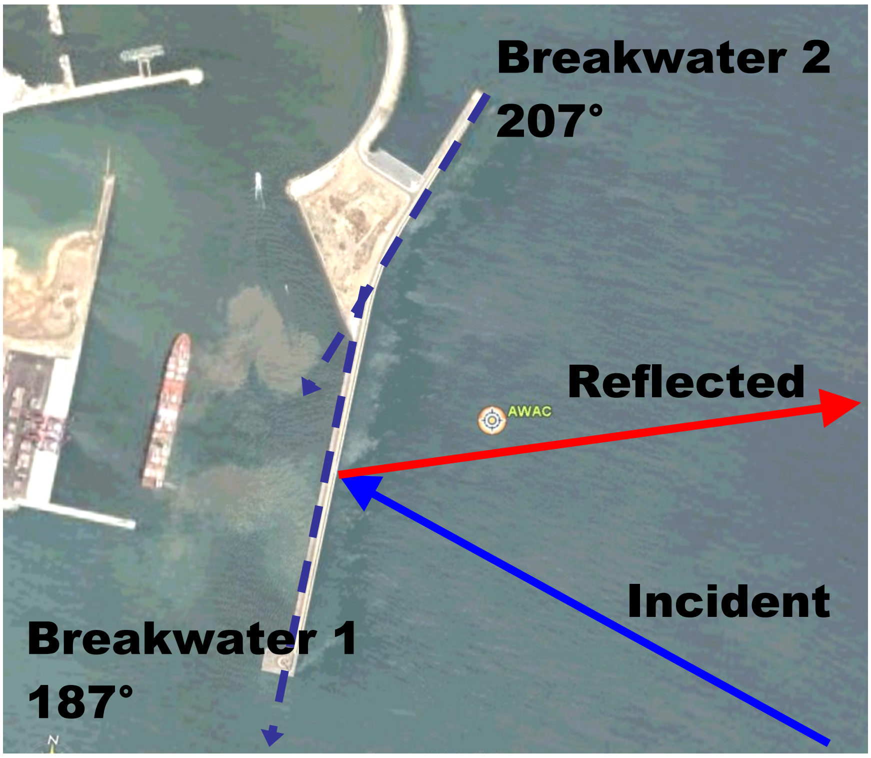

Figure 4 **The two breakwater system at Malaga, Spain. The AWAC position is indicated by the circular mark. The dashed lines indicate the orientation of breakwaters 1 and 2. The two arrows are examples of incident and reflected waves directions expected at this site.**

This particular breakwater is unusual because it is actually composed of two breakwaters; one running at an angle of 207 degrees and the other at an angle of 187 degrees. This complicates the study because we have waves reflected from the breakwater at two different angles causing some locations in front of the breakwater to be subjected to one or both of the reflected waves. Naturally, the composition of this multi-reflection is unique to each specific location and the incident wave direction. Fortunately for this study, most of the waves were from the south-southeast.

Conditions during the test were quite variable; calm periods lasting several days with significant wave heights of no more than 0.25 meters, and storms generating significant wave heights near 2 meters (H_{max} nearly 3 meters). The sea state is presented in Figure 5. The incident wave direction varied between the east and south, but most often were from the south-southeast. Figure 5 also presents the wave estimates of period and peak direction. The peak direction estimates here are calculated using the standard definition of peak period, which is based on the first pair of Fourier coefficients that described the directional distribution. These estimates are in fact are in error since they represent a weighted average of the incident and reflected wave directions. Clearly, an alternative method must be employed when wave measuring devices are placed in close proximity to reflecting structures. This misleading result can be avoided by using the suggested procedure of using the full directional spectra and then separating the incident and reflected wave events.

