

# Experimental study for the hydraulic efficiency of an overtopping type wave energy converter with a circular runup ramp

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## Abstract

*In this study, overtopping rates on a circular cylindrical overtopping ramp under regular waves have been measured and hydraulic efficiency of the device as a wave energy converter has been assessed by analyzing the energy budget of the overtopped water mass. The study has been carried out by conducting two-dimensional physical model tests. The variation of overtopping rates with wave parameters has been studied and an empirical formula has been evaluated for the estimation of overtopping rates. The efficiency of the system has been calculated as the ratio of the mean power of the overtopped water mass to the wave energy flux. Results indicate that the hydraulic efficiency based on the kinetical komponent can reach 40% for the case of steep waves and the efficiency is reduced with increasing wavelength.*

**Keywords:** Wave overtopping, wave energy converter, hydraulic efficiency.

## Dairesel yüzeyli aşma tipi bir dalga enerjisi dönüştürücüde hidrolik verimin deneysel incelenmesi

## Özet

*Bu çalışmada, dairesel silindir formundaki bir tırmanma yüzeyi üzerinde düzenli dalgalar etkisinde meydana gelecek aşma debileri ölçülmüş ve aşan su kütlelerinin enerji bütçesinden yola çıkılarak sistemin bir dalga enerjisi dönüştürücü olarak hidrolik verimi incelenmiştir. İki boyutlu fiziksel modelleme teknikleri uygulanarak*

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*gerçekleştirilen çalışmada aşma debilerinin dalga parametreleri ile değişimi incelenmiş ve debilerin tahmini için ampirik bir bağıntı önerilmiştir. Hidrolik verim, aşan su kütlesinin ortalama gücünün dalga enerji akısına oranı cinsinden elde edilmiştir. Çalışma, özellikle kısa periyodlu dalgalarda yapının %40'a yakın bir hidrolik verim sağladığını göstermekte olup verimin artan dalga boyu ile azaldığını ortaya koymuştur.*

*Anahtar kelimeler: Dalga aşması, dalga enerjisi dönüştürücü, hidrolik verim*

## 1. Introduction

The increase in global population and personal energy consumption due to technological advances, coupled with the reducing reserves of fossil-based fuels and their environmental effects boosted the use of renewable energy and hence the research on devices converting renewable energy in developed and developing countries. Main sources of renewable energy are defined as solar energy, wind energy, hydropower and marine based energies such as tidal, current and wave energy. Wave energy has become a challenging field of study in the global scale due to its vast energy containment and availability, and a large number of wave energy converters have been defined, even some of them did reach the operational stage. Fundamental types of wave energy converters are defined as the oscillating water column (OWC), where air compressed due to wave action drives a turbine, oscillating systems driving a mechanical closed-conduit pump system to power a turbine and systems using the water directly at the turbines. The majority of the last group utilize wave overtopping mechanism for the power generation, hence they are names as overtopping type wave energy converters (OWEC).

### 1.1. Overtopping type wave energy converters

In an OWEC, waves reaching the device are forced to run up over an inclined ramp and to spill into a reservoir located behind the ramp, leading to a pressure head between the reservoir and the mean water level. The pressure head is used to drive low head turbines installed at the bottom of the reservoir in order to convert hydraulic energy to electricity at generators attached to the turbines.

During the last three decades, different types of OWECs have been designed and tested [2, 3], some of which even have found prototype scale applications. TapCHAN [3] and SSG Slot Cone Generator [4] are typical onshore OWECs with TapCHAN being the oldest OWEC ever deployed, and SSG Slot Cone Generator is a recent development especially suitable for use on seawalls and breakwaters. Regarding offshore OWECs, the most researched type is the Wave Dragon [5], whereas some other types also have been recommended such as the Wave Pyramid [6] and the Wave Plane [7]. All devices mentioned here except the Wave Plane utilize low head turbines, whereas a hydrokinetical converter is used on the Wave Plane, for which very limited data is available.

### 1.2. Wave overtopping

Wave overtopping has been a topic of vital importance for coastal engineers regarding the stability and functionality of coastal structures. The overtopping discharge  $q$  is defined as the volume of water crossing the crest of a 1m wide cross section of any structure in unit time. Studies related to estimation of overtopping discharges initiated in

