# Development of an Integrated Tool for Numerical Modelling of OWC-WECs in Vertical Breakwaters

M.T. Reis[1], E. Didier[1], J. Dias[1], A. Mendonça[1], J.M.P. Conde[2], M.G. Neves[1], C.J.E.M. Fortes[1] & P.R.F. Teixeira[3]

*[1]Harbours and Maritime Structures Division (NPE), Hydraulics and Environment Department (DHA), National Laboratory for Civil Engineering (LNEC), Lisbon, Portugal*

*[2]UNIDEMI, Faculdade de Ciências e Tecnologia (FCT), Universidade Nova de Lisboa (UNL), Caparica, Portugal*

*[3]Escola de Engenharia, Universidade Federal do Rio Grande, Rio Grande, RS - Brazil*

*E-mail: treis@lnec.pt*

ABSTRACT: This paper describes the advances on the research project DITOWEC – "Development of an Integrated Tool for Numerical Modelling of Oscillating Water Column Wave Energy Converters Integrated in Vertical Breakwaters", whose main objective is developing an innovative integrated tool for numerical modelling of wave propagation from offshore to nearshore, of wave-structure interaction and of the complex nonlinear hydrodynamic and aerodynamic phenomena that occur in an OWC-WEC. Its development is supported by experimental data from physical model tests carried out at LNEC. The tool will directly allow the simulation of the OWC-WEC of Pico, Azores (Portugal), at prototype scale, with real bathymetry and offshore wave climate, eliminating any problem related to scale effects that may occur in physical modelling. This application allows the comparison of numerical results and prototype measurements for different incident wave conditions, given that this structure has been monitored since 2005. Methodologies of the DITOWEC project and accomplishments achieved so far are herein described, with the focus on its more relevant results.

## 1. INTRODUCTION

Breakwaters play a role of dissipating incident wave energy and sheltering harbour basins and entrances against waves, guarantying the safety of ship manoeuvres. From the several types of existing breakwaters, the rubble mound and the vertical breakwaters are the most commonly used to shelter harbour basins. The choice of the most appropriate type depends, for example, on the local wave regime and bathymetric characteristics.

Besides the breakwater's classic functions, they have recently been assigned a complementary function: to be the support of wave energy plants for electric production. An example of that is the use of the Oscillation Water Column (OWC) technology. In this technique, as waves enter and exit the plant, the water column inside the OWC plant moves up and down producing an air flow that induces the rotation of a turbine connected to an alternator (Falnes, 2007). This type of wave energy device can be integrated, during the construction, on a vertical breakwater consisting of caissons of great dimensions. Examples of this innovative solution are the wave energy plants of Sakata in Japan (1990) and, more recently, of Mutriku in Spain (2011) (Figure 1).

The integration of Wave Energy Converter (WEC) devices on vertical breakwaters has several advantages:

- Financial amortization of the infrastructure through the exploitation of wave energy;
- Reduced environmental impact, since the device integration area has already been affected by harbour/coastal protection structure;
- Production of renewable energy;

- Location of the WEC in areas of higher wave energy than on the coast (the local depth, in the case of vertical breakwaters, is typically of the order of 20-25 m, which favours the conservation of incident wave energy);
- Reduced maintenance costs due to the ease of access to the WEC.

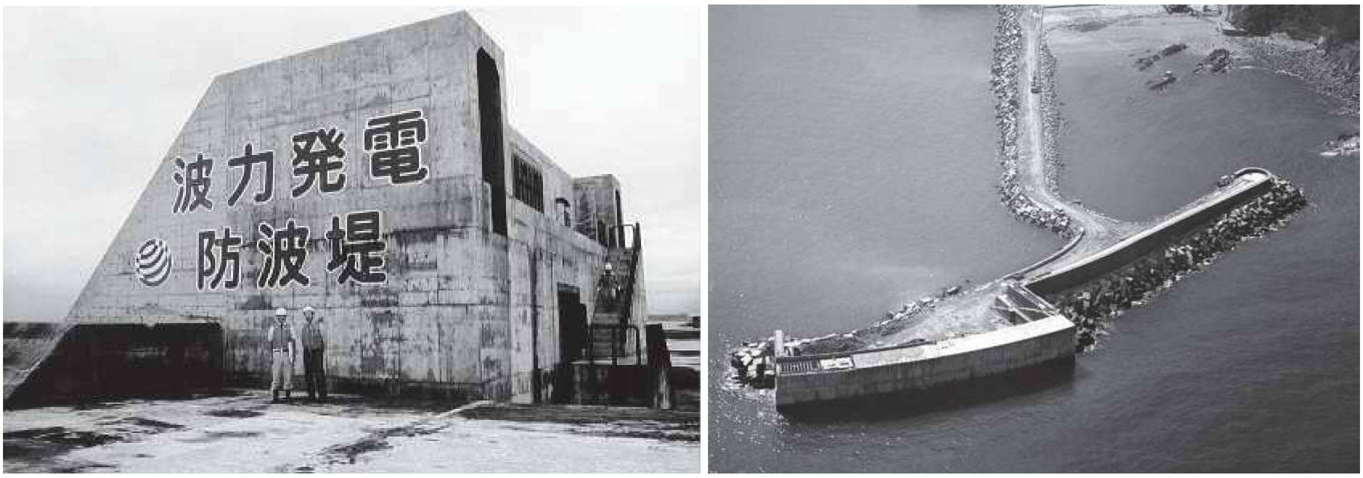

Figure 1. Examples of wave energy plants integrated on vertical breakwaters: Sakata (Japan) and Mutriku (Spain).

