MODELLING OF WAVE ATTENUATION INDUCED BY MULTI-PURPOSE FLOATING STRUCTURES USED FOR POWER SUPPLY AND COASTAL PROTECTION

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Experiments have been performed in the Shallow Water Wave Basin of DHI (Hørsholm, Denmark) within the EU FP7 Hydralab Programme, on large farms of up to 25 heaving point absorber type Wave Energy Converters (WECs). For a range of geometric lay-out configurations and wave conditions (regular, polychromatic, long- and short-crested irregular waves), WEC response and modification of the wave field have been measured to provide data for the understanding of WEC farm interactions and for the evaluation of farm interaction numerical models. A first extensive wave farm database is established. The experimental arrangement and the obtained database are presented, as well as results for wave height attenuation downwave of the farms. For long-crested irregular waves, up to 18.1 % and 20.8 % reduction in significant wave height is observed downwave of the 5x5-WEC rectilinear and staggered farm, respectively. Wave height attenuation is expected to be larger, since in practical wave farm applications WECs will be controlled to extract a large amount of power from the waves, and therefore the array will cause larger wave height dissipation. These findings present the ability to combine the harvesting of energy from sea waves with coastal defence systems, resulting in cost reduction for both applications when WECs operate as multi-purpose devices.

Keywords: coastal protection, wave energy converters, WEC farms, WEC parks, wave height attenuation, floating structures, point absorber WECs, EU FP7 HYDRALAB IV, DHI Shallow Water Wave Basin

INTRODUCTION

Research background and objectives

Coastal zones worldwide occupy less than 15 % of the earth's land surface, yet they accommodate more than 60% of the world's population (Eurosion, 2004). This socioeconomic and demographic significance of coastal areas, in combination with climate change forecastings, reveal the actual need for coastal protection against the rising sea level and increasing storm intensity and frequency. However, human intervention and developments in coastal zones create additional risks since coastal geomorphological systems are exposed to erosion and deposition as they adjust to changing environmental conditions (O'Connor et al., 2009). Often hard structures (e.g. seawalls) may cause larger problems especially when no nourishing or maintenance is undertaken, as a result of no consideration of the natural shoreline, due to high wave reflection of such structures, or because of cutting off sources of the beaches, dunes, shingles, etc. (Allsop, 2014).

At the same time, the current dependence on the shrinking fossil fuel reserves and the increasing energy demand enhance the interest in sustainable and renewable energy sources, including wave energy. The available global ocean power potential is comparable to the world's power consumption (Falnes, 2007) which stimulates fast ongoing developments of wave energy technologies. Energy from ocean waves can be utilized by installing Wave Energy Converters (abbreviated as WECs) in the sea, which are devices that convert the kinetic and/or potential energy of waves into electricity. However, in order to extract a considerable amount of wave power, large numbers (tens) of WECs will have to be arranged in farms (or parks) using a particular geometrical lay-out. WECs interact with each other within a farm, resulting in different behaviour compared to an isolated device (known as park-effect). Moreover, as a consequence of energy extraction, WEC farms create a region of reduced wave height downwave (referred to as far-field effect), which is likely to influence neighbouring activities in the sea, navigation through and around the devices for ship transport and maintenance of the farms, coastal eco-systems and even the coastline and the coastal defence conditions.

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The combination of the above actual needs results in a real challenge: satisfying the energy demand in coastal areas by, simultaneously, providing or enhancing coastal protection and securing local sea activities and navigation. However, even though WEC farm developers often promote the multi-functionality of wave devices, there is only a very small number of relevant studies available, based on numerical and small scale physical modelling with low number of devices. This practical application of technology which aims to link renewable energy projects to coastal defence systems is the topic of the present paper.

Knowledge gap in the literature of wave energy systems

The importance of far-field effects and of the geometric lay-out of a WEC farm is illustrated using the example of Figure 1, where the wave propagation model MILDwave (Troch, 1998) is employed. Results are presented in terms of the disturbance coefficient Kd (=Hm0/Hm0,GB, with Hm0 the local significant wave height based on the spectral density, and Hm0,GB the wave height at the wave generation boundary). The far-field effects in the lee of the WEC farms are clearly visible, indicated by areas of reduced Kd, reaching values of 0.65.

