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Innovative rubble mound breakwaters for overtopping wave energy conversion

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ABSTRACT

This paper intends contributing to the development of an economically and environmentally sustainable coastal infrastructure, which combines rubble mound breakwaters with Wave Energy Converters (WEC). The energy is produced by collecting wave overtopping in a front reservoir, which is returned to the sea through turbines. Wave loadings and average wave overtopping rate at the rear side of the rubble mound breakwater and in the front reservoir are discussed on the basis of physical 2-D model tests carried out at Aalborg University (DK). The experiments have been analyzed and compared with results from model tests and wave load design formulae by Nørgaard et al. (2013) for traditional rubble mound crown walls. The existing prediction methods seem unable to predict the hydraulic performances and loadings on the front reservoir and thus new prediction formulae are proposed based on the new experiments. The formulae are provided with the aim to be of direct use to engineers in the preliminary design of a first prototype of combined breakwater and wave energy converter.

1. Introduction

Global energy demand is expected to increase around 35% from 2010 to 2040. Therefore, a diverse, reliable and affordable energy sources will be needed to provide the demand that enables economic growth and societal advancements.

Oil will remain the largest single source of energy to 2040 (Exxonmobil, 2012). The discussion on alternative source of energy in Europe started during the oil crisis of the 1970s and it was involving the competition for founding between nuclear energy and renewable energy ending up giving more trust to the investment in nuclear energy. Nowadays the nuclear risks of disaster and waste management are bringing back interests to many sources of renewable energy including wave energy. However, since wave energy is not going to be economically competitive, it will be very difficult to become a possible contender in the energy market. One of the recent problems that give more strength to the wave energy is the fact that the oil prices are currently strongly affected by political instability rather than by production issues. Moreover, oil prices are forecasted to continue to increase in price for the foreseeable future. These price fluctuations may provide an essential driver for investments in renewable and thus also wave energy technologies. Countries that have limited fossil fuel reserves and large wave energy capacity are the optimum countries on which to focus investment (AEA, 2006).

Wave power along the European west coast has been estimated to be able to cover all of the Western European electric energy consumption (Brooke, 2003; Clement et al., 2002; Falnes, 2002). Recently, there have even been estimations on wave energy conversion also in milder climate sea areas like Baltic Sea, Danish part of the North Sea and Mediterranean Sea indicating an even greater worldwide availability for wave power (Bernhoff et al., 2003; Henfridsson et al., 2007; Martinelli, 2011; Vicinanza et al., 2011a, 2013a).

Wave Energy Converters (WECs) are currently under development and still in an immature phase. The number of concepts is very large. Over 1000 WECs are patented worldwide (Falcão, 2010). In this frame WECs will become more economically competitive with conventional fossil fuels and other renewable energy devices essentially answering the following two requests from the market:

- How reliable is the specific WEC technology?
- How much is the profit (costs vs payback analysis)?

There is a considerable case history and experience on the use of specific devices, and consequentially a large amount of reliable data is available. WECs have not been helped by the fact that some wave energy prototype generators were destroyed in storms (Falcão, 2010). Technology has to establish reliable confidence levels that will attract investors, partners and utility providers. Most of the various ocean

