HYDRODYNAMIC EFFICIENCY OF U-OWC WEC THROUGH GEOMETRIC INVESTIGATION: A DESIGN FORMULATION APPROACH

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INTRODUCTION

Due to an increasing global energy consumption and an improved understanding of the probable consequences of climate change, the demand for clean and sustainable energy sources has never been more pressing. Wave energy converters (WECs) are one of the technological solutions that might be adopted. Among the types of wave energy conversion systems, the fixed Oscillating Water Column (OWC) WECs is a well-documented and widely studied classic solution that can be installed in breakwaters to improve their viability. However, the understanding of their design has not been fully codified.

This study investigates the hydrodynamic efficiency of U-shaped OWC structures utilizing physical model experiments and re-analysis of existing literature data, where geometrical parameters were systematically varied. Additionally, the present study explores the effect of wave steepness on wave energy converter's efficiency and determines the natural frequency of U-OWC structures to tune for local wave conditions targeting highest capture width ratio. Finally, several design formulations are derived based on the experimental measurements and the dataset formed in this study collecting the available data from the literature.

GEOMETRICAL PARAMETERS AND EFFICIENCY OF U-OWC WEC

Boccotti (2007) made a significant stride in the realm of Oscillating Water Column (OWC) WECs by proposing a crucial innovation. He introduced the concept of integrating an additional vertical duct on the side facing the incoming waves, giving birth to what is now commonly referred to as the U-OWC WEC. The incorporation of a vertical duct highlights the main distinction between the traditional OWC and the U-OWC design. The system's performance characteristics are greatly improved by this adjustment.

Existing literature indicates a lack of a complete design approach that systematically investigates the effects of U-OWC geometry on hydrodynamic responses and energy generation. In the present study, we gather information from various experimental and numerical studies (e.g., Vyzikas et al., 2017; Wilbert et al., 2013; and Zhu et al., 2023). During the data digitization process, it is seen that resulting figures of the available studies are predominantly plotted based on the *kd* number, which incorporates information about wave period and water depth. On the other hand, in the 2D analysis of a U-OWC model, several key factors significantly influence energy efficiency. The capture width ratio (*CWR*), defined as the ratio of absorbed wave power to incident wave power, depends on various factors. These include wave height (*H*), wavelength (*L*) or alternatively wave number (*k*), water depth (d), and several geometric dimensions. These dimensions are the chamber width (*w*), bottom opening depth (*a*), width of the U-shaped vertical duct (*b*), height of the air chamber (*l*), height of the structure (*ht*), and the diameter of the orifice (*e*). For better analytical clarity, orifice opening ratio (o_r) is introduced. This non-dimensional term signifies the ratio between the orifice area and the top area of the structure. All geometric parameters are expressed as functions of *CWR* in Eq. 1 and shown in Fig. 1.

$$Cw = f\left(H, L, d, w, a, b, o_r, l, t, g, \mu, \rho\right) \qquad \text{Eq. 1}$$

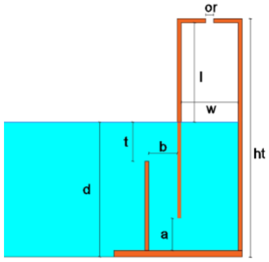

Figure 1 - Cross-section of U-OWC WEC with geometric parameters.

OVERVIEW OF THE EXPERIMENTAL STUDIES

It is clear that the influence of wave steepness has not been thoroughly examined in current literature. Typically, the dominant indicator for assessing hydrodynamic efficiency in prior studies has been the wave period. Consequently, this experimental study focusses on the influence of wave steepness, as well as to explore its correlation with wave period and orifice ratio. The model experiments of a U-OWC breakwater were carried out in COAST laboratory at the University of Plymouth. The wave flume, employed for these experiments, is 35 meters in length with a water depth of 0.675 meters. Positioned at the end of the flume, a U-OWC breakwater is situated with the back wall of the structure located 27 meters from the wave paddle (Fig. 2).

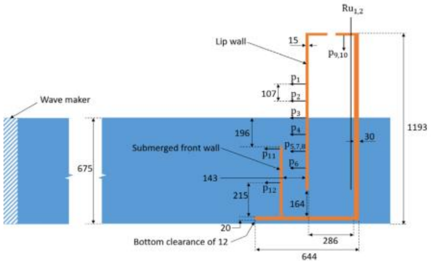

Figure 2 - Side elevation view of the U-OWC model in the wave flume (All dimensions are in mm).

The experiments involved varying the power take-off damping from 0.1 orifice ratio to 1.5%. Additionally, the study is subjected to a range of wave steepness values, spanning from 0.01 to 0.06 at intervals of 0.01.