1950's [8-10], where some typical structures of well defined cross sections have been tested experimentally. Accordingly, the applications of the results are limited. Attempts to evaluate a general expression for the overtopping process by introducing dimensionless parameters have been done by Paape [11] and Shi-Igai and Kono [12]. Weggel [13] carried out a dimensional analysis and recommended some dimensionless equations by using the data achieved from previous works. Studies following Weggel's work usually did consider a certain type of a coastal structure with deploying test parameters as the structure crest height and wave parameters in order to apply the general overtopping equations to different types of structures. In many of these studies [14-18], the recommended overtopping equation is given as simple exponential expression written as:

$$Q = a \exp(-bF_R) \quad (1)$$

In Eq. 1,  $Q$  is the dimensionless overtopping discharge,  $a$  and  $b$  are coefficients and  $F_R$  is the relative freeboard. The dimensionless discharge has two fundamental definitions; it has been defined as the ratio of the overtopping discharge to the volume of water entrapped between the crest level of the incident wave and mean water level [11], which, according to linear wave theory can be calculated as:

$$Q = \frac{2\pi qT}{HL} \quad (2)$$

A second definition, later having found wider application for coastal structures, adopts the weir equation to wave overtopping. The dimensionless discharge is given as [12]:

$$Q = \frac{q}{\sqrt{gH^3}} \quad (3)$$

The second parameter in Eq. 1, the dimensionless freeboard  $F_R$  is defined as the ratio of the structure crest level, i. e. freeboard, to the incident wave height. It can be observed that many overtopping studies adopted Eq. 1 for different coastal structures by modifying the coefficients  $a$  and  $b$ , whereas in some studies the overtopping discharge is defined as a direct function of the dimensionless freeboard [19-21].

A study carried out by van der Meer and Janssen [17] introduced further parameters to Eq. 1, such as spectral wave properties, shallow water effect, wave breaking, influence of a berm or a composite slope and oblique wave attack. A fundamental deviation has been made by introducing the Iribarren number into the equations, which actually is a definition of wave runup and wave breaking. The resultant equations are given as:

$$\begin{aligned} \frac{q}{\sqrt{gH_s^3}} \sqrt{\tan \alpha} &= 0.06 \exp\left(-5.2 \frac{F}{H_s} \frac{\sqrt{s_{op}}}{\tan \alpha} \frac{1}{\gamma}\right) ; \xi_{op} < 2 \\ \frac{q}{\sqrt{gH_s^3}} &= 0.2 \exp\left(-2.6 \frac{F}{H_s} \frac{1}{\gamma}\right) ; \xi_{op} > 2 \end{aligned} \quad (4)$$

A common point in these studies about wave overtopping is the existence of a continuous structure between the sea bottom and the structure crest. In other words, no wave transmission takes place under the structure. This is mainly due to the fact that wave overtopping has been assessed as a shore protection related topic, and the structures focused are usually conventional seawalls or breakwaters. However, a new era in overtopping studies has started by the development of offshore OWECs, where structure blockage becomes limited for floating systems. Some modifications have been recommended by Kofoed (2002) for the OWEC Wave Dragon [22], where correction factors to Eq. 4 have been recommended, however, the main form of the equation is retained.

Research of wave overtopping is still a crucial topic in research, and while all the studies carried out hold their validity in their tested structure type and range [23], further improvement works are still in progress [24, 25]. A very recent summary of studies carried out has been published [26], but it still does not contain any data about non-continuous structures. For a more comprehensive literature review, the reader is referred to the author's work [27], which is the source study of this paper.

In this study, an overtopping equation has been evaluated for a runup surface of circular profile by carrying out physical modeling tests. In the following, the energy budget of the overtopped water volume has been inspected and the hydraulic efficiency for an OWEC using a circular ramp shall be derived. The power take-off (PTO) unit has been excluded from the study due to limited funding availabilities.

## 2. Experimental Study

### 2.1. Wave flume and model setup

The physical model study has been carried out in the Hydraulics Laboratory of Istanbul Technical University. A wave flume, 24.00 m long, 0.98 m wide and 1.00 m deep has been used during the study. The flume is equipped with a flap-type wavemaker, able to generate both regular and irregular wave series. To minimize reflections from the downstream end of the flume, a 1:7 sloped gravel beach has been constructed. Tests have been carried out at a water depth of 0.70 m. The plan and profile view of the wave flume are given in Fig. 1.