When the geometric lay-out and the number of WECs change (Figure 1(a–d)), the wave field downwave of the WEC farm changes as well. Specifically, Figures 1(a-b), where a row of three WECs is simulated, show the importance of the spacing between the devices. As such, the resulting far-field effects downwave of WECs with small lateral spacing (Figure 1a) are very different compared to the far-field effects downwave of the same number of WECs with much larger spacing (Figure 1b). Furthermore, Figures 1(c-d) show the importance of the devices' geometric lay-out, for a farm of nine WECs. As such, the resulting far-field effects downwave of a 9-WEC rectilinear farm (Figure 1c) differ compared to those caused by a 9-WEC staggered farm (Figure 1d).
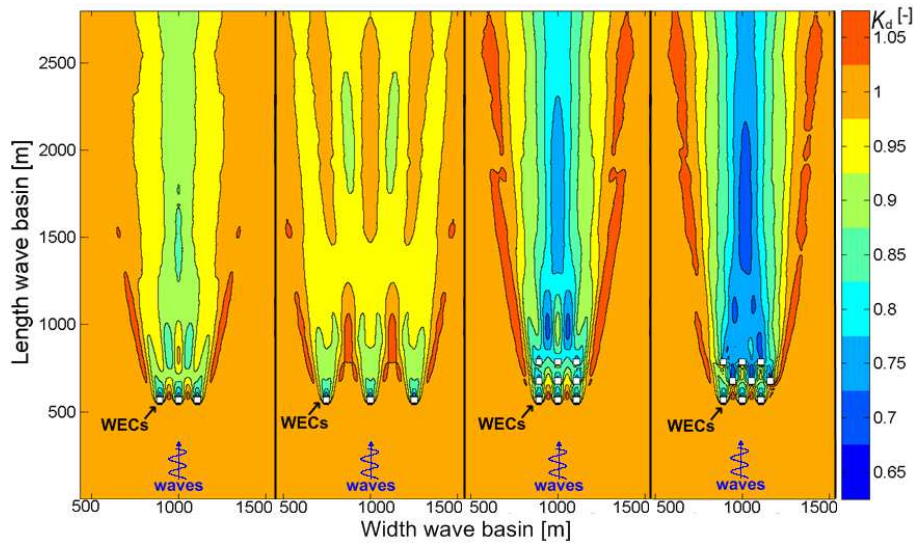

Figure 1. MILDwave simulation of *far-field effects* downwave of farms (generic WECs of the overtopping type with a specific power absorption). Wave height attenuation downwave of the WECs is illustrated by the reduction of the disturbance coefficients K_d (=$H_{m0}/H_{m0,GB}$). Farms of: (a) 3 WECs; (b) 3 WECs of larger lateral spacing; (c) 9 WECs in rectilinear lay-out; (d) 9 WECs in staggered lay-out. Results by Troch *et al.*, 2010.

Numerical models are widely used nowadays to study WEC farms (Folley et al., 2012), however, to date, there has been very limited validation by physical scale models. Moreover, in contrast to the large quantity of experimental work concerning individual or pairs of WECs (e.g. Vantorre et al., 2004; Budal et al., 1979), there is limited published data on WEC farms. As part of the PerAWaT project, several studies of wave energy converter farms have been conducted, both of idealized geometries and scale models of WEC systems under development by private companies. The few available experimental studies concern typically less than 12 WECs and have been conducted focussing mainly on response and power output under long-crested irregular and regular waves (e.g. by Weller et al., 2010; Thomas et al., 2008), while only a small number of studies investigate wave spectra changes across WEC farms (e.g. Alexandre et al., 2009). Practical and effective wave energy applications, however, will demand the installation of farms composed of large numbers of WECs. Consequently, there is a clear need for experiments with large wave farms.

State-of-the-art advances: the first experiments with large WEC farms

As seen in the previous, presently, no experimental studies are reported in literature detailing simultaneously WEC response, power output and wave field modifications due to wave farms.

Such experimental data are essential for the evaluation of the accuracy of the used numerical tools, for their validation and for their further development and optimization. Accurate measurements of individual WEC response, WEC farm power output and spatial variation of wave conditions in the vicinity of the devices are required to improve understanding of the fundamental processes influencing wave conditions down- and up-wave of wave energy converter farms. Moreover, results from testing various WEC farm geometric configurations are necessary for the optimization of the farm geometrical lay-outs for practical applications.

Recently, experiments with large farms of generic floating WECs have been performed in the DHI Shallow Water Wave Basin (width x length: 35x25 m), as part of PhD research (Stratigaki, 2014) and within the "WECwakes" project (Stratigaki et al., 2014), funded by the EU FP7 HYDRALAB IV programme and the Research Foundation Flanders (Belgium). The present paper presents results from these experiments. The employed methodology included testing of a large number of different farms of both rectilinear and staggered configurations with varying WEC number (illustrative examples in Figure 2(a-b)).

Figure 2. The 5x5-WEC rectilinear (a) and staggered (b) farm in the DHI Shallow Water Wave Basin under irregular long-crested waves with θ = 0°. View from behind the wave generator.