REGRESSION ANALYSIS METHODS

This study employs two complementary data analysis approaches: multiple linear regression and decision tree regression. Multiple linear regression, a well-established statistical method, examines the connections between a dependent variable and independent variables, aiming to find the optimal linear combination for prediction. This method operates under the assumption of a linear relationship between variables, allowing us to assess each variable's significance. It is applied to analyze the relationship between the capture width ratio (*CWR*) and other dimensionless parameters. In addition, the decision tree regression method uncovers complex dependencies and intricate patterns between variables. It constructs a tree-like model of decisions to explore intricate relationships within the data, offering insights into the interaction between geometric parameters and *CWR.*

The research employed the multiple linear regression method to predict *CWR* based on existing literature, which included data from 251 experiments. A thorough analysis of R-squared parameters across the entire dataset, in conjunction with a comparison of measured and predicted data, revealed an important observation. Measurements with *kd* > 0.75 displayed a notable percentage error when subjected to a single formula. To address this discrepancy and ensure accurate predictions, two distinct formulas were developed. The formulas for different *kd* ranges are given in Eq. 2 and 3.

$$Cw = \left(\frac{w}{d}\right)^{0.8} \left(\frac{b}{d}\right)^{0.28} \left(\frac{l}{d}\right)^{0.01} \left(\frac{a}{d}\right)^{-4.04} \left(\frac{t}{d}\right)^{-0.03} \left(o_r\right)^{1.04} \left(kd\right)^{1.66} \qquad \text{Eq. 2}$$

$\textit{where } 0.41 < kd \le 0.75.$

$$Cw = 1211\left(\frac{w}{d}\right)^{2.18} \left(\frac{b}{d}\right)^{0.5} \left(\frac{l}{d}\right)^{1.01} \left(\frac{a}{d}\right)^{0.8} \left(\frac{t}{d}\right)^{-0.17} \left(o_r\right)^{0.90} \left(kd\right)^{-2.28} \qquad \text{Eq. 3}$$

$\textit{where } 0.75 < kd \le 2.92.$

The predicted *CWR* values using the formulas above and measured *C*WR values are compared in Fig. 3

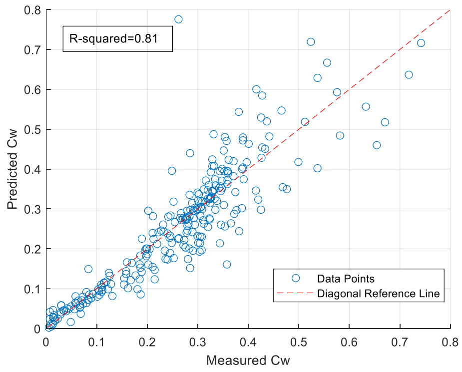

Figure 3 - Comparison of predicted CWR values using multiple linear regression with measured CWR values.

Moreover, the same existing literature dataset is analyzed using the decision tree method, which yielded a higher R-squared accuracy for whole dataset, as shown in Fig. 4.

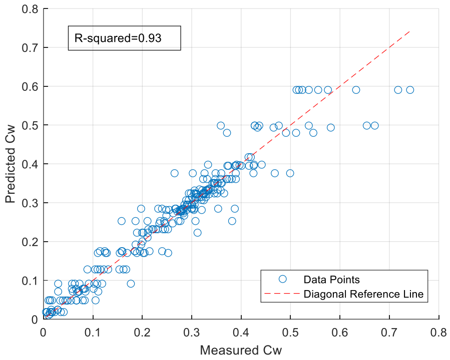

Figure 4 - Comparison of predicted *CWR* values using decision tree method with measured *CWR* values.

The decision tree method is also employed to predict *CWR*, using the experimental data from the present study considering the influence of factors such as wave steepness (*sm*), wave number (*kd*), and orifice ratio (o_r) based on data from 440 experiments. Furthermore, a method based on the decision tree algorithm is developed to predict the natural frequency of U-OWC based on a dataset formed with 26 different geometries by collecting data from the present experiments and the literature.

RESULTS AND DISCUSSIONS

This study enhances our understanding of U-OWC system hydrodynamics and aids in practical structural design. For the sake of simplifying the design of U-OWC structures, the linear regression method offers a straightforward formula that can be readily applied. On the other hand, the decision tree method involves a trained machine learning model file that can be utilized for input data, enhancing the precision of predictions, which can be provided upon request. Overall, the results obtained from these findings illustrate a notable level of accuracy when compared to actual data. These models demonstrate robust estimation capabilities across a spectrum of input variables, offering a comprehensive framework for the design and enhancement of U-OWC structures. These outcomes contribute significantly to our understanding of U-OWC system behavior and provide a pathway for the development of more efficient and sustainable wave energy conversion solutions and design.

ACKNOWLEDGMENTS

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