Studies of devices integrated in vertical breakwaters are complex, involving hydrodynamic and aerodynamic phenomena, strong interactions between the two phases (i.e. water and air) and non-linear phenomena due to:

- Wave propagation;
- Wave-structure interaction;
- Interaction between the air and the up and down movement of the water column inside the OWC chamber;
- Cyclic air compression and expansion in the pneumatic chamber due to the reduction of the area between the pneumatic chamber and the duct section where the turbine is located;
- Effects of pressure loss at the turbine responsible for a strong interaction with the free surface movement in the chamber.

To study the integrated OWC-WEC in vertical breakwaters or on the shoreline, physical model studies can be performed. However, the costs are high, tests are very time consuming, scale problems can appear and versatility of the physical model device is low.

Numerical modelling can be an interesting solution when applied and used carefully. However, numerical models currently used cannot simultaneously model the wave propagation, the wave-structure interaction and the airflow in an OWC pneumatic chamber. The purpose of this project is the development of an innovative integrated tool capable of modelling all these phenomena.

The tool development consists in coupling the numerical models SWAN (Booij *et al.*, 1999) and COULWAVE (Lynett & Liu, 2004), for the wave propagation from offshore to nearshore, and URANS (Unsteady Reynolds Averaged Navier-Stokes) numerical models OpenFOAM (OpenFOAM Foundation, 2011), FLUINCO (Teixeira *et al.*, 2009), FLUENT (FLUENT, 2006) and IH2VOF (Lara *et al.*, 2011) for wave-structure interaction, hydrodynamics and aerodynamics of the OWC device.

This integrated tool is validated with experimental data from physical model tests at LNEC before being applied to the OWC-WEC of Pico, Azores (Portugal) (Falcão, 2000), for real bathymetry and offshore wave climate (Tolman, 1999; Simões, 2006). This power plant has been monitored since 2005 by the Portuguese Wave Energy Centre (Brito Melo *et al.*, 2007), which allows comparing numerical and prototype results for several incident wave conditions.

The numerical integrated tool is built to support ocean and coastal engineering projects, for implementation of coastal/harbours structures taking into account the real bathymetry and offshore wave climate, for wave propagation from offshore to the structure (and inside the OWC device), for wave-structure interactions, for nonlinear phenomena and for interactions between hydrodynamics and aerodynamics of a OWC-WEC.

## 2. OUTLINE OF THE METHODOLOGY

The development of the integrated tool, consisting in the coupling of the numerical models SWAN, COULWAVE and URANS, is based on the following approach:

- To carry out physical model tests in one of LNEC´s wave flumes to obtain data compatible with the analysis of the numerical models, to validate the URANS models and the integrated tool;
- Development of a coupling methodology, similarly to that of the integrated system HIDRALERTA (Fortes *et al.*, 2014), for the models SWAN, COULWAVE and URANS, to obtain the integrated tool;
- To perform a rigorous and detailed analysis of the URANS models for modelling hydrodynamic (wave propagation, wave-structure interaction) and aerodynamic (airflow in the pneumatic chamber and turbine duct) phenomena, for mesh convergence for hydrodynamic and aerodynamic flows, for numerical scheme accuracy, for turbulence models, for CPU time, for capturing (Volume of Fluid – VOF method) and tracking (Arbitrary Lagrangian Eulerian - ALE method) approaches for wave propagation and wave breaking, among others;
- To validate the URANS models and the integrated tool with data from LNEC's physical models;
- To apply the integrated tool to a prototype and functioning WEC, the OWC power plant of Pico island, Azores (Portugal) (Falcão, 2000), taking into account the real bathymetry and offshore wave climate, which will be defined based on wave data from the CLIMAAT project (Simões, 2006) and the numerical results from the hindcast model WaveWatch III (Tolman, 1999). This power plant has been monitored since 2005 by the Portuguese Wave Energy Centre (Brito Melo *et al.*, 2007).

Sections 3 to 6 describe, for each of the above steps, the work planned within the scope of the DITOWEC project and what has been accomplished so far.

## 3. WAVE FLUME PHYSICAL MODELLING

To study the hydraulic functionality of an OWC-WEC power plant integrated in a vertical breakwater or in the shoreline, a set of 2D physical model tests are being conducted at LNEC. The main goal of these tests is twofold: the study of the hydrodynamic characteristics of the plant and the validation of the developed numerical model.

The tests are performed in one of LNEC's wave flumes, which is approximately 50 m long and it has an operating width and an operating water depth of 0.80 m. The flume is equipped with a random absorbing piston-type wave maker and resistive-type wave gauges are used to determine the wave characteristics in front of the wave maker and in front of the tested structures. A geometric scale of 1:35 is used in order to reduce scale effects.

Three simplified plant geometries are tested (Figure 2): i) a chamber with a fully opened airway, allowing free air flow in and out of the chamber; ii) a chamber with a partially opened airway (delivering air flow by means of an area reduction duct); and iii) a chamber delivering air flow to a turbine model, simulated by a porous membrane.

