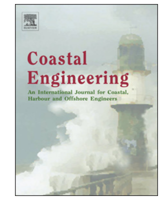
Coastal Engineering 91 (2014) 181–190

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng



Decomposing damped incident and reflected waves using correlation and quasi-linearization methods

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ARTICLE INFO

Article history:
Received 6 January 2014
Received in revised form 24 April 2014
Accepted 28 April 2014
Available online xxxx

Keywords:
Waves
Attenuation
Decomposition
Incident
Reflected
Mud

ABSTRACT

Water waves propagating over a layer of soft mud or submerged aquatic vegetation can drastically attenuate over distances comparable to several wave lengths. The attenuation in the case of mud has been found previously to be reasonably described by an exponential decay. Waves reflect from beaches and any structures that they impact. The reflected waves affect wave heights measured in the field or laboratory wave basins.

Decomposition of small amplitude waves into incident and reflected waves is a linear problem. However, the presence of the exponential damping introduces nonlinearity to the decomposition problem and requires an iterative process for solving the problem. Despite considerable experimental research on attenuation of waves over mud, none of the existing methods for decomposition of incident and reflected waves have accounted for this case.

Here, the Newton Algorithm was used to account for the effect of wave decay over mud by quasi-linearizing the nonlinear equations. Also, a second method using a new error function and a commercial nonlinear solver was proposed in both time and frequency domain. The performance of both methods has been verified using artificial as well as laboratory data.

1. Introduction

Wave heights have been observed to drastically damp over space as they travel over a soft bed (see Gade, 1957; Nagai et al., 1984; Sakakiyama and Bijker, 1989 among many). Similar effect has been observed in the case of waves propagating over submerged or emergent aquatic vegetation, e.g. Asano and Setoguchi (1996); Wayne (1976). Water waves in a laboratory wave basin or in the field reflect from beaches and any coastal structures that they impact. While wave absorbers and mildly-varying beaches have been used to reduce the reflection, its presence affects wave heights measured spatially. Waves at a given location consist of the incident waves and the reflected waves. Depending on wave phases, the local wave height may be large (the sum of the two waves) or small.

The presence of soft mud bottoms, arrays of cylinders, or submerged aquatic vegetation can lead to strong dissipation of the waves, such that the incident waves are spatially diminishing as is the reflected wave train. This complicates the separation of the incident and the reflected waves. Decomposition of the measurements is essential for obtaining the actual value of incident waves as well as determining the reflection coefficient (defined as the ratio of incident amplitude to reflected amplitude) of absorbers. In the case of exponentially attenuating wave heights, obtaining the damping coefficient of the incident waves can be affected by presence of reflected waves (Gade, 1957) noted that reflected waves affected the data noticeably, especially for cases of thicker lower layers. The current practice is to obtain the damping coefficient by fitting an exponentially-decaying model to wave heights measured along the tank without direct quantification of reflection, e.g. Sakakiyama and Bijker (1989); Zhao et al. (2006).

In this section, a brief review of the existing methods for decomposition of incident and reflected waves is given and then, the existing approaches for solving the problem with exponential damping of waves will be reviewed.

1.1. Existing studies

A number of studies have been performed on separation of incident and reflected waves using recorded time histories of water surface displacements in a wave tank by stationary and/or mobile gages. The existing studies can be categorized based on the methods utilized. Table 1 presents information about a few of these studies that mainly used stationary gages.

One of the earliest approaches for decomposing incident and reflected waves from measured time histories is referred to as the 2-point method (uses simultaneous recordings of two stationary wave gages in a reasonable vicinity of each other along the direction of

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http://dx.doi.org/10.1016/j.coastaleng.2014.04.013
0378-3839/

Table 1
Some of the existing studies on decomposition of incident and reflected waves and details of each study.

Method	Investigator(s)	No. of gages	Irregular waves
Energy conservation	Thornton and Calhoun (1972)	2	✓
Energy conservation	Goda and Suzuki (1976)	2	✓
Least squares	Mansard and Funke (1980)	3	✓
Energy conservation	Kimura (1985)	2	✓
Energy conservation	Isaacson (1991)	3	–
Weighted least squares	Zelt and Skjelbreia (1993)	Min. of 2	✓
Digital filtering	Frigaard and Brorsen (1995)	2	✓
Energy conservation	Nallayarasu et al. (1995)	3	–
Digital filtering	Baldock and Simmonds (1999)	2	✓
Transfer function	Zhu (1999)	2	–
Doppler shift	Brossard et al. (2000)	1 or 2	–
Simulated annealing	Medina (2001)	Min. of 2	✓
Energy conservation	Chang and Hsu (2003)	2	–
Least squares	Lin and Huang (2004)	min. of 4	–
Wavelet transform	Ma et al. (2010)	2	✓

wave propagation). This method, hereafter referred to as GS, was proposed by Thornton and Calhoun (1972) and further developed by Morden et al. (1976) and Goda and Suzuki (1976). In this method, which can be used for regular as well as irregular waves, using spectra of two simultaneous wave measurements at adjacent locations and using energy considerations, one can estimate the incident and reflected wave heights. It should be mentioned that in general and in the above method, positioning any pair of gages at a distance equal to an integer multiple of half a wave length leads to collecting redundant information and introducing a singularity to the problem. Therefore, adequate attention must be paid to the application range (defined as all the possible arrangements for the gage locations excluding the ones that result in singularities) of these methods.