This unique experimental set-up of 25 WECs in a farm lay-out is at present the largest of its kind, studying WEC farm effects that are also extrapolated to the nearshore wave climate. A wide range of different wave conditions have been tested focussing on realistic multi-directional waves. The experiments have resulted in the first comprehensive non-confidential wave farms database (publically available under the Hydralab rules), in which WEC response, wave induced surge forces on the WECs, and wave field modification are reported simultaneously. The acquired data include also force and wave field measurements around fixed buoys, resulting in an extended application field of the database. Finally, the performed experiments aim to cover the existing literature gap and advance the present state-of-the-art, as reported in more detail in the discussion part.

EXPERIMENTAL SET-UP

Description of an individual Wave Energy Converter

Each WEC is a point absorber type device (a heaving buoy) that comprises three main parts: (i) a hemispherical ended buoy of diameter, $D = 31.5$ cm, and draft, $d_{buoy} = 31.5$ cm and overall height 60.0 cm, (ii) a vertical steel supporting shaft of 40 mm square section with a gravity metal base, and (iii) a power take-off system based on friction brakes comprising *Teflon* blocks and 4 linear springs. The dry mass of the buoy is $m = 20.490$ kg and the natural period, by decay test and response measurement in regular waves, is $T_n = 1.176$ s. The upper part of the buoy is a horizontal PVC cover, on which the power take-off system is installed.

Details on the WEC development, evaluation and experimental study for the preparation of the *WECwakes* project are presented by Stratigaki *et al.*, 2013. The preparatory testing of a few first prototype WECs, was followed by the construction of 25 identical devices, realized at the workshop of Ghent University (Belgium). Preliminary results for WEC response amplitude operator (RAO) and power output, show good agreement between measured response for individual WECs, and power output and WEC response predicted using a linear time domain model.

The experimental arrangement

The complexity of the tested WEC farm lay-outs has been increased gradually. The experiments started with the testing of individual WECs at different locations within the basin. Furthermore, WEC farms have been tested, of various geometric configurations and increasing WEC number.

For the installation of the WECs in the wave basin, the supporting shaft has been bottom mounted to the gravity metal base, and at the same time, fixed to adjacent structures at the top (a metal frame) as shown in Figure 3. An approach has been developed in order to deal with time consuming installation issues; all slender WEC support shafts remained in place throughout the entire testing period, while the "unused" WECs were held stationary above the water surface. In this way, by using a specific stencil of the WEC shafts, a large number of different WEC farms can be considered in short time. This methodology allowed the performance of time efficient experiments for 28 different WEC configurations in a large-scale facility, while the effect of the presence of the WEC support structures on the wave climate is confirmed to be small by Stratigaki *et al.* (2014).

In Figure 4, a plan view is presented of the general experimental arrangement in the wave basin and of the configuration comprising the 5x5-WEC rectilinear farm. The standard locations of the wave gauges are also shown. The lateral, *w*, and longitudinal, *l*, spacing between the WECs (centre-to-centre spacing) are $w = l = 5D = 1.575$ m (where *D* is the WEC diameter). The wave generator of the basin has a total length of 22.0 m and thus, does not extend across the entire basin width of 35.0 m. Vertical guide walls have been installed in order to avoid diffraction of the generated waves to either side of the basin. This technique results to a larger *effective* domain within the wave basin. Moreover, it simplifies the numerical treatment of the experimental set-up, using e.g. fully reflective boundaries for simulating the guide walls. The distance between the guide walls and the outermost WECs of the 5x5-WEC farm, is nearly $25D = 7.875$ m, and so reflection of waves, scattered and radiated by the wave farm do not influence the findings.

