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Short communication

Assessment of classical and approximated models estimating regular waves kinematics

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ABSTRACT

The planning and management of many coastal activities require the knowledge of the wave mechanics in a target area. Many theoretical models have been developed to describe the evolution of a regular wave, with different levels of accuracy, but it is hard to evaluate which model is the most suitable one to reproduce a precise marine process.

In this regard, an experimental program, started up at the Technical University of Bari, aims to provide some useful references to practitioners in the field. The present work enriches the existing experimental dataset and analyzes two new experimental regular breaking waves, examined in the shoaling zone. Their cross-shore and vertical velocities have been measured together with their elevations by means of a 2D Laser Doppler Anemometer and a resistive gauge, respectively. Several classical theories and approximate methods have been used to reproduce the waves kinematics, in order to test their validity and applicability. Mainly, the study outlines that i) an increasing error in the reproduction of the wave kinematics is observed while increasing its non linearities; ii) approximate methods tend to better perform in comparison with classical theories, even if in some cases they are more sensitive to the surface boundary conditions.

1. Introduction

The accurate prediction of wave theories for kinematics in deep water has been developed in support of offshore oil and gas developments, while in shallow water has been established in support of coastal engineering. This kind of knowledge and information should be provided even more to consultants and decision makers, because it is necessary in the perspective of the conservation and sustainable use of sea resources. We need only think of potential threats from global warming, which include sea level rise and coastal erosion, generation of electrical power by offshore wind turbines or WEC (i.e. Wave Energy Converter), development of ports, protection of the seashores against the waves by means of breakwaters and possible beach nourishment. In all these processes the role played by wave kinematics is fundamental.

As an example, it is worth to remember that the bed shear stress responsible for putting bottom sediments in suspension is the sum of the bottom stress produced by sea currents (De Serio and Mossa, 2014) and that one generated by wave bottom orbital velocities. Moreover, the impacts that could results from resuspension of bottom sediments are increased turbidity and, for areas of pollutant rich sediments, the potential for pollutants to be mobilized into the water column (De Serio and Mossa, 2015). Turbine support structures are subject to loading by sea waves and the Morison equation, commonly used to predict wave forces on slender structures, predicts the total force as a sum of drag, proportional to the square of the fluid flow velocity, and inertia, proportional to its acceleration. Also the efficiency of breakwaters depends on the interaction between the structure, the wave dynamic features and the seabed.

Therefore, the knowledge of both wave elevation and kinematics is crucial to the understanding and assessment of all these phenomena (Gudmestad, 1993; De Serio and Mossa, 2013). Consequently, a pivotal and continuous challenge for maritime researchers has been to propose analytical or approximate methods able to describe the wave motion field. As stated by Grue et al. (2014) there are gaps in the knowledge regarding the wave-induced kinematics, particularly referring to waves that are strongly affected by breaking, because they exhibit velocity fields that differ from waves that are regular. As a consequence, an experimental investigation of the wave-induced kinematics on finite water depth is strongly desirable. It should be considered that the finite depth affects the initial state of the wave field, developing non linearity and dispersion and making a change of the velocity

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profile below the wave crest, compared to deep water. In fact, near the crest of the wave the velocity increases, and below the mean water line it decreases (Grue et al., 2003).

Wave flow kinematics can be determined from both measurements and calculations. Actually, it is easier to gauge in situ wave elevation rather than wave velocity components, being their acquisition more technically difficult and more expensive, so that they are usually computed. For these reason many methods approximate the kinematics starting from known wave elevation time series or spectra (De Serio and Mossa, 2006a). The principal merit of some of these models is the simplification of the mathematical procedures. In fact, increasing difficulties in calculations do not always guarantee a better simulation of the physical phenomenon, nor more trustworthy results. Moreover, it is difficult to evaluate all the parameters involved in the wave evolution by using only one method with the same level of accuracy (Dean, 1970; Graw, 1994) and to define the ranges in which a method should be applied to obtain better results. Hattori (1986) suggested to compare the maxima and minima theoretical and experimental velocities. While Vis (1980) defined as discriminating criteria a relative error for each velocity spectral frequency component, i.e. the difference between the theoretical and experimental values rated by the latter one.

Beside the aforementioned engineering models, the so called classical theories (Graw, 1994) still hold out, being the principal source of reference for these approximate methods. It is worth noting that the classical theories compute theoretical results for both wave elevation and velocity components, differently from the engineering methods which describe the velocity field once the time history of wave elevations is known.