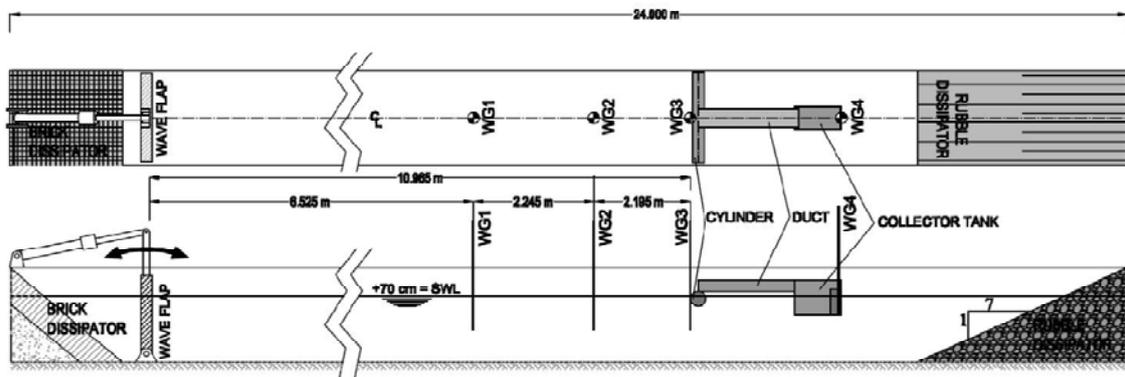


Figure 1. Plan and profile view of the wave flume.

The model used in the study consists of a horizontal circular cylinder followed by a duct, leading to a reservoir at the other end. The system has been mounted on a steel frame suspended from the top of the tank and fixed along the side railing. The 125 mm diameter cylinder is made of PVC whereas the duct and the reservoir are made of plexiglass. The cylinder has been deployed in such a way that 88% of its diameter is submerged and 12% emergent. The duct is rectangular, 200 mm wide and 105 mm deep; starting at the top of the cylinder and extending along 1050 mm shoreward, to be used for inspecting the propagation of the overtopped water volumes. A container with a storage volume of 25 lt has been attached to the end of the duct to measure the overtopping rates. Measurement of overtopping rates has been carried out by a resistance type wave probe deployed into the reservoir in a perforated vertical pipe guide acting as a stilling well.

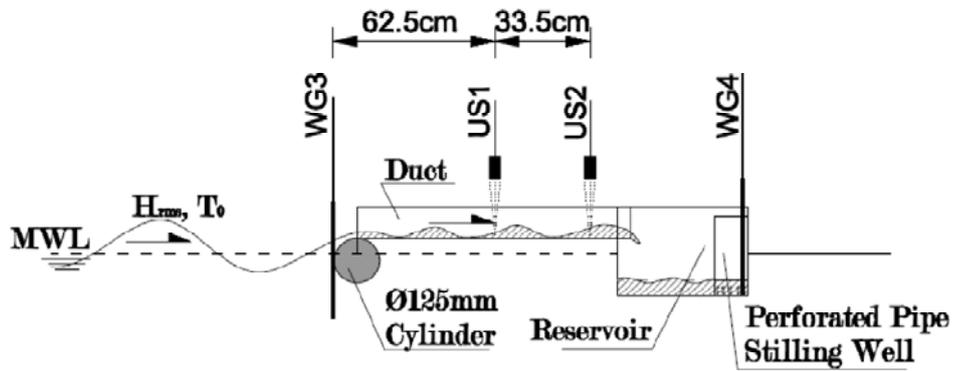


Figure 2. A sketch of the overtopping model and related instrumentation.

Three resistance type wave probes have been deployed in order to measure wave data, these are used at a sampling rate of 25 Hz. In order to inspect the motion of the overtopped water volume, two ultrasonic elevation sensors have been installed along the duct, with spacings of 625 mm and 960 mm from the top edge of the cylinder. The sampling rate for these cylinders has been set to 250 Hz.

## 2.2. Test matrix

Since the wave flume used does not contain an active wave paddle, effective time for each test is limited. Hence only regular wave series have been used during the tests. A total of 30 different regular wave series have been generated and applied to the model, which cover following range of characteristics:

$$\begin{aligned} 5.69\text{cm} &\leq H_{\text{rms}} \leq 14.88\text{cm} \\ 1.50\text{s} &\leq T_0 \leq 0.86\text{s} \end{aligned} \quad (5)$$

By using dimensionless expressions with respect to the cylinder diameter  $D$ , the test range can be given as:

$$\begin{aligned} 0.46 &\leq H_{\text{rms}}/D \leq 1.19 \\ 0.04 &\leq D/L_h \leq 0.11 \end{aligned} \quad (6)$$

## 2.3. Data processing

The water surface elevation time series achieved from the wave probes has been processed by zero-crossing method. For each set, "clean" test durations have been calculated in order to avoid re-reflection disturbances from the wave paddle. Though this process significantly reduces the number of waves to be assessed, especially for low frequencies, comparisons with pilot tests carried out in the blank channel did show that the variation in wave height is less than 5% for such cases. Some tests have been repeated to ensure the reliability of the results.