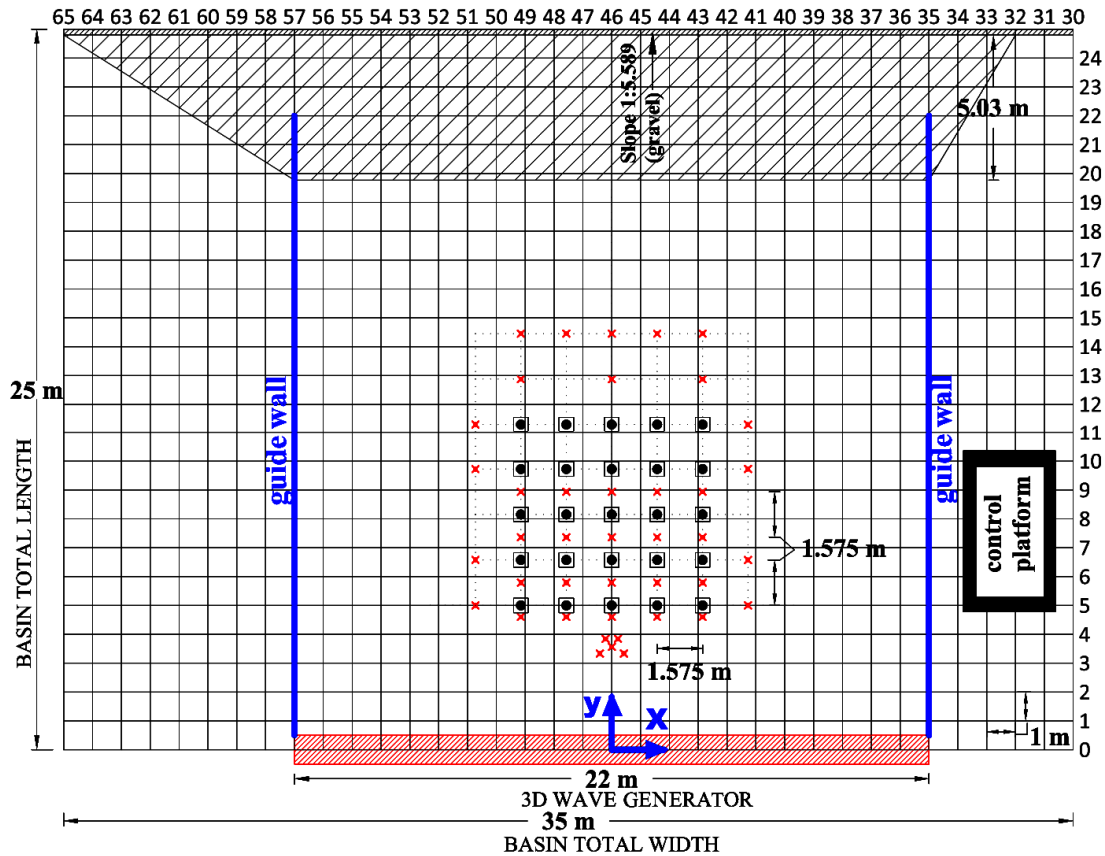**Figure 3. Construction of WEC support structures in the DHI wave basin.**

Figure 4. Plan view of the WECwakes experimental arrangement in the DHI wave basin and standard 5x5-WEC rectilinear farm. Grid at 1.0 m increments, wave gauge arrangement (x) and WEC positions (●) are indicated. The hatched region along the x-axis at the bottom of the figure denotes the extent of the wave paddles, while at the opposite end, the wave absorbing beach is indicated. At the sides, plywood guide walls are used. Water depth is constant, d_w = 0.70 m.

Instrumentation and acquired data

- **Wave field measurements**

A network of 41 resistive wave gauges (Figure 4) have been used to record time series of surface elevations at specific locations throughout the wave basin. A CERC 5 wave gauge array has been

placed in front of the WECs for estimating wave directionality and wave reflection. The undisturbed wave field has been recorded in an empty wave basin (without any WECs or support structures) for all generated wave conditions, at wave gauges positioned around and at the centres of the WECs.

- **Measurements of the WECs heave displacement**

Potentiometers (25, in total) have been attached to each WEC for measuring time series of the heave displacement. These measurements provide information on the WEC response, as well as data for calculating power output of the wave farms.

- **Measurements of the surge force on the WECs**

The wave induced surge force has been measured on 5 devices situated in the central column of the WEC farm geometric configurations (Figure 4). An arrangement with load cells has been used to measure surge forces on the WECs, developed and constructed at the workshop of Ghent University. These data is used for calculating power output of the wave farms.

- **Video acquisition**

Video measurements (40 fps) have been recorded for all WEC farm configurations, from: (i) a location behind the wave generator and (ii) a location at the opposite end of wave basin, behind the wave absorbing beach.

Experimental test programme and main characteristics of the established database

A wide range of farm lay-outs and wave conditions have been investigated focussing on regular, polychromatic, irregular long- and short-crested swell and wind waves (Tables 1- 5). In order to ensure reproducibility of the obtained measurements, experiments have been repeated in the beginning and at the end of the testing period. These test repetitions confirm that the research results and generated wave fields are reproducible with good accuracy (Stratigaki *et al.*, 2014).

For the majority of the tests, two wave periods have been considered (T = 1.18 s; 1.26 s). Wave period, $T = T_p$ = 1.18 s corresponds to the natural period of the WEC, T_n. Wave period, $T = T_p$ = 1.26s has been selected based on the ratio between the wave length, L, and the lateral, w, and longitudinal, l, spacings between the WECs (O'Boyle, 2013). The water depth has been kept constant throughout the entire testing period at d_w = 0.70 m. In Table 1, a summary of the tested wave basin and WEC farm configurations with regard to the studied wave conditions is provided.