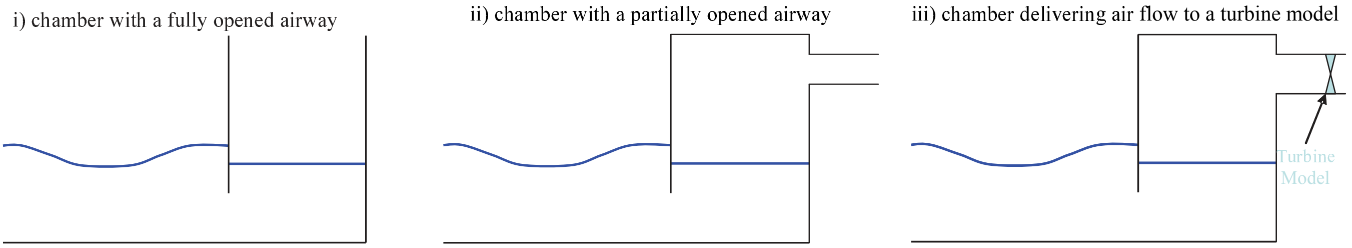
i) chamber with a fully opened airway
ii) chamber with a partially opened airway
iii) chamber delivering air flow to a turbine model

Figure 2. Simplified plant geometries tested at LNEC.

The different characteristics of the measured quantities (air pressure and water levels inside the chambers), which have different scale effects and different peculiarities to be taken into account, makes this model especially interesting. Particular attention has to be paid to ensure a staunch model, to avoid any air leakage from the chambers, a crucial issue to the air pressure measurement accuracy. The analysis of the air pressure is especially important to design the walls of the hydro-pneumatic chamber, the valves and other equipment. The water level inside the plant is important to evaluate the cases when air enters the chamber, to define when the turbine access should be closed and to determine the level of the chamber entrance. To prevent turbine damage and plant lower production, no water should be allowed to enter the turbine area, which limits the maximum level inside the chamber. Having all of these in mind, pressure and water level inside the chamber are measured and analysed in detail, as well as possible scale and model effects and their influence on the results.

A PC is used to store and analyse the physical model data. Simultaneous acquisition of wave and pressure at different points along the model and the chamber is carried out. In order to measure free surface elevation inside the OWC device, three resistive-type wave gauges are used for geometry i) above and two laser displacement sensors are used for geometries ii) and iii). Data are especially designed for validation of the numerical model, for different level of the chamber complexity.

Up to the present date, physical modelling of the chamber with a fully opened airway (geometry i)) has been performed for a regular wave height, *H*, of 0.038 m and a wave period, *T*, ranging from 0.67 to 2.30 s (Figure 3). Water depth was 0.46 m at the wave maker and 0.15 m at the chamber entry. The chamber has 0.20 m width and an opening 0.075 m wide, which is half the water depth at the chamber.

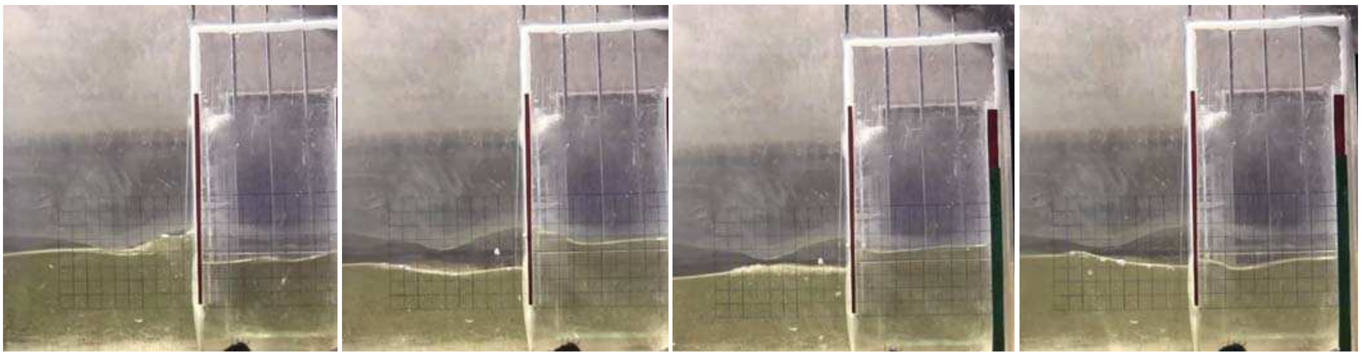

Figure 3. Physical model near the water chamber for different instants during a test carried out for *T*=1.0 s and *H*=0.038 m.

Figure 4 shows a scheme of the wave flume, water chamber and wave gauge positions. Free surface elevation was measured at ten sections of the wave flume, near the wave maker, at the toe of the smooth ramp, on the ramp, before and inside the water chamber. Each wave condition was repeated eight times to ensure the accuracy of the experimental results.

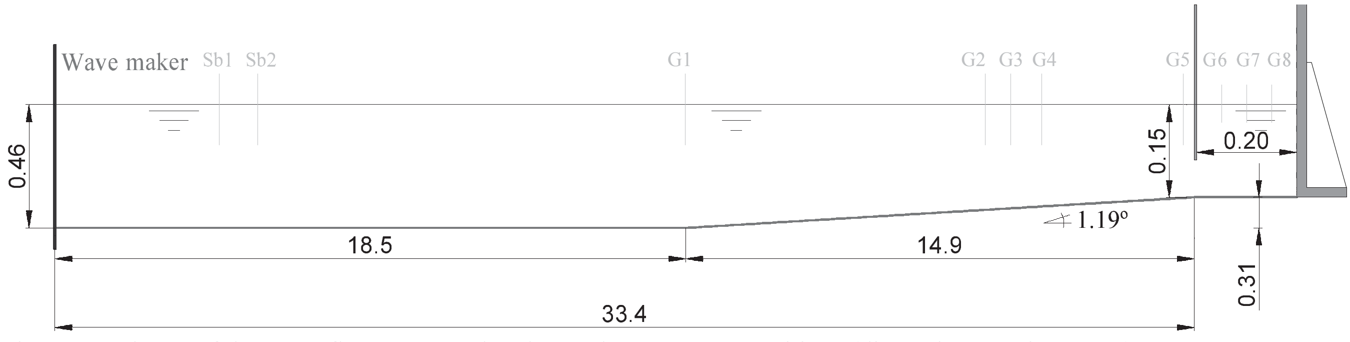

Figure 4. Scheme of the wave flume, water chamber and wave gauge positions (dimensions are in meters).

