Optimal Design of Overtopping Breakwater for Energy Conversion (OBREC) Systems using Python

1 Introduction

The effects of climate change are becoming more and more evident in the last years. As a result, organized efforts to combat the phenomenon are increasing. The EU has set itself some major targets for this ambition that should have been achieved by 2020, such as reducing greenhouse gas emissions by at least 20 %, increasing the share of renewable energies to 20 %, increasing energy efficiency by 20 % and investing 3% of gross domestic product in research and development.
In the recent decades, the global scientific community has shown a great interest in the generation of electricity from waves.According to the International Energy Agency, wave energy is estimated to be sufficient to cover 10% of the planet's electricity needs. Obrec device is used to produce electricity at the shoreline. This device type is easily accessible and not expensive in the construction of it. On the other hand,the produced energy is less, since the directional spreading of the wave climate is restricted nearshore and also phenomena as wave breaking, refraction, diffraction and shoaling alter the energetic wave content. The main objective is to find a device with high energy efficiency and environmentally sustainable operation.
The methology that is followed to achieve this, aims to identify the optimal combination of crest height and hydraulic height of water above water turbine of Obrec reservoir,in order to maximize its performance.To achieve this is used combined application of wave propagation equations that simulate the compound wave field near coastal structures with an optimization algorithm, that takes under consideration every possible scenario and identify the optimal dimensions of Obrec Reservoir.If some parametres of this algorithm change, it can be used in every port.In order to demonstrate the effectiveness of the methodology, the port of Foiniki in the island of Karpathos in Greece, is used as a case study.

2 Geometric features of an Obrec device

An OBREC device consists of a concrete top element, which can be installed in new or existing breakwater. It is provided with a sloping plate that conveys the overtopping waves inside a reservoir, which later flow in the rear chamber, where the turbine should be installed. The front reservoir captures the overtopping waves to produce electricity.An illustration of the device is presented in Figure 1.

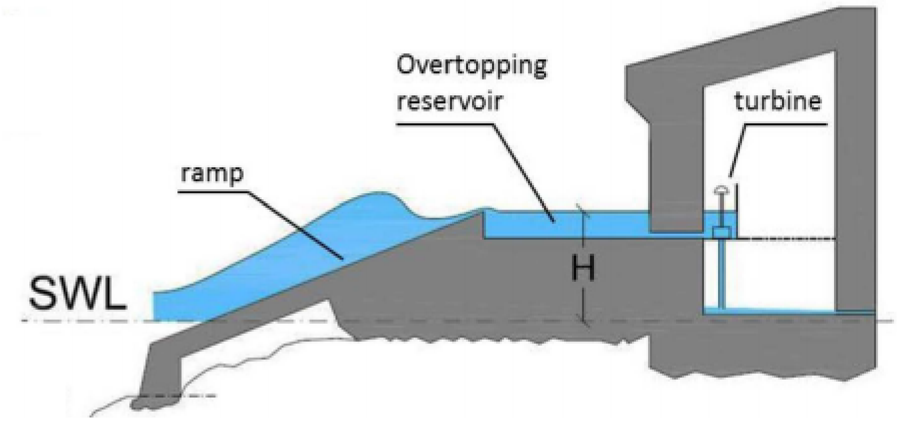

Figure 1: Obrec illustration (source: luppa et al.2016)

In a wave energy converter the aim is to calculate the crest freeboard Rc, that describes the height between the upper point of the sloping plate of the front reservoir and MSL, the average wave overtopping rate q and the output energy. A variety of mathematical models have been developed which are applied in coastal protection works and in the installation of wave energy converters. Based on Owen's model the wave overtopping rate is calculated by the following equation:

$$\frac{q}{Tm * Hs * g} = A * \exp\left(-B\frac{Rc}{Tm * \sqrt{g * Hs}}\right)$$

where: q defines the mean wave overtopping inflow (m3/s/m), Hs defines the incident wave height (m), Rc defines the crest level (m) and parameters A and B are best-fit coefficients determined from the experimental data.
Hedges and Reis reanalyzed the data Owen used and they proposed a new model.The equation that is created by Hedges and Reis is been written as:

$$\frac{q}{\sqrt{g * R\max^{s}}} = A\left(1 - \frac{Rc}{Rmax}\right)^{B} \qquad \text{for } 0 \leq \frac{Rc}{R\max} \leq 1$$

$$= 0 \qquad \text{for } \frac{Rc}{R\max} \geq 1$$

where: q defines the mean wave overtopping inflow (m3/s/m), Rc defines the crest level (m), parameters A and B are best-fit coefficients determined from the experimental data and Rmax the maximum wave run - up (m).
In 1994 Van der Mer proposed a different formula to find the overtopping inflow.This wave- overtopping formula is presented below:

$$\frac{q}{\sqrt{g * Hs^{3}}} = \frac{An}{\sqrt{\tan a}}\gamma b * \xi o\rho * \exp\left(-Br\frac{Rc}{Hs} * \frac{1}{\xi o\rho * \gamma b * \gamma f * \gamma\beta * \gamma r}\right)$$