The regular waves (Table 2) are defined in terms of a wave period, T, and a wave height, H. For the majority of the tests, H = 0.074 m has been used. Wave attack of different directions is also considered with waves propagating from the wave paddles to the WEC farms under wave angles, θ = 0°, 10° and 20°.

Polychromatic waves (Table 3) have been considered as well, which consist of consecutive regular waves with different wave lengths, L. The wave period, T, and wave height, H, thus vary during a test. A polychromatic wave can be expanded as a sum of regular (monochromatic) waves. These waves have been defined based on (O'Boyle, 2013), applying a random starting phase to each wave component, with θ = 0°.

The irregular waves (Table 4) are defined by a JONSWAP spectrum and have been performed for a wider range of significant wave heights, H_{m0}, and peak wave periods, T_p. However, for the majority of the tests, significant wave height, H_{m0} = 0.104 m has been used to achieve equivalent energy contents to the regular waves with H = 0.074 m.

The short-crested irregular waves (Table 5) have a directional spread that is defined by a parametrical cosine power 2*s* model (Longuet-Higgins *et al.*, 1963). The spreading parameter, *s*, gives the degree of directional energy concentration. Short-crested irregular waves with *s* = 75 and *s* = 10 have been considered to represent swell with long decay distance and wind seas, respectively (Goda and Suzuki, 1975). The selection of the irregular short-crested wave conditions is based on research findings by Troch *et al.* (2010).

Table 1. Summary of the tested WEC (farm) configurations.

Configuration	Types of tests regarding wave conditions						
	Regular	Polychro-matic	Irregular (swell)	Irregular (sea)	Only diffraction (fixed WECs)	WEC decay motion	WEC lay-out sketches
Waves only	√	√	√	√	√ (shafts)	N/A	-
Individual WEC	√	√	√	√	√	√	
2-WEC column (longitudinal spacing, *l*, 5*D* to 20*D*)	√	√	√	√ (l=5*D*)	√ (l=5*D*)	√	
2-WEC row (lateral spacing, *w*, 5*D* to 20*D*)	√	√	√	-	√ (w =5*D*)	-	
5-WEC column (*all columns)	√	√	√	√ (middle column)	√ (middle column)	√ (middle column)	
5-WEC row	√	√	√	-	-	-	
10-WEC, 2 columns	√	√	√	-	-	-	
5 × 5-WEC rectilinear farm	√	√	√	√	√	-	
5 × 5-WEC staggered farm	√	√	√	√	√	-	
3 × 3-WEC rectilinear 10*D*	√	√	√	√	-	-	
3 × 3-WEC rectilinear 5*D*	√	√	√	√	-	-	
13-WEC staggered farm	√	√	√	√	√	-	

Table 2. Target sea state characteristics used to generate regular waves.

Wave height, *H* (m)	Wave period, *T* (s)	Wavelength, *L* (m)	Wave angle, θ (°)		
0.074	1.180	2.133	0	10	20
	1.260	2.384	0	10	20

Table 3. Target sea state characteristics used to generate polychromatic waves (θ = 0°).

Wave height, H (m)	Wave period, T (s)	Wavelength, L (m)
0.024	0.870	1.186
0.030	1.008	1.581
0.036	1.178	2.109
0.032	1.217	2.231
0.030	1.260	2.367
0.022	1.385	2.761
0.018	1.510	3.152

Table 4. Target sea state characteristics used to generate irregular long-crested waves defined by a JONSWAP spectrum (θ = 0°).

Significant wave height, H_{m0} (m)	Peak wave period, T_p (s)	Wavelength for peak wave period, L_p (m)
0.075	1.050	1.733
0.082	1.100	1.890
0.104	1.180	2.156
	1.260	2.405
	1.350	2.687
	1.500	3.154

Table 5. Target sea state characteristics used to generate irregular short-crested waves (θ = 0°).

Directional spreading parameter, s (-)	Significant wave height, H_{m0} (m)	Peak wave period, T_p (s)	Wavelength for peak wave period, L_p (m)
75	0.104	1.260	2.405
10	0.104	1.260	2.405

WAVE HEIGHT ATTENUATION INDUCED BY WEC FARMS

The oscillation of WECs under wave action results in the combined incident-diffracted-radiated wave field (or else the *total* wave field). To simulate wave farm power extraction, damping of the WECs' motion has been applied through the devices' power take-off system. In this paper, results are presented for the 5x5-WEC farms illustrated in Figures 2(a-b) with spacing between the WEC equal to 5*D*. In order to quantify the effect of the heaving WECs on the recorded undisturbed wave field, the decrease in significant wave height (H_{m0}) has been calculated. For this quantification, the difference percentage term defined in Equation [1] has been plotted in Figures 5 and 6 for farms under long- and short-crested irregular waves, respectively:

$$\frac{'recorded\ total\ wave\ field' - 'recorded\ undisturbed\ wave\ field'}{'recorded\ undisturbed\ wave\ field'}\ x\ 100\ \% \qquad (1)$$