Obviously, nowadays a broad range of numerical models solving the governing equations of the flow is available, but they often require long computational times and high computational power, discretizing the flow domain in fine meshes, with a grade of detail not always necessary. The principal aim of this study is to provide some references to proper choose among some commonly used wave kinematics models, when dealing with coastal design. Consequently, among all the possible models, we have selected those which could provide results with an acceptable level of accuracy, requiring undemanding computation and thus being of immediate applicability.

The present research is part of an ongoing experimental program, started up at the Department of Civil, Environmental, Building Engineering and Chemistry (DICATECh) of the Technical University of Bari. De Serio and Mossa (2006a) reviewed some engineering models adopted for estimating wave orbital velocities, referring to different sets of waves propagating in a wave channel. By comparing calculated and measured velocity amplitude spectra, they deduced that generally the predicted cross shore velocities are more accurate than the vertical ones. They also derived that the best fitting method is strictly connected to wave non linearities, so that it is difficult to reproduce the wave kinematics in both deep waters, shoaling region and surf zone with the same model and with the same level of accuracy. In order to extend their convincement, in the present paper two new regular wave trains have been examined. Moreover, in addition to previously investigated kinematics models, five new ones have been examined here, focusing on deep waters and shoaling region. In summary, three classical solutions have been considered, i.e. the Stokes 2nd and 3rd order theories and the Fenton (1985) solution of the Stokes 5th order theory for steady waves, extensively validated both mathematically and experimentally (Kriebel et al., 1999; Sobey et al., 1987; Gudmestad, 1993). As approximate models, the Koyama and Iwata models (Koyama and Iwata, 1986) for both linear and non linear waves have been tested, as well as the Wheeler stretching method (Wheeler, 1970) together with its 2nd order approximation (Gudmestad and Connor, 1986) and the Chakrabarti's 1st and 2nd order approximation approach (Chakrabarti, 1970; Gudmestad and Connor, 1986). Also the linear method in frequency domain, following the Woltering and Daemrich (1995) procedure, has been applied. In this way a direct comparison of engineering and classical theories reliability can be displayed. It is worth to note that sea waves are not regular, but random in form and propagation. In any way, they can be considered as composed by superposing waves with different amplitudes and phases. Consequently, the study of regular wave models is still reliable, being a guidance to successive refined attempts of modeling irregular waves.

The paper is structured in the following way: in the first section, the investigated basic theories and approximations are illustrated. Successively the experimental apparatus and the measurement procedures are described. In the second section, the results of the models and the experimental data are analyzed, by means of velocity amplitude spectra. Finally, a relative error is calculated and discussed in order to estimate the best matching between measurements and velocities reproduced by the adopted models.

2. Methods

As previously written, it is difficult to select the best theory fitting the wave experimental data, with the same accuracy and referring to all the parameters involved in wave kinematics (Dean, 1970). In the examined case, as an example, according to the classic Le Méhauté's diagram (Yuan et al., 2007) in the sections of the wave channel in deep waters the first tested wave could be well described by Stokes 2nd order theory, whilst the second one by Stokes 3rd order theory. Approaching breaking, they both fall in the region of Stokes 3rd order theory. On the contrary Iwagaki abacus (Sawaragi, 1995) suggests the use of Stokes 3rd order theory for both waves in deep waters. Therefore, it is important to distinguish the regions of applicability of the wave theories and to describe their principal advantages and limitations.

2.1. Theoretical background

Firstly, we consider the small amplitude wave theory, which solves the 2D regular wave kinematics by taking the wave height much smaller than the wave length and the still water depth. As a principal consequence it enables to linearize the non linear terms of the boundary condition and to apply the boundary condition at the still water level. Starting from the linear wave theory, which seeks a linear solution to the Laplace equation and to the kinematic and dynamic boundary conditions for the velocity potential of a 2D regular wave, new solutions have been developed.

The perturbation method with successive approximations by Stokes assumes that the solution is represented by the Fourier series whose coefficients can be written as perturbation expansions with parameter ka, being k the wave number and a the amplitude of the wave at lowest order. The terms in the perturbation expansion can be found by satisfying boundary conditions on the free surface, and solving the resulting set of equations. Theoretically, the expansion of the series can be done infinitely far. On the contrary, the Airy wave theory is the lowest order approximation.

This Stokes' wave expansion method is formally valid under the condition $H/h << (kh)^2$ and $H/L << 1$, being H and L respectively the wave height and length and h the local water depth. Consequently, the range of applicability is conditioned by a severe wave height restriction, in particular in shallow waters, where different procedures should be used (Gudmestad, 1993). For example, the