Experimental study and numerical modelling of intra-array interactions and extra-array effects of wave energy converter arrays

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Coastal zones worldwide occupy less than 15% of the earth's land surface, yet they accommodate more than 60% of the world's population. 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** due to the use of 'hard' shoreline protection structures, i.e. groynes, breakwaters, seawalls, revetments, etc. The usual problems caused by such structures are related to beach erosion, sediment deposition and high wave reflection. Therefore engineers often seek shoreline protection solutions within 'soft approaches' to limit impact on coastal systems.

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. An example is **Belgium** that nowadays deals with a challenging energy need: a **threatening power supply shortage**. Moreover, the need to reduce greenhouse gas emissions has led to measures that are being taken at European level, as well as by Member States at national level, so that the EU succeeds in meeting its targets under the Kyoto Protocol and the '20/20/20' objectives.

The available global **ocean power** potential is comparable to the world's power consumption 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 **WEC farms** (or else known as '*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 (so-called '*far-field*' *effects*), which is likely to influence neighbouring activities in the sea, other marine (energy) projects, 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.

Consequently, the combination of all the above needs results in a real challenge: satisfying the energy demand in coastal areas by providing or enhancing coastal protection but at the same time securing local sea activities, navigation and marine and coastal eco-systems. 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 in the literature. These studies are mainly based on numerical modelling and small scale experiments employing typically less than 10 WECs tested under basic sea states, e.g. regular waves.

The general objective of the present doctoral research aims to **link renewable wave energy projects to coastal defence systems**.

In order to achieve this objective, an accurate understanding of the '*WEC farm effects*' is required, which consist of both the interactions between WECs in a wave farm (park effect) and their impact on the environment (far-field effects). With this knowledge, the optimal geometric lay-out of WEC farms can be determined and changes in wave conditions can be quantified.

Therefore, this PhD research focuses on WEC farm effects and deals with fundamental **literature knowledge gaps**:
(1) the lack of experiments with large WEC farms and the absence of a database for validation of numerical models;
(2) the lack of a generic and simple WEC to be used in farm experiments, as the large number (~150) and high complexity of the existing WEC concepts makes tests with large WEC farms difficult and expensive;
(3) the lack of a numerical approach suitable for WEC farm effects in order to tackle both interactions between the WECs (park effect) and far-field effects of wave farms, simultaneously.

Taking into account the above mentioned shortcomings of the present state-of-the-art, this doctoral work has focused on the following **research deliverables**, which are discussed throughout three main parts of the PhD manuscript (following the same numbering as that of points 1–3 listed above):

(1') The major research achievement is the realization of the **first experiments with large wave energy converter farms**, to investigate WEC farm effects in detail. For this purpose, experiments using large farms of up to 25 heaving point absorber type WECs have been performed in the Shallow Water Wave Basin of the Danish Hydraulic Institute – DHI (width x length: 35 mx25 m), as part of this PhD research and within the 'WECwakes' project. This research has been funded by the FP7 EU 'HYDRALAB IV programme' and the Research Foundation Flanders – FWO (Belgium). This experimental set-up of 25 WECs in a farm lay-out is at present the largest of its kind.

The employed methodology included testing of farms with varying WEC number, using both aligned and staggered configurations (examples presented in Fig. 1 -top and bottom-, respectively).

As a result, a comprehensive database has been crea ted, which includes measurements of device response under wave action and modification of the wave field for a wide range of geometric lay-out configurations and wave conditions. The aim was to quantify WEC farm effects and to provide data for the understanding of WEC interactions and for the evaluation of numerical models.

(2') Before performing these experiments, the **development of a simple WEC** has been achieved, specially designed for wave farm testing. The developed device has been experimentally and numerically tested in detail, prior to the WEC farm experiments, in order to ensure high performance. The developed WEC has been then reproduced in 25 identical copies for use in the farm experiments.

(3') In addition, a methodology has been developed for the numerical simulation of the wave field modifications as a result of wave energy extraction by wave devices. A coupled numerical modelling has been developed for the combined simulation of WEC farm effects, resulting in a **time-efficient and accurate numerical tool**.

Extended data analysis of the performed WEC farm experiments has shown that **power production and wave attenuation** induced by large WEC farms 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. In other words, for practical wave energy applications, WEC farm effects have an influence on neighbouring activities in the sea, coastal eco-systems, the coastline and the coastal defence parameters, and even ship navigation.

The **data analysis** of the WEC farm experiments aims to investigate the effect of changing the WEC farm configuration and the sea state conditions, on the resulting power output and wave height attenuation.

In order to quantify the effect of the heaving WECs on the undisturbed wave field, the decrease in wave height due to wave power extraction by the WECs, has been calculated for the 25-WEC farms presented in Fig. 1. As such, 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 aligned geometric configuration (illustrated in Fig. 1-top). Wave height attenuation increases at the same areas, reaching 20.8%, when the same 25 WECs are arranged in staggered geometric configuration by shifting two WEC rows (illustrated in Fig. 2-bottom). The staggered WEC farm causes higher wave attenuation due to its higher power extraction, as a result of the geometrical lay-out of shifted rows.

The same WEC farms under conditions representing short-crested waves (so called '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 of WECs 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.