Figures 5 and 6 present the time series of free surface elevation, $\eta$, at gauge G1 (located at the toe of the smooth ramp) and of the mean free surface inside the water chamber (obtained from gauges G6 to G8), for a wave period *T*=1.0 s and a wave height *H*=0.038 m. As expected, Figure 5 shows that the incident wave is correctly generated at the wave flume and Figure 6 indicates that the free surface inside the water chamber presents a periodic trend, with a regular mean wave height.

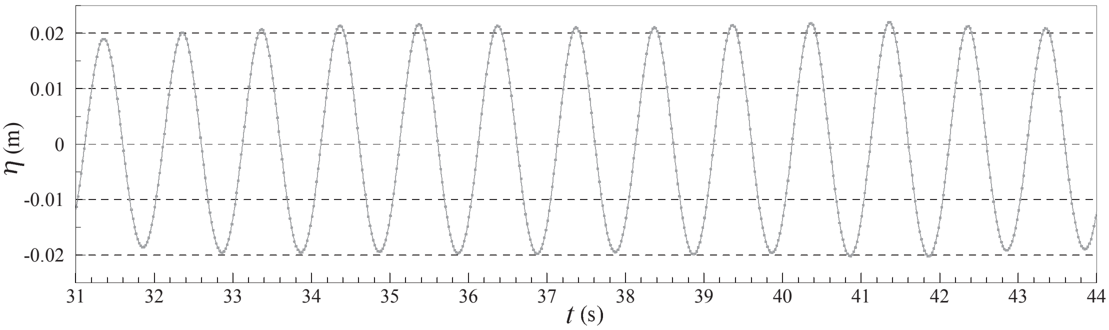

Figure 5. Time series of free surface at gauge G1, at the toe of the smooth ramp, $T$=1.0 s, $H$=0.038 m.

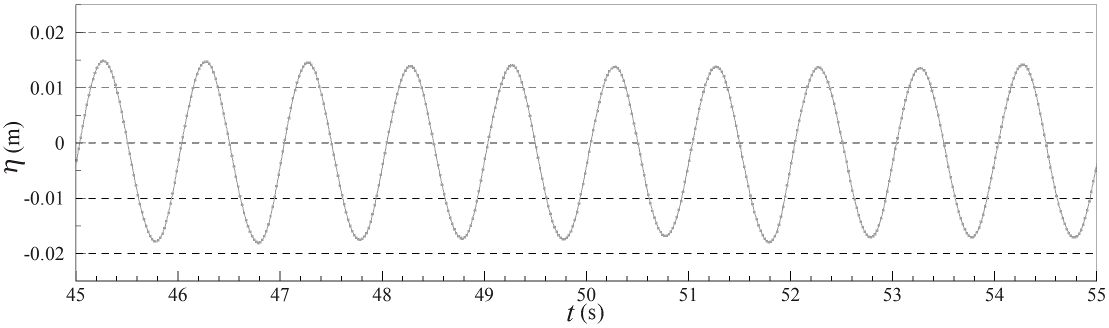

Figure 6. Time series of mean free surface inside the water chamber, $T$=1.0 s, $H$=0.038 m.

## 4. DEVELOPMENT OF THE INTEGRATED TOOL

The main objective of the integrated tool to be developed within the scope of the DITOWEC project is to permit the characterization of the wave field from offshore to the vicinity of the OWC and the structure of the device, of the wave-structure interaction and of the air flow inside the OWC chamber.

Therefore, three types of numerical models are coupled: the wave propagation model SWAN (Booij *et al.*, 1999), the COULWAVE model (Lynett & Liu, 2004) and URANS models (Teixeira *et al.*, 2009; OpenFOAM Foundation, 2011; FLUENT, 2006; Lara *et al.*, 2011) for studying wave-structure interaction and air flow inside the OWC chamber.

SWAN is a third-generation numerical wave model for spectral wave-current propagation (Booij *et al.*, 1999) that allows simulating the generation, propagation and dissipation of sea waves from offshore to inshore. COULWAVE (Lynett & Liu, 2004), based on the Boussinesq equations, is a surface wave model that solves problems related with depth integration, taking into account phenomena like wave breaking and friction. While SWAN is more adequate for large areas, it does not give an accurate description of waves in the surf zone, as COULWAVE does. Phenomena like wave breaking, bottom friction, run-up and others are better simulated with COULWAVE model. However, COULWAVE is quite demanding in terms of CPU computational time and therefore cannot deal with large areas. Since COULWAVE is a depth integrated model, it cannot describe the wave-structure interaction and specially the air flow in the pneumatic chamber. So, URANS models are used in a coupled manner, to reduce their own limitations, for modelling hydrodynamics and aerodynamics of the device.