The difference percentages presented in Figures 5 and 6 are positive when the heaving WECs cause increase of the total wave field compared to the undisturbed incident wave field. On the other hand, negative differences correspond to decrease in significant wave height (H_{m0}) due to wave power extraction by the devices.
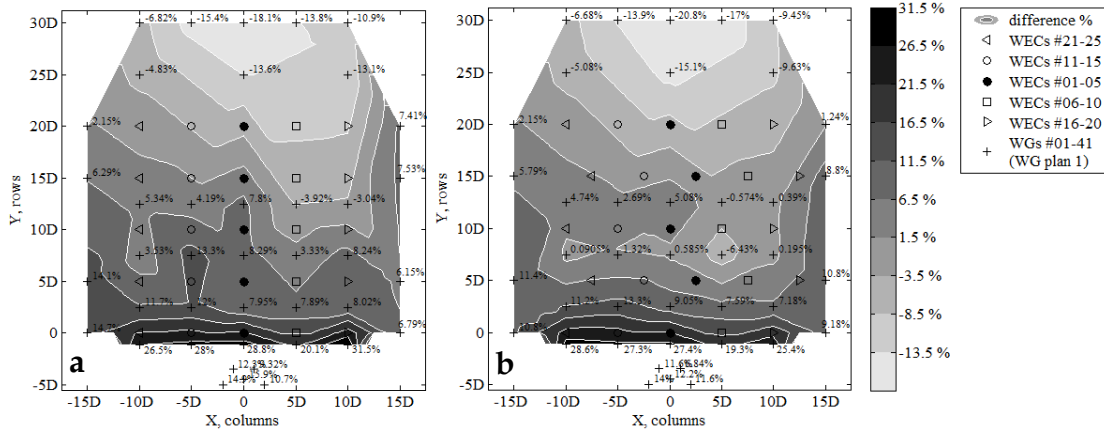
Figure 5. Non-dimensional percentage of change of H_{m0} at locations within and around the 5x5-WEC rectilinear ((a), illustrated in Fig. 2(a)) and the staggered ((b), illustrated in Fig. 2(b)) farm. Results concern the total wave field for heaving WECs with damping applied. Unidirectional irregular waves of T_p = 1.26 s and H_{m0} = 0.104 m. The basin width (X, columns) and length (Y, rows) are expressed in number of WEC diameters, D = 0.315 m.
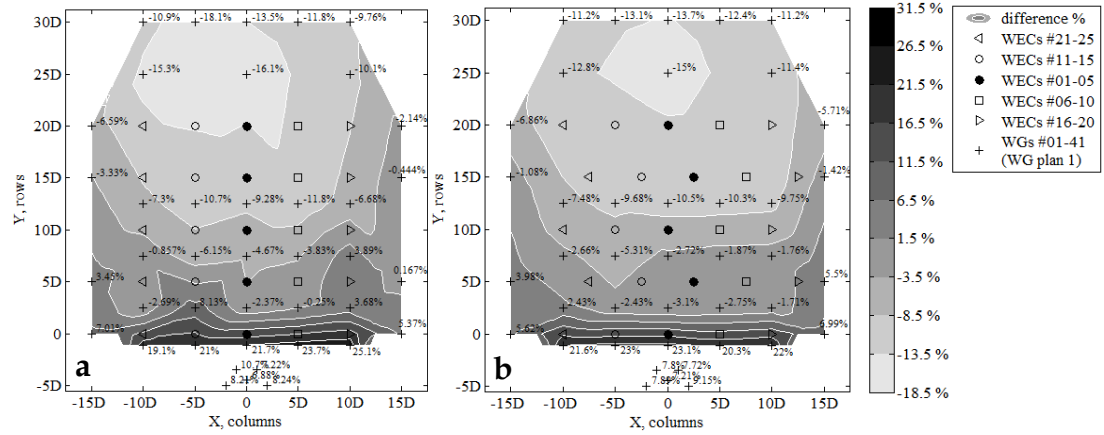

Figure 6. Non-dimensional percentage of change of H_{m0} at locations within and around the 5x5-WEC rectilinear ((a), illustrated in Fig. 2(a)) and the staggered ((b), illustrated in Fig. 2(b)) farm. Results concern the total wave field for heaving WECs with damping applied. Short-crested irregular waves of T_p = 1.26 s, H_{m0} = 0.104 m and spreading parameter, s = 10. The basin width (X, columns) and length (Y, rows) are expressed in number of WEC diameters, D = 0.315 m.