and has a maximum value of:

$$\frac{q}{\sqrt{g * H^{3}}} = 0.2 * \exp\left(-2.3\frac{Rc}{Hs} * \frac{1}{\gamma f * \gamma\beta}\right)$$

where: a is a slope angle, is a breaker parameter based on the spectral period, reduction factors $\gamma b, \gamma f, \gamma\beta, \gamma r$ include effects of a berm,surface roughness, oblique wave attack, and a vertical wall on top of the slope, respectively. The coefficients n and Br have been taken there values from the average values of all test data. This values are for An= 0.06 and for Br = 5.2.
In 2002 Kofoed proposed his formula to find the wave overtopping discharge and used the results of Van der Meer for comparison.The equation he concluded is presented below:

$$\frac{q}{\lambda\alpha * \lambda dr * \lambda s * \lambda m} = 0.2 * \exp\left(-2.6\frac{Rc}{Hs} * \frac{1}{\gamma b * \gamma f * \gamma\beta * \gamma r}\right)$$

where $\lambda a = \cos\left(as - 30°\right)^3$ accounting for the effect of using a slope angle different from 30, dr accounting for the reduction in overtopping rates due to ramp not extending all the way to the seabed and $\lambda s = (0.4\sin(2\pi/3R) + 0.6, R < 0.75 \mid 1, R \geq 0.75$, accounting for low relative crest freeboards. The reduction factors are the same in Kofoed model as it is in Van der Meer model.
In the following table are presented all the equations that are used in order to export the geometrical features of the device as well as to export the output power. In Table Hk defines the hydraulic height of water above water turbine(m).

Calculation of geometric features	
Power obtained	$Phydro = \rho \cdot g \cdot Rc$
Power that is passing through a vertical cross section of the water column	$Pwave = \frac{g^2}{64\pi}H^2 \cdot TP$
Hydraulic efficiency	$nhydraulic = \frac{Phydro}{Pwave}$
Output energy	$Pk, el = nhydralic \cdot \rho \cdot g \cdot qk, s \cdot Hk$

Table 1: Calculation of geometric features

3 Case-study Area: The port of Foiniki,Karpathos

Karpathos is the second largest island of the Dodecanese after Rhodes. It is located in the middle of the Carpathian Sea between Rhodes and Crete. Its area, along with the surrounding islets, is 324.7 square kilometers. According to the 2011 census, the island's total population is 6226 people with 2788 of them located in the island's capital, Pigadia while the rest of the inhabitants are scattered around the island.
According to the Regulatory Authority for Energy, Karpathos is one of the islands with the highest wind potential in Greece and this was the main reason that the specific island has been selected as a study area.In the table below are presented the frequency of each wind operating in the selected port as well as the effective fetch prices for the port(**Table 2** and **Table 3**)

Wind power(BF)	N	NE	E	SE	S	SW	W	NW	Calm	Summary
0									4.704	4.704
1	0.143	3.697	0.121	0.869	0.814	1.793	0.385	1.551		9.373
2	0.825	7.008	0.286	2.410	1.804	4.753	1.826	7.614		26.526
3	1.551	4.698	0.187	2.057	1.144	3.488	1.848	11.761		26.734
4	2.101	2.993	0.110	1.331	0.462	1.870	0.990	9.154		19.011
5	1.793	1.584	0.020	0.627	0.154	0.847	0.363	3.829		9.296
6	1.353	0.660	0.011	0.165	0.055	0.330	0.066	0.847		3.487
7	0.418	0.132	0.001	0.033	0.011	0.033	0.011	0.077		0.726
8	0.099	0.011	0.000	0.011	0.011	0.000	0.000	0.000		0.132
9	0.000	0.000	0.000	0.011	0.000	0.000	0.000	0.000		0.011
10	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000
11	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000
Summary	8.283	20.783	0.825	7.514	4.455	13.144	5.489	34.833	4.704	100.000

Table 2: Wind Power(BF)

Feff W	246.40
Feff SW	84.22
Feff NW	187.52

Table 3: Effective Fetch(km)

4 Optimization Model

The purpose of this study is to find the dimensions of Obrec device that maximize the produced energy as well as to find the energy that is produced for all the different dimensions of an Obrec device.To achieve this is developed a model that takes into account the environmental conditions (effective fetch and wind frequence) and the water column inside the pipe above water turbine (Hs) as input parameters.The hydrodynamic problem is solved using an analytic model developed in Python. The optimization model provide results for four different wave overtopping discharge models that have been presented above (Owen model, Hedges and Reis model , Kofoed model and Van der Meer model).
The program has been executed for all the the possible values of hydraulic height of water above water turbine, emerging different size scenarios of the OBREC device. Each scenario presents the geometric shape of the reservoir that maximizes the power of the turbine and the power that is produced for every different value of crest freeboard. To find all the different scenarios for the hydraulic height of water above water turbine two constraints have been used. The first one is that the height of crest freeboard must be bigger than the hydraulic height of the water above the water turbine($Rc > hk$) and the second one is that hk must be bigger than zero($hk > 0$).Using this two parameters and changing the value of the water column in the reservoir in range from 0m to 3.5m with a step of 0.05m all the different size scenarios are tested.
The program is executed for all the prevailing wave conditions in the area of study, emerging different size scenarios of the OBREC device. Each scenario

presents the geometric shape of the reservoir that maximizes the power of the turbine, for the steady wave condition that has been introduced as input to the program and finally the scenario that maximize the produced energy is chosen.