Overtopping discharges have been calculated by using the water surface elevation time series achieved from the wave probe in the reservoir. Cumulative overtopping volume-time curves have been plotted by multiplying the water surface elevation data with the tanks base area and the average overtopping discharges have been calculated as the slope of the cumulative overtopping discharge-time curve:

$$Q = \frac{dV}{dt} \quad (7)$$

### 3. Evaluation of Test Data

#### 3.1. Variation of overtopping rates with wave parameters

Since water depth and bottom slope have been kept constant during the tests, the effective wave parameters can be given as the wave height and wave period. The effect of wave period can also be introduced by using the wavelength, defined according to the linear theory by:

$$L_h = \frac{gT^2}{2\pi} \tanh\left(\frac{2\pi h}{L_h}\right) \quad (8)$$

Most of the waves used during the tests fall into the transition zone, actual wavelengths have been calculated by solving Eq. 8 iteratively. Two dimensionless parameters have been introduced: The dimensionless wave height has been defined as the ratio of the RMS wave height  $H_{rms}$  to the cylinder diameter  $D$ , and the dimensionless wavelength, formally known as the diffraction parameter in wave hydrodynamics, has been defined as the ratio of the cylinder diameter  $D$  to wavelength  $L_h$ .

In order to inspect the variation of overtopping rates with wave height, tested wave series with the same wave periods have been grouped. Thus, by keeping all other parameters constant, the effect of wave height on overtopping rates has been plotted in Fig. 3.a, indicating that overtopping rates increase with increasing wave height. A similar grouping of the test waves has been made by keeping the wave heights constant in order to see the effect of wavelength on overtopping rates. Plotted in Fig. 3.b, it can be seen that overtopping rates decrease with increasing wavelength. A further parameter, known as the wave steepness  $s_h$  and defined as the ratio of the wave height to the wavelength has also been inspected. In order to comply with the literature, the variation of overtopping discharges with the square root of the wave steepness has been plotted in Fig. 3.c, clearly indicating that overtopping rates increase with increasing wave steepness.

As the second parameter, the variation of overtopping rates with the dimensionless freeboard  $F/D$  has been inspected, shown in Fig. 4. In Fig. 4.a, the freeboard of the cylinder has been taken as its freeboard at the still water level. It has been observed that some setup takes place in front of the cylinder under wave attack, thus, a correction has been introduced by substituting the still level freeboard values ( $F$ ) with the freeboard