There is clearly wave attenuation in the lee of the WEC farms, indicated by up to 18.1 % and 20.8 % reduction in significant wave height downwave of the 5x5-WEC rectilinear and staggered farm (Figure 5), respectively, for long-crested irregular waves (T_p = 1.26 s and H_{m0} = 0.104 m). For unidirectional waves, the staggered WEC farm causes higher wave attenuation due to higher power extraction (Stratigaki, 2014), as a result of the geometrical lay-out of shifted rows and of the uniform wave direction.

For short-crested wind waves (spreading parameter, s = 10), wave height attenuation reaches 18.1 % and 15.0 % downwave of the 5x5-WEC rectilinear and staggered farm, respectively. In this case, the rectilinear farm causes higher wave height dissipation which is also supported by the results for higher power extraction of this farm configuration compared to the staggered configuration. This results from the effect of the geometrical lay-out and of the wave directionality, as less wind waves appear to travel in-between the WECs due to the shifted rows of the staggered farm. Moreover, as incoming waves come from various directions, horizontal forces on the buoys eliminate each other resulting in less optimal conditions for power extraction. Finally, wave attenuation reduces for wind waves, and the wave field appears to recover faster in the lee of the farms compared to unidirectional irregular waves.

The wave field findings presented in this paper derive from a unique set of experiments, yet are confirmed by numerical studies concerning large wave farms and by smaller scale experimental

investigations, both performed by others. This agreement in wave field patterns serves as a first-stage validation, strongly indicating the reproducibility of the results based on the performed data analysis. A few agreement examples are provided:

1. Wave height attenuation downwave is also found by Alexandre *et al.*(2009) who conducted experiments with 5x1 and 5x2-farms.
2. Local wave height increase at the front WEC row is also found by Beels *et al.*(2010a) who presented numerical simulations of 9 generic WECs.
3. Wave height increase at the sides of wave farms is also found by e.g. Beels *et al.* (2010a), Troch *et al.* (2010), Borgarino *et al.* (2011) who performed numerical simulations of the resulting wave field due to the presence of WEC farms. This wave height increase is due to diffraction effects.
4. For wind sea waves, limited wave height increase at the sides is found also by Beels *et al.* (2010a) and Troch *et al.* (2010).
5. The highest wave height dissipation downwave, at least along a zone of width 10*D*, is also found by Beels *et al.* (2010a) and Troch *et al.* (2010).
6. Staggered lay-outs result in higher wave height dissipation for long-crested irregular waves, also confirmed by e.g. Troch *et al.* (2010).
7. Short-crested waves result into sooner wave height recovery downwave, which conclusion is also confirmed by numerical studies, e.g. by Beels *et al.* (2010a) for 9 generic WECs, and by Borgarino *et al.* (2011) for 18 Oscillating Surge WECs.

DISCUSSION ON OVERALL RESEARCH FINDINGS

More extended data analysis exhibiting a variation of the test parameters presented in Table 1, has shown that wave attenuation and power output can be significantly affected, either positively or negatively, depending on the geometrical arrangement of the farm, the spacing and the number of the devices and the wave conditions. Also for the power results is found agreement with numerical and experimental studies performed by others (e.g. by Stallard *et al.*, (2008); Weller *et al.* (2010); Babarit (2010)), similarly to the wave field findings. A detailed discussion and conclusions on the obtained power output results and wave field modifications by all tested wave farms is provided by Stratigaki (2014), where, also based on the existing literature, recommendations and a first series of guidelines for design of WEC farms have been derived.

This paper focusses on wave field modifications caused by wave farms for a set of irregular long- and short crested wave conditions. The wave field modifications due to wave energy extraction and due to the WECs' motion have been quantified for the 5x5-WEC farms, in terms of the non-dimensional percentage of change of H_{m0}, at locations within and around the farms. This data analysis aims to investigate the effect of changing the WEC farm configuration and the sea state conditions, on the WEC farm far-field effects and especially on wave height dissipation downwave.

Large farms of 25 WECs are shown to have significant effect on the resulting wave field downwave, which, for practical wave energy applications, can influence neighbouring activities in the sea, coastal eco-systems, the coastline and the coastal defence parameters, and even ship navigation.There is clearly wave height attenuation in the lee of the WEC farms. For long-crested irregular waves, up to 18.1 % of wave height decrease is observed downwave of 25 WECs arranged in rectilinear geometric configuration. Wave height attenuation increases, reaching 20.8 %, when the same 25 WECs are arranged in staggered geometric configuration. The 5x5-WEC farms under wind seas result also in large wave height attenuation, but smaller than that caused under irregular long-crested waves. For wind seas the zone of wave attenuation downwave is shorter in length, resulting in faster wave height recovery. Moreover, the wave attenuation patterns within the WEC farms differ for different sea states; for short-crested wind waves, wave height decrease is observed already after the front row of WECs, while for long-crested waves this decrease occurs only after the third row of WECs. Wave height attenuation has been measured for the first time in the lee of large farms. However, note that in practical wave farm applications WECs are designed to be "*controlled*" in order to achieve higher wave power extraction in irregular seas, and therefore similar WEC farms are expected to create even larger regions of higher wave height dissipation.