The development of the integrated tool is performed in two phases:

- Phase 1 - Construction of the tool:

(i) Identification of the SWAN wave variables that will constitute the boundary forcing conditions of the COULWAVE model, and subsequently, the COULWAVE results that will constitute the boundary forcing conditions of URANS models;

(ii) Modification of the COULWAVE and the URANS input and output files to automatically incorporate the boundary conditions given by SWAN and COULWAVE, respectively.
Some integrated models have already been developed at LNEC, such as the HIDRALERTA system (Fortes *et al.*, 2014) that includes six wave propagation models based on mid-slope equations (DREAMS, REF/DIF1 and REF/DIF S), on the Boussinesq equation (FUNWAVE 1D and 2D) and

on the spectral wave propagation model (SWAN).

Coupling with URANS models can be performed through the transfer of parameters from COULWAVE, such as reconstructed velocity profiles, free surface levels or spectral distribution at boundary inlet of URANS computational domain.

- Phase 2 - Validation of the above tool using results from the physical models developed out at LNEC. This permits the analysis of the performance of the integrated tool in simple test cases, the error elimination and the calibration of the tool itself (COULWAVE and SWAN depend on a set of parameters that has to be calibrated).

The work performed so far comprises data transfer between the models SWAN and COULWAVE. Outputs from SWAN, such as significant wave height, peak or mean period, mean wave directions and wave spectrum, are the input variables of the COULWAVE model. The COULWAVE interface is being constructed and linked to SWAN interface. The next step encompasses the development of an URANS interface and its link to the other model interfaces.

## 5. NON-LINEAR HYDRODYNAMIC/AERODYNAMIC NUMERICAL MODELLING AND VALIDATION

The main objective of the numerical modelling undertaken within the DITOWEC project is to develop/adapt fully non-linear time-domain hydrodynamic and aerodynamic numerical codes based on URANS equations:

- The FLUINCO code (Teixeira *et al.*, 2009), a finite element code based on the free surface tracking method to model the free surface flow and on an Arbitrary Lagrangian-Eulerian formulation;
- The OpenFOAM code (OpenFOAM Foundation, 2011), a finite volume open source code, based on the free surface-volume capturing method VOF (Volume of Fluid);
- The IH2VOF code (Lara *et al.*, 2011), a finite volume code based on the free surface-volume capturing method VOF (Volume of Fluid);
- The FLUENT code (FLUENT, 2006), a finite volume code based on the free surface-volume capturing method VOF (Volume of Fluid).

With these four numerical codes it is possible to assess the non-linear effects due to wave-structure interaction, interaction between free surface flow motion in pneumatic chamber and air inside the OWC and the air flow inside the OWC (chamber and duct). However, IH2VOF code allows only the simulation of the hydrodynamic flow, FLUINCO code allows the simulation of the hydrodynamic flow, with pressure effects in the pneumatic chamber modelled using a constant/variable charge method similar to the one proposed by Josset & Clément (2006) and OpenFOAM and FLUENT codes allow the direct simulation of both the hydrodynamic and the aerodynamic flows inside the pneumatic chamber, including turbine pressure drop. Consequently, the numerical time-dependent calculations will be performed using these four codes, capable of modelling wave propagation, fluid-structure interaction, viscous and turbulence effects in the water and in the air, and the dumping caused by a power take-off (PTO) system.

An interim objective of this numerical modelling is the determination of which of the options used in the numerical codes produce faster and more accurate solutions in simulating the phenomena occurring in this type of fluid-structure interaction. For this determination, it is necessary to:

- Assess which models/numerical schemes, from those options available in the code, are most accurate/stable for wave propagation and breaking. Several options are available: implicit or explicit VOF scheme; 1st or 2nd order time integration; free-surface capture scheme (HRIC, CICSAM, GEO-Reconstruct); pressure-velocity coupling algorithm (SIMPLE, SIMLEC, PISO); turbulence models;
- Choose/implement a pressure drop model (pressure drop, porous jump, porous medium, actuator disk) to simulate the dumping effect occurring due to the air pressure drop at the PTO (usually a self-rectifying Wells or impulse turbine);
- Analyse the grid convergence;
- Implement: a wave-maker for simulating an incident irregular wave; and an active generating and absorbing incident boundary condition suitable for application to the study of wave-structure

interaction and coupling with a global model of wave propagation.

The numerical modelling results will be validated using, mainly, the physical model data collected at LNEC. It aims at optimizing the simulation parameters (mesh discretization, models, schemes and algorithm) and the accuracy of the simulations. This validation is of paramount importance.

To allow direct and fair comparison between the numerical model results and the experimental data, the models will be run using the same geometrical scale as that applied in the experiments. The validation covers the three different plant geometries tested (Figure 2) and the following parameters:

- Free-surface elevation (both in the flume and in the chamber);
- Amplification factor and phase angle;
- Sloshing in the OWC;
- Air pressure in the chamber, in the turbine duct and at the turbine section.

Before applying the developed integrated tool to a real case study of an OWC wave energy plant, its performance is evaluated by applying the tool to the physical model conditions tested and by analysing the performance of each numerical model coupled within the tool (global and local wave propagation models; wave-structure interaction models; head loss model to account for the turbine effect).

Up to now, several numerical tests have been performed with FLUENT and IH2VOF codes for the chamber with a fully opened airway, using the same scale as in the physical model (scale 1:35), for validating the numerical models.

Figures 7 and 8 present the time series of the free surface elevation at gauge G1 and of the mean free surface elevation inside the water chamber, respectively, comparing experimental data with FLUENT numerical results for $T$=1.0 s and $H$=0.038 m. FLUENT results are obtained using a mesh with 201559 control volumes, with refinement at the free surface and inside and near the water chamber for accuracy modelling of free surface and flow at the chamber entry.