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Nomenclature

b [−] empirical constant in reflection formula;
B [m] berm width;
B_r [m] reservoir width;
B_s [m] emerged sloping plate width;
D_{n50} [m] equivalent cube side length exceeded by 50% of the stones;
d_w [m] height of sloping plate;
$d_{w,low}$ [m] height of sloping plate in the low configuration;
$d_{w,high}$ [m] height of sloping plate in the high configuration;
f [s^{-1}] frequency;
f_p [s^{-1}] peak frequency;
$F_{H,Nørgaard}$ [kN] calculated by Nørgaard et al. (2013) formula;
$F_{H,meas}$ [kN] measured horizontal force;
$F_{H,Ucw}$ [kN] horizontal force on OBREC upper crown wall;
$F_{H,Lcw}$ [kN] horizontal forces on OBREC lower crown wall;
g [m/s^2] gravity acceleration;
h [m] water depth at the toe of the structure;
H_{m0} [m] incident significant wave height in the frequency domain at the toe of the structure;
$H_{m0,r}$ [m] reflected significant wave height in the frequency domain at the toe of the structure;
$k_{m\text{-}1,0}$ [−] wave number referenced to $L_{m\text{-}1,0}$;
K_r [−] $H_{m0,r}/H_{m0}$ = reflection coefficient;
$L_{m\text{-}1,0}$ [m] deep water wave length referenced to $T_{m\text{-}1,0}$;
M [kN] Moment Flux;
m_0 [m^2] zero order moment of wave power spectrum;
m_{-1} [m^2 s]
first negative moment of the incident wave spectrum;
q [l/m/s] average overtopping rate;
q_{rear} [l/m/s] average overtopping discharge rear the traditional rubble mound breakwater crown wall or rear OBREC crown wall;
q^*_{rear} [−] non-dimensional overtopping discharge rear the traditional rubble mound breakwater crown wall or rear OBREC crown wall;
$q_{reservoir}$ [l/s/m] average overtopping discharge in the reservoir;
$q^*_{reservoir}$ [−] non-dimensional overtopping discharge in the reservoir;
R [−] correlation coefficient;
R_c [m] crest freeboard of crown wall; i.e. the vertical distance between the crest of the vertical wall and the still water level;
R_r [m] crest freeboard of front reservoir; i.e. the vertical distance between the crest of the sloping plate and the still water level;
R_c^* [−] R_c / H_{m0} = relative crest freeboard of crown wall;
R_r^* [−] R_r / H_{m0} = relative crest freeboard of front reservoir;
$R_{ui\%}$ [m] run-up level exceeded by i per cent of the incoming waves;
$s_{0m\text{-}1,0}$ [−] $2\pi H_{m0} / g T^2_{m\text{-}1,0}$ = wave steepness using deep water formula;
s_p [−] wave steepness using peak incident deep water wave period;
s_{Rr}^*[−] non-dimensional wave–structure steepness;
T_m [s] mean wave period;
$T_{m\text{-}1,0}$ [s] m_{-1} / m_0 = spectral incident energy wave period at the toe of the structure;
T_p [s] $1 / f_p$ = peak incident wave period;
α [deg] slope angle of the structure;
γ [−] peak-enhancement factor;
γ_f [−] reduction factor for slope roughness;
γ_β [−] reduction factor for oblique wave attack;
γ_b [−] reduction factor for berm;
γ_{runup} [−] proposed runup modification factor;
$\gamma_{falling}$ [−] proposed free-falling parameter modification factor;
Δq^*_{rear} [%] overtopping discharge variation with respect to traditional breakwater;
Δ_{Rc} [m] $R_c - d_w$;
μ [−] mean;
$\xi_{m\text{-}1,0}$ [−] $\tan\alpha / (s_{m\text{-}1,0})^{0.5}$ = breaker parameter using $T_{m\text{-}1,0}$;
ξ_{op} [−] $\tan\alpha / (s_p)^{0.5}$ = breaker parameter using T_p;
ξ_m [−] breaker parameter using T_m;
ρ [kg/m^3] water density;
σ [−] standard deviation.

energy conversion systems are still in pre-commercial phase (Güney and Kaygusuz, 2010) but several have demonstrated to be a proven technology and are moving toward full scale prototype sea trials.

WEC costs are currently too high compared to other renewable energy technologies. An effort is needed to reduce significantly the manufacturing, constructing and installation costs as well as improve the technology (Waveplam project, 2010). One solution to reduce the device costs is to move from standalone device to hybrid systems embedded in other costal or offshore structure (offshore wind farms, offshore oil platforms, ports, costal defenses). An example of integration is a floating power plant called Poseidon which consists of offshore wind turbines that are mounted on a wave energy plant sharing common components, such as power connection and anchor system (Kallesøe et al., 2009).

Integration and sharing costs could become a solution for WECs to be competitive with other renewable energy devices.

Coastal engineers design breakwaters generally with the aim to "dissipate incoming wave energy" mainly by wave breaking and porous flow in the mound and/or partly reflecting wave back to the sea and transmission into harbor due to penetration and overtopping. Modern coastal engineers should start to move from this traditional design approach to a new concept of "capturing the wave energy". Under this vision the research reported in this paper has as principal aim to give information on an innovative coastal structure designed in terms of safe hydraulic performance and global stability but able to produce electricity in a balanced cost–benefit frame.

Moving from previous work on WECs overtopping devices like Wave Dragon (Kofoed et al., 2006), WaveCat (Fernandez et al., 2012), and in particular, Sea-wave Slot-cone Generator (Vicinanza and Frigaard, 2008; Vicinanza et al., 2011b, 2012a), a new WEC named Overtopping BReakwater for Energy Conversion (OBREC) is under development. The device consists of a rubble mound breakwater with a front reservoir designed with the aim of capturing the wave overtopping in order to produce electricity. The energy is extracted via low head turbines, using the difference in water levels between the reservoir and the mean sea water level.

The new design should be capable of adding a revenue generation function to a breakwater while adding cost sharing benefits due to integration. The design can be applied in harbor expansions, existing breakwater maintenance or upgrades due to climate change for a relatively low cost considering the breakwater would be built regardless of the inclusion of a WEC.

Physical model tests on OBREC have been carried out at Aalborg University (Denmark) in 2012. A few preliminary results on hydraulic performances and loadings have already been presented (Vicinanza et al., 2012b, 2013b). This paper provides a detailed analysis.

This paper is organized as follows: After a description of the experiments, a comparison between hydraulic performance and wave loading acting on a traditional rubble mound breakwater versus OBREC is