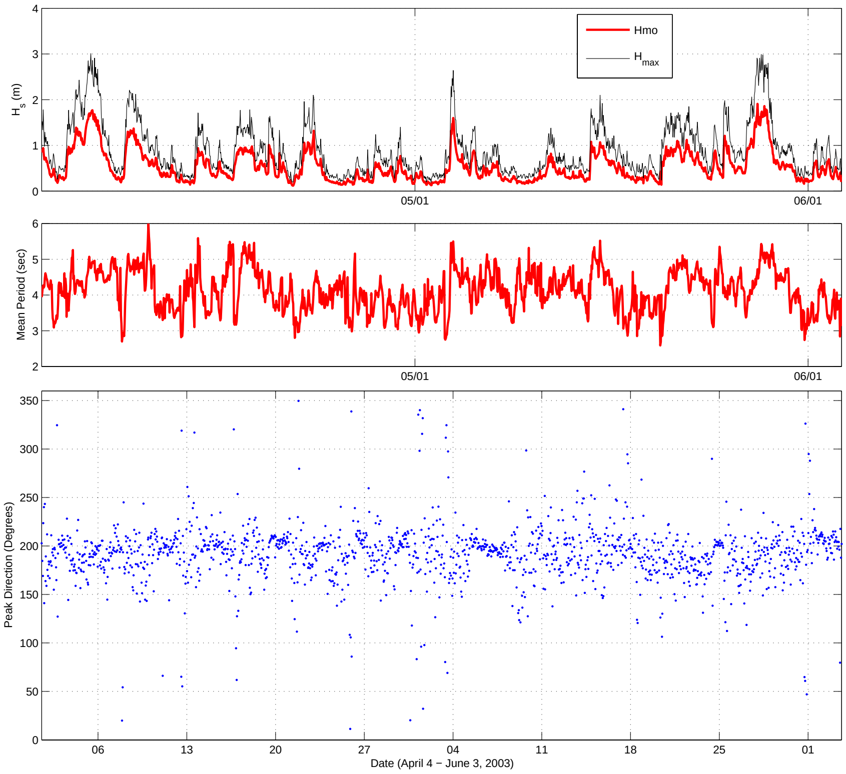

Figure 5 Wave burst estimates for Malaga, Spain: (A) upper plot is Hm0 (thick line) and H_{max} (thin line) (B) the middle plot is the mean period, (C) Example of the Peak direction based upon the first pair of Fourier coefficients, which gives an misleading direction.

Peak Direction Analysis

We look at the peak direction to first evaluate how well we separated the incident and reflected wave events. This is done by dividing the full directional spectra (from the Maximum Entropy Method) into two regions that represent the incident and reflected directions. Next, the mean peak direction is calculated from these two wave events. If the peaks of these two events are correct then the resulting angle should be equal to the directional orientation of the breakwaters.

This is presented in Figure 6; where we see the mean peak direction contained within the directions of the two breakwaters (dashed and solid lines).

There were periods when data appeared noisy, due to either low sea state or times when the incident wave direction was approximately the same direction of the breakwaters. These data are removed (Hm0 < 0.5 meters and incident Peak Dir > 170 degrees) and presented in Figure 7. Following this filter process we were left with 558 useable wave burst measurements. The bisected or mean peak, direction is almost exclusively bound between the angles of the two breakwaters. In fact, the mean bisect angle is 197 degrees with a standard deviation of 5.3 degrees. This is a very encouraging result and suggests the basic peak structure output from the Maximum Entropy method valid for this case of incident and reflected waves.

Reflection Coefficient Analysis

The second evaluation of our technique to separate the incident and reflected waves involved estimating the reflection coefficient, K_R, which provides a measure of the energy distribution in the two regions. The total energy for either the incident or reflected wave field is the sum within a region that is bounded by direction and frequency. The directional bounds are 20 and 200 degrees. The frequency band was between 0.1-0.3Hz.

We expect the incident region will always contain more energy than the reflected region. Therefore, anytime $K_R > 1.0$ (indicating the reflected region contains more estimated energy than the incident) would suggest either the technique is showing signs of error in the solution or there is something unique occurring at the site (such as amplification or focusing of energy).