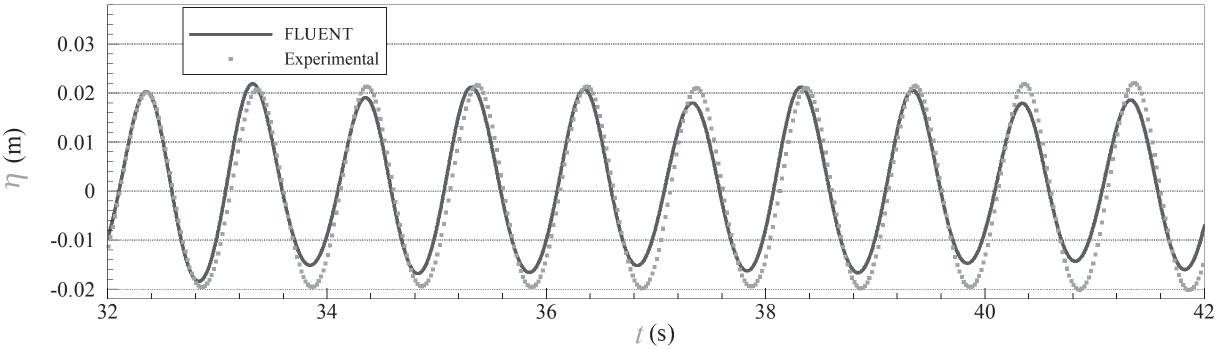

Figure 7. Time series of free surface elevation at gauge G1, at the toe of the smooth ramp, $T$=1.0 s, $H$=0.038 m.

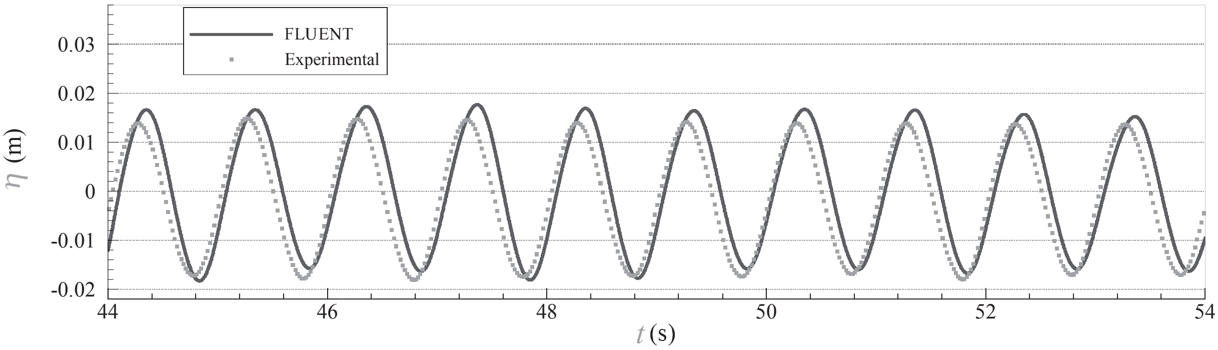

Figure 8. Time series of mean free surface inside the water chamber, $T$=1.0 s, $H$=0.038 m.

A good agreement was obtained between experimental and numerical results for both time series. The amplification factor, ratio between the mean wave height inside the water chamber and the incident wave height, was 0.818 and 0.864 for experimental and numerical results, respectively. Phase lag, which is the angular difference between the wave inside and outside the chamber, was 132º and 135º for experimental and numerical results, respectively.

Figure 9 shows the free surface position and velocity vectors for the wave crest and the wave trough position of mean free surface inside the water chamber.