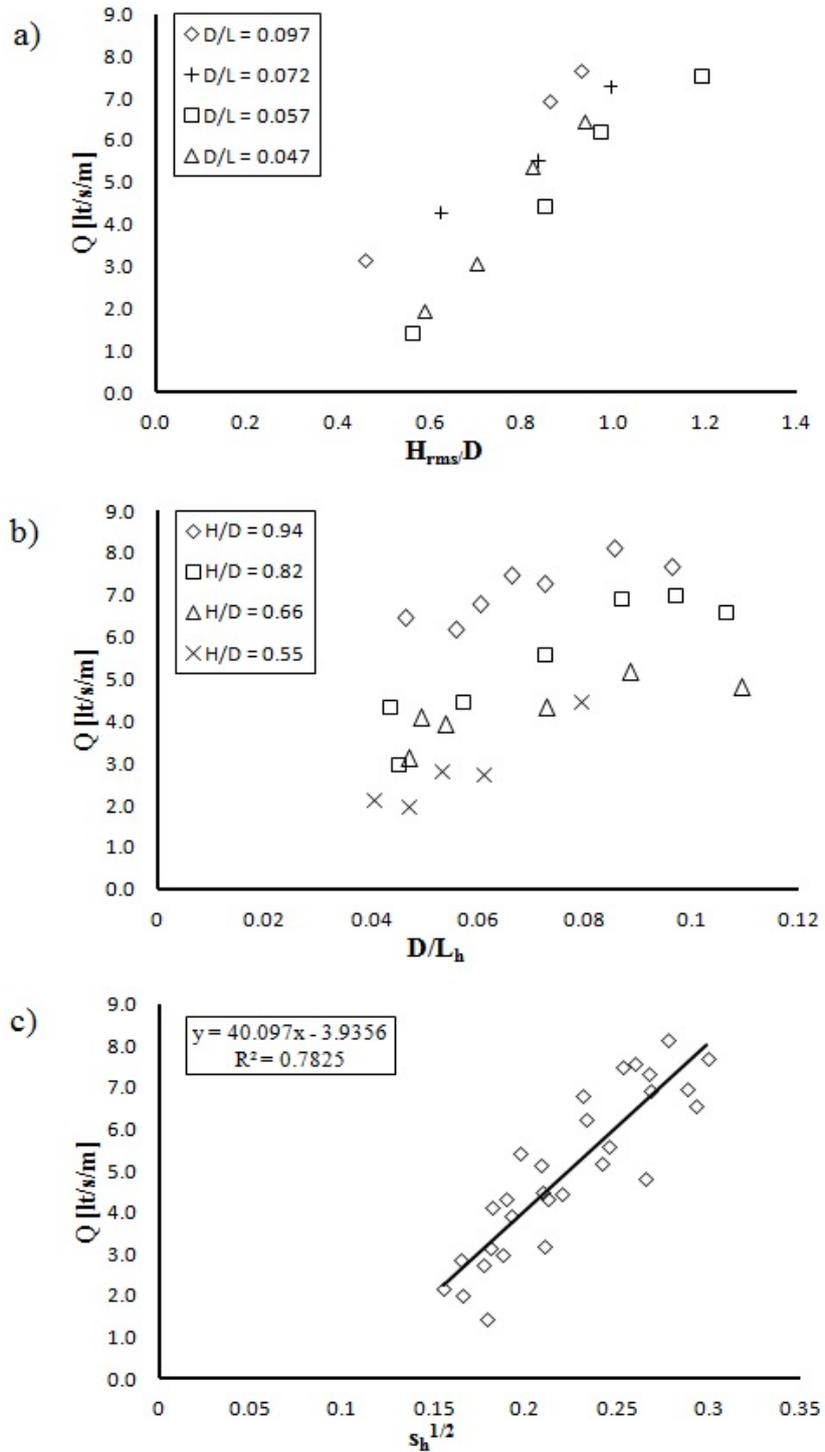


Figure 3. Variation of overtopping rates with (a) dimensionless wave height, (b) diffraction parameter and (c) wave steepness.

values under wave attack  $F_D$ , i.e. the "disturbed" freeboard, calculated from the time series read at the wave probe tangent to the offshore edge of the cylinder. The variation of the overtopping rates with the disturbed freeboard values  $F_D$  has been plotted in Fig. 4.b. As it can be observed from Figs. 4.a and 4.b, the effect of this setup taking place in front of the cylinder on wave overtopping is significant, and an exponential curve may be used to describe the relationship between the overtopping rates and the relative freeboard.

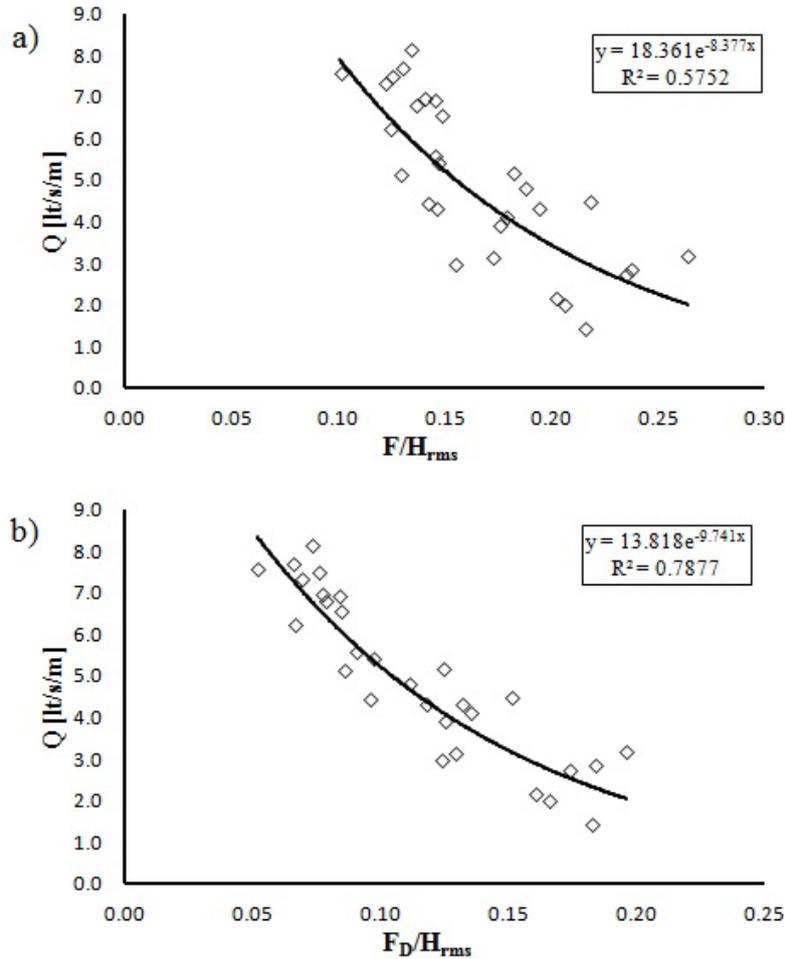


Figure 4. Variation of overtopping rates with (a) dimensionless freeboard and (b) disturbed dimensionless freeboard.