Later, a 3-point method (uses simultaneous recordings of three stationary wave gages), originally derived by Marcou (1969), and advanced by Mansard (1976) and Mansard and Funke (1980), hereafter referred to as MF, became very popular and is currently being widely used in coastal laboratories. This method uses the least-squares method to solve for the unknown parameters (incident and reflected amplitudes) by minimizing the error (difference between data and model). This method can be used for both regular and irregular waves as well. MF has a larger application range and is less sensitive to noise compared to GS. In general, using more sensors leads to larger range of application, i.e. more freedom in choosing the spacing arrangement of the sensors. Zelt and Skjelbreia (1993) extended the same idea to an arbitrary number of gages and used the weighted least squares method. They studied the effect of using more than three gages using simulated data and did not observe a noticeable improvement. However, use of more than three gages together with weighted least squares lead to improvement of results.

Isaacson (1991) proposed a 3-point method using 3 wave height recordings without using any phase information. The proposed method was compared with approaches of GS and MF in terms of accuracy and application range using simulated data. MF was found to be the most accurate having the largest application range. All three methods were extended for the case of oblique waves. Later, Nallayarasu et al. (1995) performed experimental investigations to compare the accuracy of the above-mentioned three methods as well as a proposed method. Methods that use phase information in the calculations were found to be of higher accuracy compared to Isaacson (1991) approach. The approach used by Nallayarasu et al. (1995) was found to be in agreement with the method of MF.

Lin and Huang (2004), hereafter referred to as LH, accounted for free and bound waves using a 4-point least-squares method. Lin and Huang (2004) compared LH with GS and MF using simulated data showed that the first harmonics obtained by these methods was exactly the same while the new method can determine higher harmonics as well.

Digital filtering was used by Frigaard and Brorsen (1995) and later by Zhu (1999) for separating incident and reflected waves over a horizontal bed. These methods can work in real time and thus can be used for active wave absorption. Baldock and Simmonds (1999) extended the method of Frigaard and Brorsen (1995) for the case of arbitrary 2D bathymetry. Medina (2001) used a local approximation method together with simulated annealing for solving the decomposition problem. Comparison of his method with the work of Kimura (1985), using simulated and experimental data, demonstrated the robustness of his method. Most recently, Ma et al. (2010) used Morlet wavelet transform to separate incident and reflected waves over constant depth. The method was further extended to the case of sloping bathymetry using linear shoaling theory.

The presence of a mud layer on the bottom affects waves and results in an exponential attenuation of waves as they propagate over a mud layer as incident waves and continue being damped as reflected waves. This behavior changes the decomposition problem into a nonlinear problem that requires an iterative procedure to solve for the incident and reflected waves.

None of the mentioned methods can be readily utilized to find the unknowns (damping and wave amplitudes) for the nonlinear case. To the best of the writers' knowledge, only Shen et al. (2001, 2003) talked about the problem and proposed minimizing the sum of squared error (difference between model and data) at each sensor location but did not provide any further details on the methodology.

Sections 2 and 3 provide details of three methods for solving this nonlinear equation and obtaining the unknowns. Section 2 develops a method using the quasi-linearization method where Section 3 develops the correlation method in time and frequency domains to solve the problem. Section 4 utilizes artificial and experimental data to verify performance of the above three methods.

2. Quasi-linearization method

Here, the method of LH will be extended to the case of exponentially decaying waves. LH used time histories of wave heights recorded by four wave gages located at four different positions along the wave tank. Fig. 1 demonstrates a schematic diagram of the problem. The Linear least-squares method was used to minimize the error term (defined as the difference between the measured time history and predicted time history, see Eq. (5) of LH) with respect to the unknowns. Using four gages lead to equal number of equations and unknowns. Therefore, a linear system of equations was formed that could be readily solved by matrix inversion (see LH for more details). However, minimizing the error term for the case of water waves over mud entails nonlinear equations that cannot be treated using linear least-squares.

In the quasi-linearization algorithm, first the problem is linearized and a system of equations which can be solved using matrix inversion is formed. Next, the solution to the linear problem will be used to reach the solution for the nonlinear problem through iterations. It should be noted that exponential damping of waves will be introduced into the equations of wave propagation through defining a complex wave number, $k = k_r \pm ik_i$ to include damping. The real part of this