However, it is important to 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 attenuation. Within the framework of this PhD work, wave height attenuation in the lee of large farms has been measured experimentally for the **first time**. Moreover, based both on the obtained results and on the existing literature, recommendations and a first series of **guidelines for design of WEC farms** have been derived.

The **lessons learned** through experiences from this PhD research can be utilized by others for similar applications. Examples of such applications are groups of any floating and heaving structures, as well as wave farms composed of any type of devices. Firstly, WECs operating within farms exhibit different response, in terms both of power production and far-field effects, compared to the response of single isolated devices. Therefore, WEC concept developers need to take into account the park-effect, which is present even for large spacings between the devices, and not only focus on the optimization of single devices which is the usual practice. Secondly, realistic sea states

and wave directionality (i.e. wind seas) should be essentially investigated (experimentally or numerically) when testing the performance of WEC farms. This remark is important, as until very recently, WEC concept and WEC farm developers have been concentrating on testing point absorber WECs mostly under long-crested regular waves (and less often, irregular waves). This practice has been performed based on the assumption that wave directionality is not significant for point absorber WECs, which however, is not valid for farms, as the geometric configuration and interactions affect the response of the devices. Thirdly, WEC farm effects are, to a high degree 'case-sensitive', and depend on the local wave conditions, the characteristics of 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**, of the established database and of the research conclusions is wide, and can also be used by others than wave farm developers for similar study cases.

For instance, knowledge of the resulting area of wave height attenuation is useful for the assessment of the environmental impact of wave farms. Specifically, the results for wave height attenuation found downwave of farms can be further used for estimating the coastline evolution due to the presence of wave 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. 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 'sheltering effect'** for coastal protection. As mentioned previously, comparative analysis from different geometrical farm configurations and wave conditions has resulted in a first series of guidelines for WEC farm design. These guidelines can be used for **WEC farm 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.

In addition, **a unique comprehensive experimental WEC farm database** with a wide field of applications has been established. The database can be used not only by WEC farm developers, but is also extrapolated to floating structures and platforms, heaving cylinders and buoys under wave action, to obtain insight in the wave impact on such structures and wave field modifications around them. This 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 wave directionality).

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 heaving 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. 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.

To conclude, the research findings point up the need to take WEC farm effects into significant consideration in order to optimize power production of such wave energy projects, by simultaneously providing coastal protection, and securing local sea activities, navigation and marine eco-systems. This research is a proof-of-application with positive economic impact, demonstrating the ability to **combine the harvesting of energy from sea waves with coastal defence systems**, resulting in **cost reduction** for both applications when wave energy converters operate as multi-purpose devices.
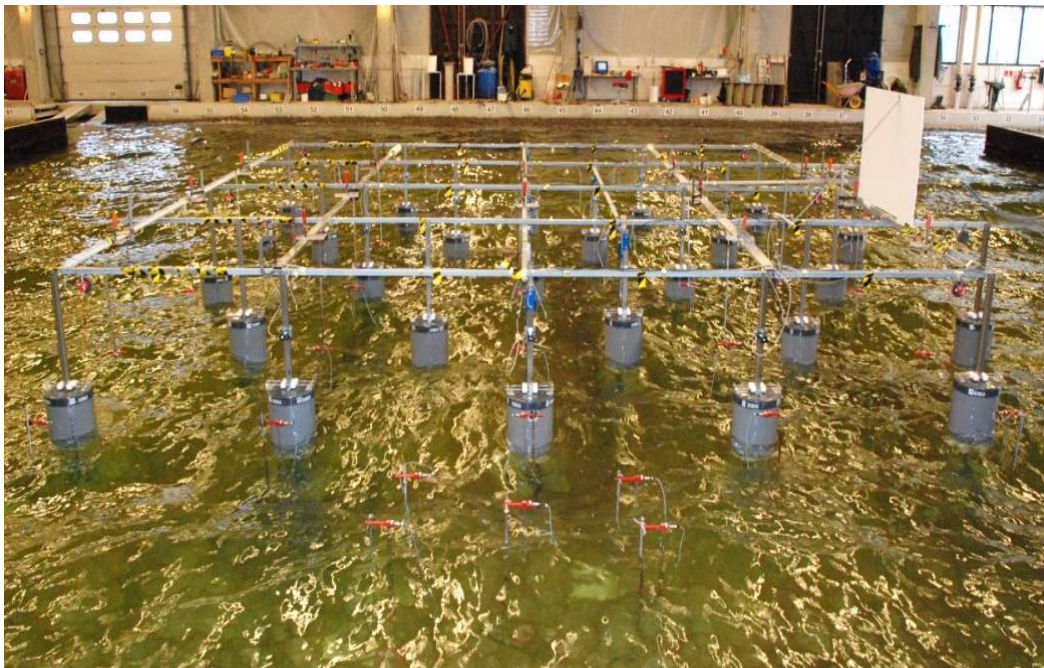
Fig. 1. The 25–WEC farm in the DHI Shallow Water Wave Basin (Hørsholm, Denmark) under irregular long–crested waves. View from behind the wave generator. Top: **aligned**; bottom: **staggered** lay–out.

Acknowledgements