The lessons learned through experiences from the present research can be related by others to similar applications. Specifically, all the examples mentioned below apply to any group of floating/oscillating structures and any type of WEC. Firstly, when WECs operate in groups (farms), their response is much different than that of individual devices due to interactions between them, in terms both of power production and far-field effects. Therefore, WEC concept developers need to take

into account the park-effect which is present even for large spacings between the devices (e.g. 10*D*, similar to Babarit (2013)) and not only focus on the optimization of individual devices. Secondly, realistic seas and wave directionality should be essentially investigated (experimentally or numerically) for WEC farms. This remark is important, as till now, WEC developers have concentrated on the testing of point absorber WECs mostly under long-crested regular and less often, irregular waves. This was under the assumption that wave directionality is not significant for this WEC type, however, this is not valid for farms, as the configuration affects the devices' response. Finally, wave farm effects are very case-sensitive, and depend on the local wave conditions, the installation site and the farm lay-out (e.g. the ratio between the wavelengths and the WEC spacing).

The application of the obtained research findings and conclusions, as well as the established database is wide, and they can be used by others than wave farm developers for related problems.

Firstly, knowledge of the resulting wave field and wave height attenuation is useful for the assessment of the environmental impact of wave farms. For instance, the results for wave height attenuation found downwave of farms can be further used for estimating the coastline evolution due to the presence of the devices, i.e. by using morphological models or by applying traditional formulae predicting the long-shore sediment transport and erosion or accretion, based on wave height parameters, e.g. as performed by Mendoza *et al.* (2013); Nørgaard and Lykke Andersen (2012). Another way of exploiting such wave field information is for the prediction of the extents of the wave attenuation region in order to take measures either to mitigate WEC farm effects on other sea activities and coastal structures, or to utilize the WEC farm "shadow effect" for coastal protection. Comparative analysis from different geometrical farm configurations and wave conditions has also resulted in a first series of guidelines for WEC farm design. These guidelines can be used for lay-out optimization in order to find a balance between sufficiently high power production and low environmental impact or high sheltering effectiveness for offering shore protection from large waves. This research is a proof-of-application with positive economic impact, showing the ability to combine the harvesting of energy from sea waves and coastal defence systems, resulting in cost reduction for both applications when WECs operate as multi-purpose devices.

Secondly, a first comprehensive experimental database has been established which can be used by WEC farm developers and which can be extrapolated to floating structures/platforms, oscillating or fixed cylinders under wave action for understanding of e.g. wave impact on the cylinders and wave field modifications around them. The created WEC farm database comprises a wide range of parameter variations such as: the farm geometric configuration, the WEC number, the lateral and longitudinal (centre-to-centre) spacing between the WECs, the WECs' motion (decay motion, fixed WECs, "free" response or damped motion of WECs with varying damping), wave conditions (varying wave period, wave heights, wave attack angles) and wave types (regular, polychromatic, irregular long- and short-crested with varying spreading parameters).

Most importantly, the data obtained from these experiments will be very useful to validate and extend a large range of numerical models employed to simulate response, power absorption and wave field modifications due to oscillating WECs (or other floating structures). Such data, dealing with large wave farms, are not available in the literature. Validation of numerical models will lead to optimization of the geometrical lay-out of WEC farms for practical applications and will therefore enable reduction of the cost of energy from wave energy systems (similarly to the case study demonstrated by Beels *et al.* (2010)). Consequently, one of the most important economic impacts of the present research is that it can contribute to the improvement of wave energy farms towards a more competitive technology compared to other renewable energy resources, i.e. wind energy.

CONCLUSIONS

Pioneering experiments have been performed in the large-scale wave basin of DHI within the EU FP7 Hydralab Programme with wave energy converter farms of different geometric configurations and for varying wave conditions. Surface elevations, the WECs' heave displacement and wave induced surge forces on the WECs have been simultaneously measured.

An extensive database for wave farms has been established, with a wide field of applications. Results of wave height attenuation have been presented and discussed, as well as the overall research findings.

The wave field findings prove the ability to satisfy energy demand in coastal areas by, simultaneously, providing coastal protection, securing local sea activities and navigation, and reducing the costs by using WECs as multi-purpose devices.

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