The reflection coefficient is presented in Figures 6 & 7, and generally yields a value less than 1.0. However, there are exceptions with the unfiltered results that are attributed to a southerly swell. The waves from the south are single peak spectra that have no reflection and thus, the procedure applied will give meaningless results. The filtered results in Figure 7 show a better performance, however there are still occurrences when $K_R>1.0$. It is possible that the AWAC is located such that it receives reflected waves from both breakwaters which would lead to greater reflected energy than incident energy; this would be a region of amplification. It also should not be ruled out that there are inaccuracies with the directional solution (Maximum Entropy for our analysis).

Apart from the occasional overestimates of K_R, we note the mean value and standard deviation for the entire test period is 0.92 and 0.075, respectively. This estimate is quite reasonable; even though we are well aware that K_R is variable and depends on such factors as the incident wave period, height, and direction.

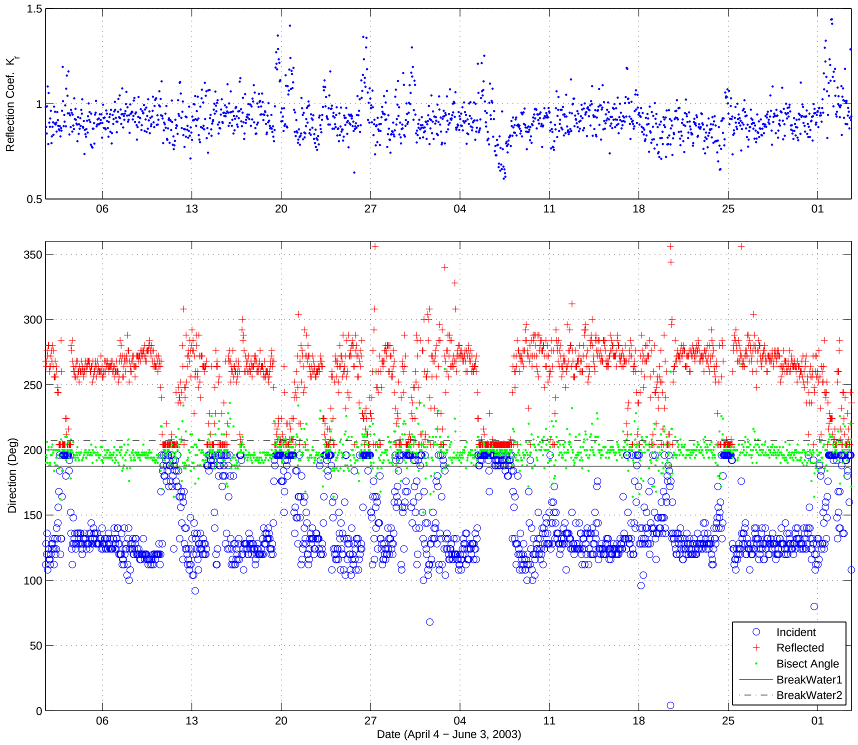

Figure 6 **Wave burst estimates for Malaga, Spain: (A) upper plot is Reflection coefficient, Kr (B) Peak direction for Incident (circles) and Reflected (crosses) waves, as well as the mean angle (dots). The dashed line is breakwater 1 (207 degrees), the solid line is breakwater 2 (187 degrees).**