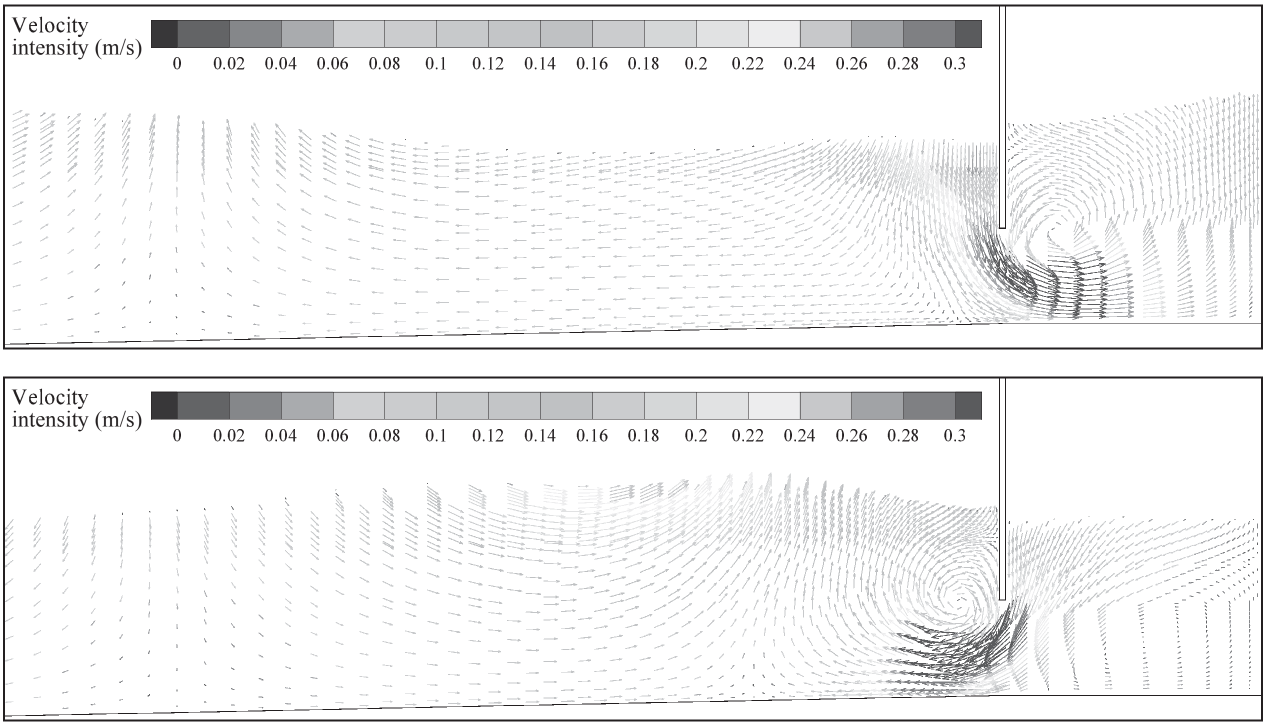

Figure 9. Velocity vectors at the crest and at the trough position of mean free surface inside the water chamber, $T$=1.0 s, $H$=0.038 m.

At the wave crest position, an anti-counterclockwise vortex was present in the water chamber. Its formation was due to the intense flux noted at the water chamber entrance and the high velocity. The vortex fills only a part of the chamber. At the wave trough position, the water flux exits from the water chamber and formed a counterclockwise vortex outside the chamber. An anti-counterclockwise vortex, with a smaller intensity than the outside one, can be observed inside the chamber.

## 6. INTEGRATED TOOL APPLICATION TO A REAL OWC-WEC

The final objective of the DITOWEC project is to apply the developed and validated integrated tool to a real case of an OWC-WEC integrated in a vertical breakwater, i.e. simulate the wave field from offshore to the breakwater vicinity, the wave-structure interaction and the water and air flows inside the OWC chamber.

To perform this application, the integrated tool will follow the subsequent steps:

- First, use will be made of either wave data from the CLIMAAT project (Simões, 2006) or numerical results from hindcast models (WaveWatch III; Tolman, 1999), combined with data on the seabed morphology and roughness, coastal geomorphology and local atmospheric conditions (such as local wind and pressure). The SWAN model (Booij *et al.*, 1999) will characterize the wave field from offshore to close to the OWC and will give the boundary condition to force the COULWAVE model;
- Then, the COULWAVE model (Lynett & Liu, 2004) evaluates the wave parameters (wave heights, periods and directions) up to the boundary condition for the URANS models. This will be carried out either for frequent offshore wave climates, single extreme events or sequences of noticeable events;
- Finally, URANS models simulate the flow effects near and inside of the OWC-WEC: water inflow/outflow of the pneumatic chamber, sloshing in the pneumatic chamber, air flow in the chamber and through the turbine, pressure drop in the turbine, resonance and phase lag in the device.

This application combines the knowledge gained throughout the project in the simulation of a real prototype, already in operation. The prototype that will be the test case to be simulated with the integrated tool is the Pico island OWC-WEC, which is located on shore, in the Azores islands, Portugal (Figure 10). It is an experimental structure for electric energy production from sea-wave energy, which has started operating in 1999 (with an installed power of 400 kW) and it is the first European converter to use the oscillating water column (OWC) technique associated to a Wells turbine.