By using the parameters mentioned above, a non-linear regression model has been set up in order to derive an equation for the prediction of overtopping rates. A new parameter for the dimensionless discharge has been introduced, which is physically defined as the ratio of the overtopping volume corresponding to a single wave to the volume of the cylinder, both for unit width. In its physical expression, the new parameter expresses the amount of blockage a wave encounters prior to overtopping, and further development is on the way to introduce the depth of submergence of the obstacle.

Denoted by  $Q'$ , the dimensionless discharge can be expressed as:

$$Q' = \frac{4qT}{\pi D^2} \tag{9}$$

The variation of the dimensionless discharge  $Q'$  with the relative freeboard is given in Fig. 5. As seen, an exponential relationship can be defined between the dimensionless discharge and dimensional freeboard, for which a non-linear regression analysis yields Eq. (10):

$$Q'\sqrt{s_h} = 0.3788 \exp\left(-12.4 \frac{F_D}{H_{rms}}\right) \quad (10)$$

It can be observed from Figure 5 that overtopping discharges can be predicted better in case of small dimensionless freeboard values.

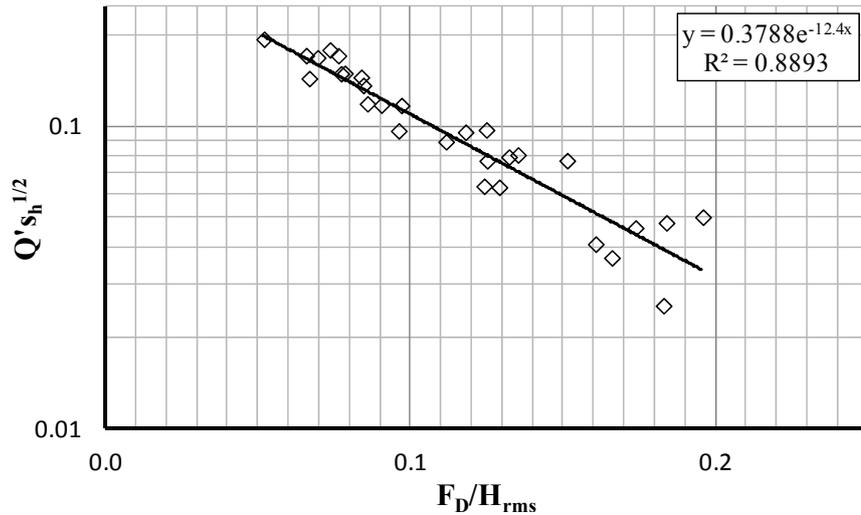


Figure 5. Variation of dimensionless discharge with disturbed freeboard.

### 3.2. Propagation of overtopped water mass

A typical water surface elevation-time curve achieved from sensors US1 and US2 is shown in Fig. 6. As seen, a profile change is taking place in the overtopped water volume while it propagates along the duct. Two parameters, identifying this profile change can be given as the maximum and minimum levels of each individual overtopping volume. The average propagation velocities for these two peak points have been calculated by using the time series and the distance between the sensors, where results show that the propagation velocity of each maxima is less than the propagation velocity of the corresponding minima, indicating clearly a profile change. It has been calculated that the maxima velocities are approximately 15% less than the trough velocities.

### 3.3. Energy and hydraulic efficiency

In order to calculate the energy budget of the overtopping water volume, the propagation velocities should be known. Following assumptions have been made in order to calculate the velocity values:

- i. Water is incompressible.
- ii. The friction loss taking place between sensors US1 and US2 can be omitted. Schüttrumpf's work [18, 28] indicates that the reduction in the velocity of the overtopped water volumes is mainly due to surface friction. Since the plexiglass channel used has a very low friction coefficient ( $f=0.01$ ) and the distance between the sensors is quite small, the effect of friction has been assumed as negligible.

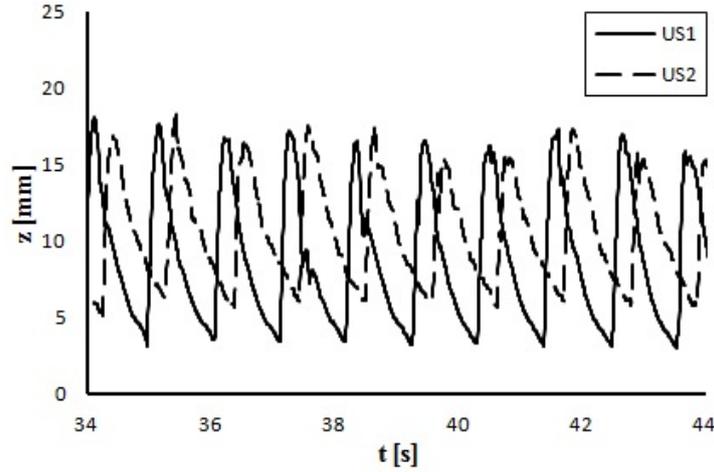


Figure 6. A synchronized water surface elevation-time series record for the water mass progressing in the channel, achieved from the probes US1 and US2.

