Coastal Engineering 57 (2010) 471–492

Contents lists available at ScienceDirect

Coastal Engineering

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

Numerical implementation and sensitivity analysis of a wave energy converter in a time-dependent mild-slope equation model

Charlotte Beels [a], Peter Troch [a,*], Griet De Backer [a], Marc Vantorre [b], Julien De Rouck [a]

[a] Ghent University, Department of Civil Engineering, Technologiepark 904, B-9052 Zwijnaarde, Belgium
[b] Ghent University, Maritime Technology Division, Technologiepark 904, B-9052 Zwijnaarde, Belgium

ARTICLE INFO

Article history:
Received 17 July 2008
Received in revised form 2 November 2009
Accepted 16 November 2009
Available online 2 March 2010

Keywords:
Numerical model
Mild-slope equations
Wave energy
Wake
Farm

ABSTRACT

Several Wave Energy Converters (abbreviated as WECs) have intensively been studied and developed during the last decade and currently small farms of WECs are getting installed. WECs in a farm are partly absorbing, partly redistributing the incident wave power. Consequently, the power absorption of each individual WEC in a farm is affected by its neighbouring WECs. The knowledge of the wave climate around the WEC is needed to predict its performance in the farm. In this paper a technique is developed to implement a single and multiple WECs based on the overtopping principle in a time-dependent mild-slope equation model. So far, the mild-slope equations have been widely used to study wave transformations around coastal and offshore structures, such as breakwaters, piles of windmills and offshore platforms. First the limitations of the WEC implementation are discussed through a sensitivity analysis. Next the developed approach is applied to study the wave height reduction behind a single WEC and a farm. The wake behind an isolated WEC is investigated for uni- and multidirectional waves; it is observed that an increase of the directional spread leads to a faster wave redistribution behind the WEC. Further the wake in the lee of multiple WECs is calculated for two different farm lay-outs, i.e. an aligned grid and a staggered grid, by adapting the performance of each WEC to its incident wave power. The evolved technique is a fast tool to find the optimal lay-out of WECs in a farm and to study the possible influence on surrounding activities in the sea.

1. Introduction

The need for renewable energy is rising at light-speed. The increasing energy demand, the greenhouse effect, the shrinking reserves of fossil fuels and consequently the increasing cost of electricity generation, have resulted in an accelerated development of renewable energy supplies, a.o. wave energy. Many concepts for wave power conversion, with an installed capacity from a few kilowatts up to more than 1 MW, have been invented. To extract a substantial amount of wave power, Wave Energy Converters (abbreviated as WECs) are arranged in several rows or in a 'farm'. WECs in a farm are interacting and the overall power absorption is affected. The incident waves are partly reflected, transmitted and absorbed by a WEC. Consequently the incident wave power is partly absorbed and partly redistributed around the WEC which has a positive or negative effect on the power absorption of the neighbouring WECs in the farm. Finally the wave height behind a large farm of WECs is reduced and this reduction may possibly influence other users in the sea.

WECs can be divided into two major categories: (i) devices based on the oscillation principle, where a body or water column is oscillating and (ii) devices based on the overtopping principle, where waves are overtopping in a basin at a higher level than the surrounding sea. The first category comprises different types of floating or submerged bodies and oscillating water columns, while the second category consists of fixed or slack moored overtopping devices. Oscillating systems absorb power by simultaneously generating a wave (Falnes and Budal, 1978). The incident wave is partly diffracted (also called scattered) and partly absorbed due to the destructive interference with the generated (also called radiated) wave. Furthermore the performance of neighbouring devices in a farm is influenced by the scattered incident wave and radiated wave from the oscillating device and vice versa. On the other hand WECs based on the overtopping principle absorb power by capturing the water volume of overtopped waves in a basin and creating a hydraulic head. Consequently a wake is created behind the WEC which affects the performance of WECs installed in that wake. The redistribution of wave power in the farm is different for both categories, as each category has its own specific way of absorbing power. This study comprises WECs based on the overtopping principle.

A lot of research has been carried out on the hydrodynamic behaviour of WECs based on the oscillation principle in an array. The hydrodynamic problem of power absorption is usually studied as a

* Corresponding author. Tel: +32 9 264 54 89; fax: +32 9 264 58 37.
E-mail addresses: charlotte.beels@ugent.be (C. Beels), peter.troch@ugent.be (P. Troch), griet.debacker@ugent.be (G. De Backer), marc.vantorre@ugent.be (M. Vantorre), julien.derouck@ugent.be (J. De Rouck).

0378-3839/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.coastaleng.2009.11.003

combination of two simpler problems: the diffraction problem (scattered incident wave field due to the presence of the WEC) and the radiation problem (wave field generated by the body or water column oscillations). An overview of theoretical methods used to calculate the hydrodynamic interactions of oscillating bodies in arrays is given in Mavrakos and McIver (1997): (i) the plane wave approximation where all scattered and radiated waves are approximated as plane waves under the assumption that the device spacing is many wave lengths (Simon, 1982; McIver, 1984, 1994), (ii) the point-absorber method where the scattered waves are neglected under the assumption that the device dimension is much smaller than the wave length (Budal, 1977; Evans, 1980; Falnes, 1980) and (iii) the multiple scattering method which accounts accurately for all hydrodynamic interactions (Mavrakos, 1991; Mavrakos and Koumoutsakos, 1987; Mavrakos and Kalofonos, 1997). A theoretical study concerning an infinite periodic array of identical oscillating water columns can be found in Falcão (2002). Recently, with the improvement of computer technology, Boundary Element Methods based on potential flow (e.g. WAMIT) have intensively been used to study the hydrodynamic interaction of multiple oscillating bodies in an array (a.o. Justino and Clément, 2003; Ricci et al., 2007; De Backer et al., 2009). Still the required simulation time is increasing rapidly with the number of bodies considered in the arrays and the dimensions of the domain.