5 Different scenarios and optimal solution

The behavior of OBREC reservoir must be tested for all the different scenarios. It is observed that the choice of different bottom height affects the final choice of crest freeboard. In particular, the closer the bottom height is selected to the mean sea level, the pressure head increase and the final crest freeboard decrease. Also, for lower bottom height of the reservoir, the energy produced by the device is increased.In Figure 2 are presented the results of the program for Van der Meer model and for every scenario that is taken into account. It is observed that for different values of hydraulic height above water turbine the optimal crest freeboard dimension is changing

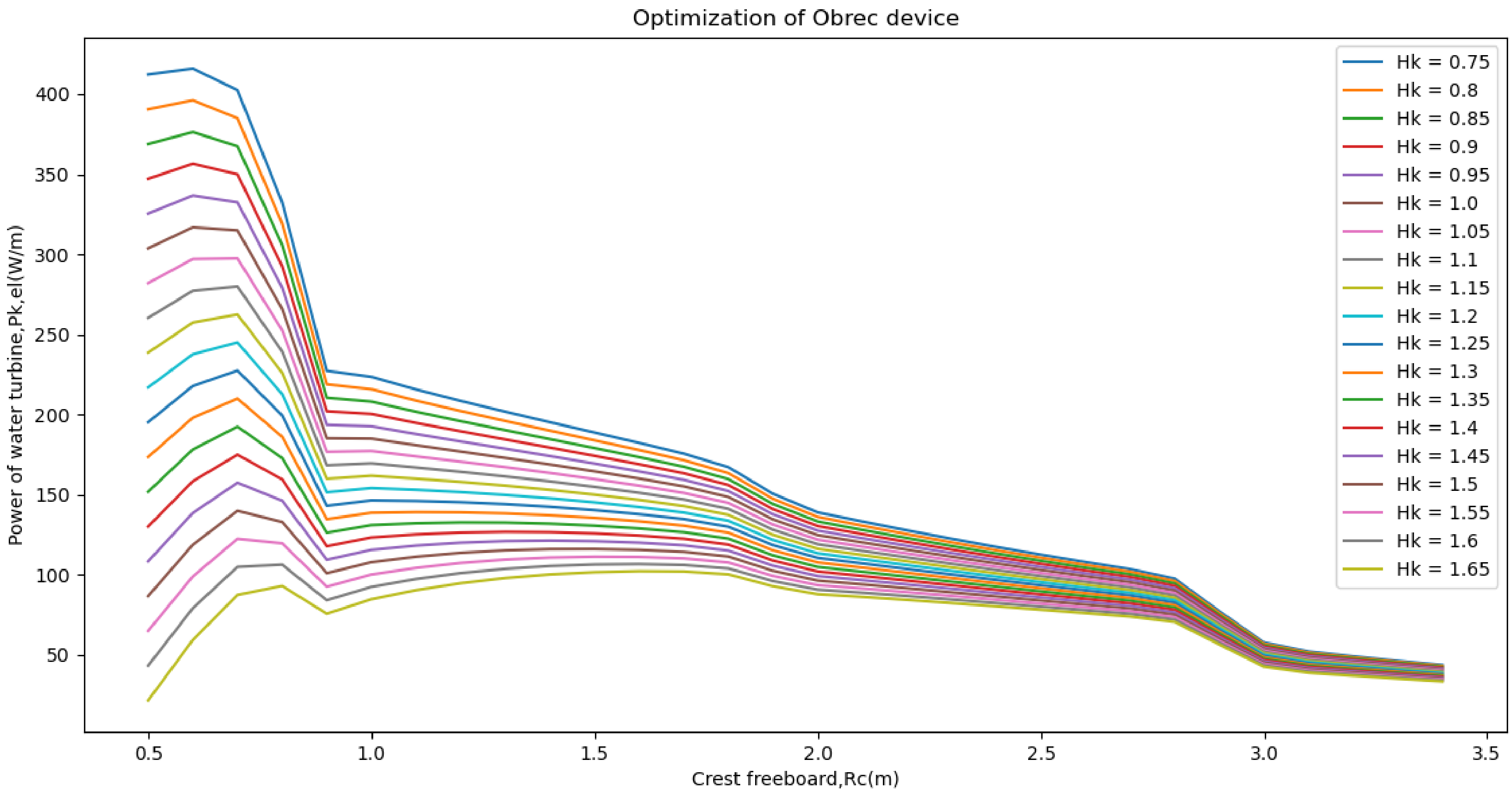

Figure 2: Obrec illustration