- iii. The crests and troughs of the overtopped water masses propagate with the same velocity. Consequently, an average propagation velocity can be defined for each particular overtopped water volume.
- iv. Vertical velocity components are omitted.

By using the assumptions made above, the unit discharge can be represented as the product of the velocity and flow depth:

$$q(t) = z(t)u(t) \tag{11}$$

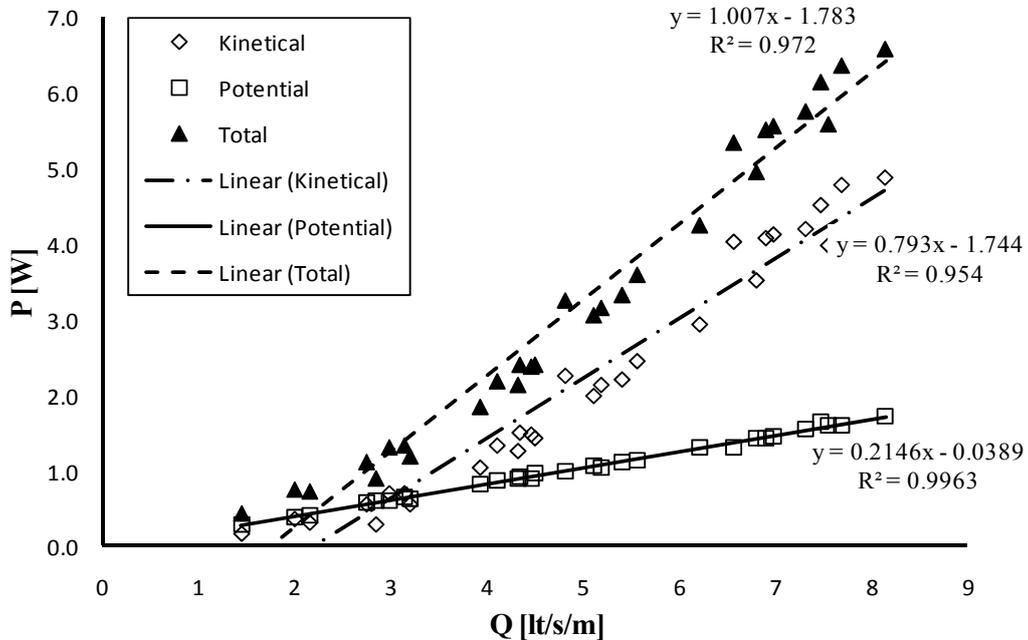


Figure 7. Variation of captured wave power with overtopping rates.

By using assumption (iii) above, Eq. 11 has been applied by using an uniform propagation velocity assumption for each individual overtopped water mass and the time axis of the records has been converted to distance. In order to provide a better

approach considering the change in the profile of the propagating water mass, the centroid of each overtopped flow volume has been calculated at both sensors and the time interval and displacement of the centroid between two sensors has been used to achieve a mean velocity value. Thus, the kinetic energy of the overtopped water volume for each wave can be represented by using the horizontal velocity of the centroid and the mass of water contained within. A similar approach has been used to calculate the potential energy of the overtopped flow volumes by considering the mass and vertical coordinate of the centroid, calculated according to the still water level reference datum.

Calculations of hydraulic power have been carried out for the kinetic, potential and total energy of the overtopped water volumes separately. Hydraulic efficiency, on the other hand, has been calculated as the rate of the energy transferred by the overtopped water volume to the energy flux of the incident waves. The variation of power with respect to overtopping rates has been given in Fig. 7. It has been concluded that the power of the overtopping water volume can be represented by a linear relationship with respect to the unit discharge, and 80% of the captured energy for the mentioned case is kinetical energy.

In addition to the findings mentioned above, the existence of a linear relationship can also enlighten a second point, where the captured wave power can be characterized by a typical "equivalent pumping head" as used in the case of steady flow. This parameter may be useful to compare different OWEC designs.