The before mentioned studies all concentrate on maximising the absorbed power of an array of oscillating bodies or oscillating water columns while the knowledge of the wake of a single WEC and the wave height reduction in the lee of a farm is as important in the design of a farm of WECs as a change in wave height behind a large farm can affect other activities in the oceans. The study of the latter aspects requires a large computational domain which makes the discussed Boundary Element Methods less convenient. Recently the coastal impact of a farm of WECs has been studied in numerical wave propagation models. Millar et al. (2006) have used the spectral wave propagation model, SWAN (Booij et al., 2004), to study the change of the wave climate caused by the installation of a farm of WECs 20 km off the north coast of Cornwall, UK. In Venugopal and Smith (2007) an array of five bottom mounted, fixed WECs have been modelled in a nonlinear Boussinesq wave model (MIKE 21). In the latter models the WEC is simplified as a porous structure which is able to extract a predefined amount of wave power. This way the incoming waves are partly reflected, transmitted and absorbed by the WEC. This simplification is only applicable to the second category of WECs, i.e. WECs based on the overtopping principle, as absorption of power is not caused by generation of waves.

In this paper a new technique to implement the combined effects of reflection, transmission and consequently absorption of a WEC is developed in a linear mild-slope model, MILDwave, based on the equations of Radder and Dingemans (1985). According to the authors knowledge it is the first time that a mild-slope equation model is used to study the wake effect of a single WEC and a farm of WECs. In a subsequent paper (Beels et al., in press) the evolved technique is applied to the wave energy converter Wave Dragon.

In the next section the use of various wave propagation models for farm modelling is discussed. A short description of the mild-slope wave propagation model MILDwave is given in Section 3. The mild-slope equations of Radder and Dingemans (1985), the generation of uni- and multidirectional waves and the finite difference scheme to solve these mild-slope equations are briefly described. Section 4 gives a detailed overview of the implementation of wave power absorption in MILDwave. Through a sensitivity analysis the limitations of the modelling approach are studied. Section 5 deals with the reduction of the wave height in the lee of a single hypothetical WEC of the overtopping type. The shadow zone behind this WEC is discussed in detail for sea states with increasing directional spread. The model's ability to simulate a farm of WECs based on the overtopping principle is discussed in Section 6.

2. Discussion on applicability of wave propagation models for farm modelling

Wave propagation models are usually classified in two types, i.e. phase-averaged spectral models and phase-resolving time domain models. Spectral models describe the evolution of the wave energy spectrum (wave action equation) while time domain models calculate the sea surface as a function of time (conservation of mass and momentum equations).

Spectral models (e.g. SWAN) take into account all relevant wave generation and dissipation processes over large spatial domains. A phase-decoupled refraction-diffraction approximation has been implemented (Holthuijsen et al., 2003) in SWAN to account for diffraction, as the wave action equation is based on refraction principles only. In Ilic et al. (2007) the wave diffraction feature in SWAN has been studied using laboratory and field data. They observed a more accurate estimation of the wave heights in the lee of the obstacle with increasing frequency and directional spread. On the other hand in Enet et al. (2006) results in SWAN have been compared with analytical results for the wave height and wave direction in the lee of a semi-infinite breakwater in water of constant depth. They concluded that the results with diffraction feature in SWAN were considerably better than the results without diffraction for a decreasing directional spread.

Millar et al. (2006) have used the phase-averaged model SWAN to implement an array of WECs as a 4 km long partially transmitting obstacle, with energy transmission of respectively 0%, 40%, 70% and 90% of the incident wave energy. The significant wave height H_s and mean wave period T_m in the lee of the obstacle have been calculated on a grid with 200 m spatial resolution for a number of reference sea states (for varying H_s, T_m and mean wave direction). Millar et al. (2006) found that the magnitude of wave height change was varying with reference sea state, level of energy transmission and location. For the most realistic wave energy transmission levels, ranging from 70% to 90% of the incident wave energy, the resulting significant wave height decrease at the shoreline, relative to the shoreline wave height when no obstacle is installed, is rather small. The average significant wave height change decreases from respectively 1.5% to 0.5%, while the maximum significant wave height change is respectively 6.7% and 2.3%. When swell waves are dominating (limited directional spread) an increased wave height change is expected, since wind waves with a directional spread of 30° have been considered in the latter study.

In Smith et al. (2007), the previous study of Millar et al. (2006) has been extended and generalised. A grid of 210 km by 400 km with a resolution of 500 m has been considered to study the wave height change over 200 km along the central axis behind the partially transmitting obstacle. Various parameters that impact on the onshore wave climate have been studied: the length of the obstacle perpendicular to the incoming wave (3 km to 15 km), the distance of the obstacle from the shoreline, the level of wave energy transmission through the obstacle (0% to 90% of the incident wave energy) and the directional distribution of the local wave climate (10° to 30°). Smith et al. (2007) observed an increasing wave height reduction in the lee of the obstacle with decreasing directional spread. Farms of WECs are not likely to be installed 210 km off the coast, as the cost of a farm is increasing with increasing distance from shore. Therefore a smaller domain can be considered when studying a farm of WECs.

The spectral model SWAN has some restrictions which need to be considered. First, when swell waves are dominating the impact on the coastal wave climate is the highest. In that case the performance of the diffraction feature in SWAN is less accurate (Ilic et al., 2007). Secondly, the dimensions of the obstacle are limited by the spatial grid resolution (500 m in Smith et al., 2007). The recommended values for spatial resolution in SWAN are 50 m up till 1000 m (Booij et al., 2004). To overcome the latter restrictions time domain models have been used.