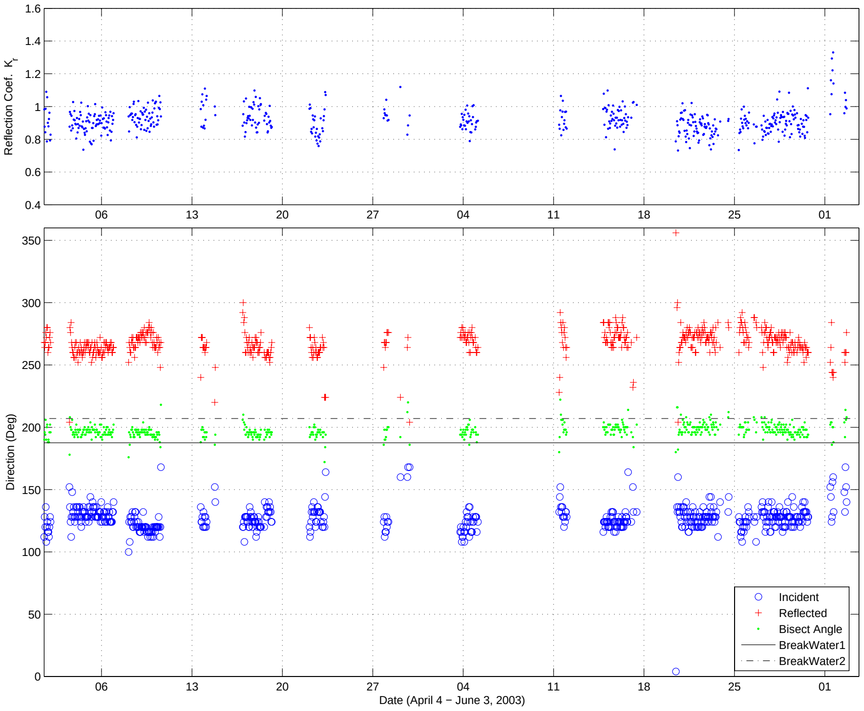

Figure 7 Wave burst estimates for Malaga, Spain: (A) upper plot is Reflection coefficient, Kr (B) Peak direction for Incident (circles) and Reflected (crosses) waves, as well as the mean angle (dots). The dashed line is breakwater 1 (207 degrees), the solid line is breakwater 2 (187 degrees).

CONCLUSIONS

Coastal wave measurements using the AWAC or similar type of bottom mounted instrument requires special attention when processing the results. It is not uncommon for processed wave estimates to be ambiguous when the wave measurement site is exposed to both the incident and transformed wave fields. The most common transformed wave field is a reflected wave.

The standard procedure for calculating wave estimates is to use the energy density spectrum for the non-directional estimates and the Fourier coefficients for the directional estimates. The problem we encounter when there are mixed or combined wave events is the incident wave direction is not correctly estimated. This is seen in the peak direction results of Figure 6&7, where the estimate is calculated from the first pair of Fourier coefficients.

A more accurate representation of the incident wave field may be determined if one uses the portion of the full directional spectrum that applies to the incident wave. This requires some prior knowledge of the site so that boundaries of incident and reflected waves can be established for further post-processing. At this point we make the assumption that the full directional spectra are accurately represented by the solution. For this test we used the Maximum Entropy Method. The accuracy of the wave separation procedure was partially tested by comparing the directional orientation of the breakwater with the mean peak directions of the incident and reflected wave peak directions (within their respective boundaries).

Provided that the separation of the incident and reflected waves is accurate, we have a valuable tool for estimating the reflection coefficient. Typically, this is an estimate that is calculated just on laboratory data (wave tanks) where parameters can be controlled and several wave gauges may be used simultaneously. An in situ estimate is rarely done because it is difficult to control and the measurement procedure is often complex.

Nonetheless, we have presented quite reasonable estimates of the reflection coefficient. Unfortunately, there is no reference data to compare, nor is there an easy way to perform a comparison. The analysis here is more afterthought than an initial intention or planned study. Future tests should consider deploying at a location that has one long, single breakwater as opposed to the complex breakwater found here at Malaga. The verification of the procedure could involve using a wave measuring device further off the coast where there is a more "pure" incident wave field.

The study here has clearly shown that there possibilities for estimating the reflection coefficient in the field. The value for this as an engineering tool is enormous, where structure response could be evaluated and aid in the design and modification of coastal structures. Additionally a structure could be "surveyed" to better understand the structures response and locations of wave attenuation or amplification.

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