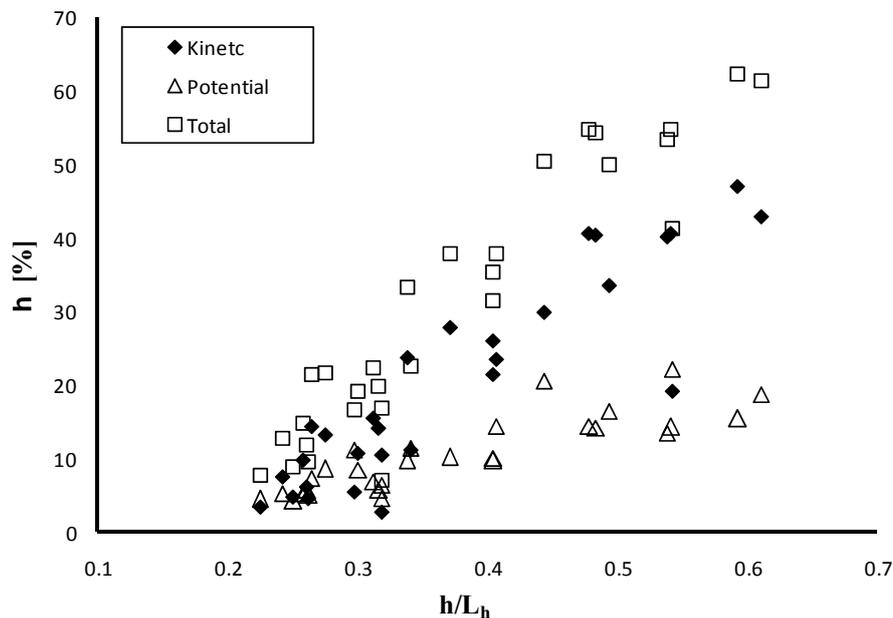


Figure 8. Variation of hydraulic efficiency with the wave parameter.

The variation of the hydraulic efficiency with the wave parameter has been given in Fig. 8. It can be observed that the efficiency is increasing with increasing wave parameter, i.e. waves with higher frequencies yield a higher efficiency. A similar plot can also be achieved if the diffraction parameter instead of the wave parameter is used for the same assessment, which is actually in compliance with the findings based on wave overtopping represented in Figs. 3-5.

#### 4. Conclusion

Overtopping rates over a partially submerged horizontal circular cylinder have been measured by carrying out physical model tests. The variation of overtopping rates with governing parameters has been inspected. By carrying out a nonlinear regression, for a relative freeboard value of  $F/D=0.12$ , an empirical equation (Eq.10) has been evaluated for the prediction of overtopping rates. For the wave range studied (Eq. 5-6), the reliability of Eq. 10 reduces with increasing dimensionless freeboard.

Kinetic and potential energy of the overtopping volumes propagating in a rectangular duct have been calculated by assuming a constant propagation velocity for each overtopping water volume and by using the centre of gravity for each individual overtopping volume per wave. Average captured power values have been calculated, and it has been found out that a linear relationship can be used to predict wave power based on overtopping volumes. The result also indicates that an equivalent "pumping height" can be evaluated for the overtopped water volumes, which may be a useful parameter in comparing different types of OWEC systems.

The hydraulic efficiency has been evaluated by dividing the captured power to the energy flux value of the incident waves. The study indicates that the tested device functions with an acceptable level of efficiency, especially in case of steep waves. It is obvious that more advanced methods such as the deployment of a PIV can be useful in order to inspect the behavior of the overtopped volumes further.

#### List of Symbols

|           |  |
|-----------|--|
| $D$       | : Cylinder diameter  |
| $F$       | : Freeboard  |
| $F_D$     | : Disturbed freeboard  |
| $F_R$     | : Dimensionless freeboard  |
| $g$       | : Gravitational acceleration   |
| $h$       | : Water depth  |
| $H$       | : Wave height  |
| $H_{rms}$ | : RMS wave height  |
| $H_s$     | : Significant wave height  |
| $L$       | : Wavelength   |
| $L_h$     | : Wavelength at a water depth of $h$ .                                     |
| $P$       | : Power  |
| $q$       | : Unit discharge   |
| $Q$       | : Dimensionless discharge  |
| $Q'$      | : Volumetric dimensionless discharge                                       |
| $s_h$     | : Wave steepness at a water depth of $h$ .                                 |
| $s_{op}$  | : Deepwater wave steepness corresponding to the peak of the wave spectrum. |
| $t$       | : Time   |
| $T$       | : Wave period  |
| $T_0$     | : Mean wave period   |
| $u$       | : Flow velocity  |
| $V$       | : Volume   |

|            |  |
|------------|--|
| $z$        | : Flow depth   |
| $\alpha$   | : Structure slope  |
| $\gamma$   | : Correction factor  |
| $\eta$     | : Efficiency   |
| $\xi_{op}$ | : Deepwater Iribarren number corresponding to the peak of the wave spectrum. |

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