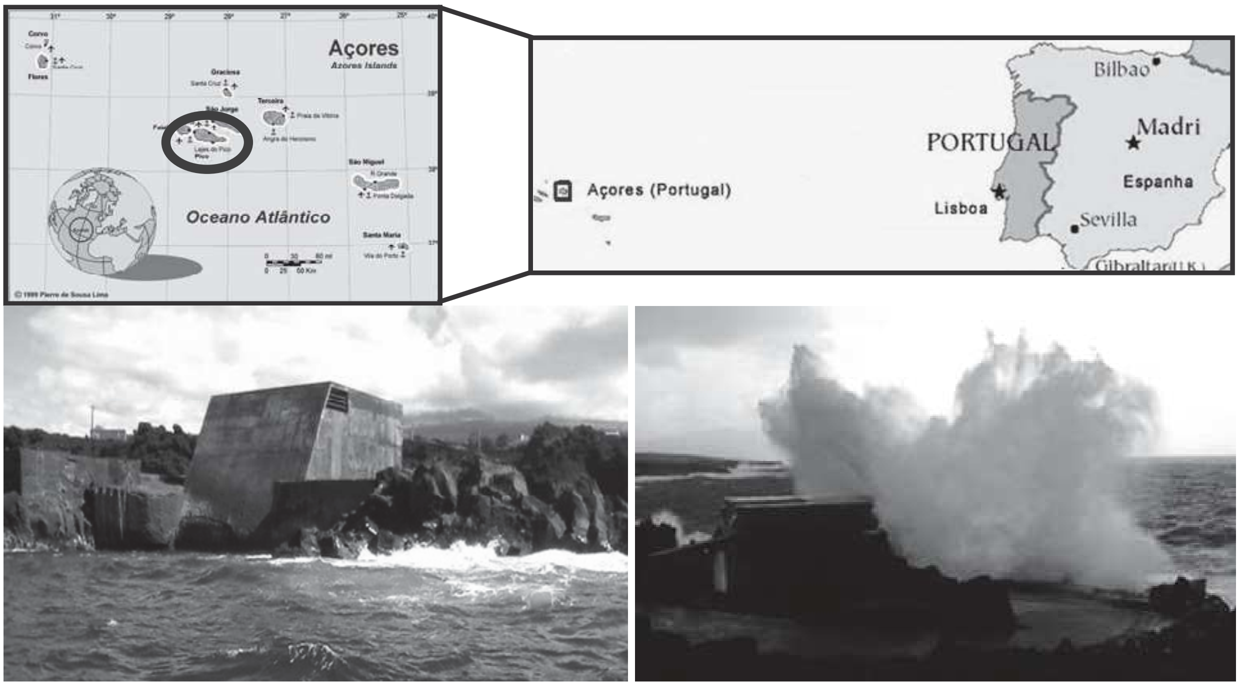

Figure 10. Location (Pico island, Azores, Portugal) and general view of the OWC-WEC that will be simulated with the integrated tool.

Three-dimensional numerical modelling of this OWC-WEC has been carried out previously by the authors using FLUENT (Figure 11).

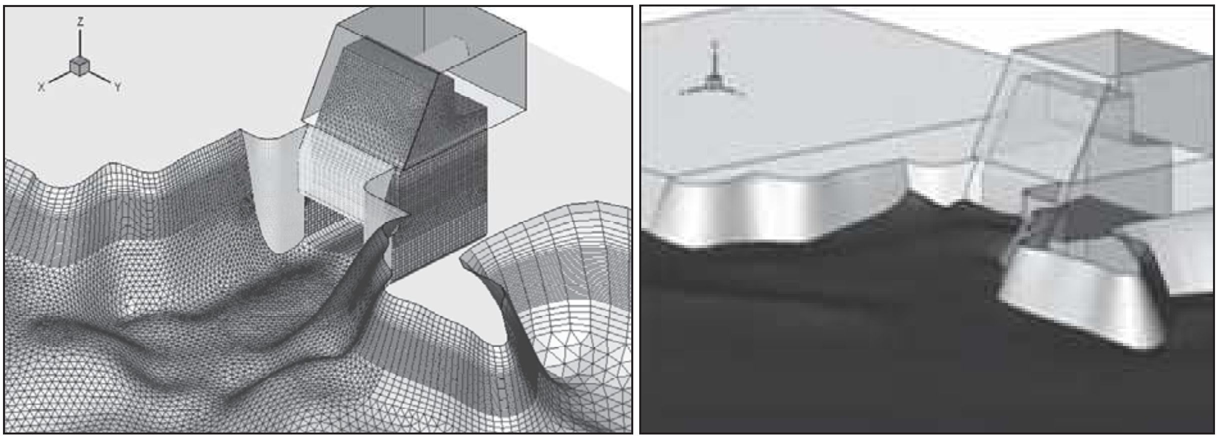

Figure 11. Three-dimensional numerical modelling of the Pico OWC-WEC carried out previously with FLUENT (FLUENT, 2006).

For this test case, in-situ measurements performed by the Portuguese Wave Energy Centre (Brito Melo *et al.*, 2007) are already available.

Applications of the SWAN-COULWAVE models are undergoing to characterize the wave regime in front of the Pico central. SWAN is forced by the offshore sea wave characteristics estimated by WAVEWATCH III (Tolman, 1999), for a period of 1979 to 2014, by the wind fields obtained with The Fleet Numerical Meteorology and Oceanography Center (FNMOC), also at a regional level, as well as by tide levels, obtained from NAVGEM (Whitcomb, 2012) and XTide (Flater, 1998) models, respectively. XTide provides only astronomical tide levels, so a constant storm surge was considered. Then, these values are transferred to the coast using the SWAN model up to the -10 m(ZH) contour. Selected waves with high wave height and mean period are then transferred with COULWAVE to the shore.

A more extensive work is also being done with SWAN applied to the whole Azores archipelago, in order to establish wave regimes around its 9 islands and the energetic potential for each island, with a special attention to several harbour structures where OWC devices could be integrated, such as Ponta Delgada and Terceira harbours.

## 7. CONCLUDING REMARKS

This paper describes the research project DITOWEC – "Development of an Integrated Tool for Numerical Modelling of Oscillating Water Column Wave Energy Converters Integrated in Vertical Breakwaters" and its accomplishments achieved until now. As the name suggests, the innovative tool, implemented in a GIS environment, follows the basic idea of using numerical modelling to simulate, wave propagation from offshore to nearshore, wave-structure interaction and the complex nonlinear hydrodynamic and aerodynamic phenomena that occur in an OWC-WEC.

The numerical models considered are the SWAN model (Booij *et al.*, 1999), the COULWAVE model (Lynett & Liu, 2004) and several URANS models, such as FLUINCO (Teixeira *et al.*, 2009, OpenFOAM (OpenFOAM Foundation, 2011), IH2VOF (Lara *et al*., 2011), and FLUENT (FLUENT, 2006).

The tool development and validation is supported by experimental data from 2D physical model tests carried out at LNEC and also by prototype data available for the Pico OWC-WEC, in the Azores, Portugal, which has been monitored by the Portuguese Wave Energy Centre (Brito Melo *et al*., 2007) since 2005.

Here we have presented the different phases of the project, the methodology involved, the work carried out so far and the prototype case study used to validate the new integrated tool, with real bathymetry and offshore wave climate, eliminating any problem related to scale effects that may occur in physical modelling.

The work carried out to date shows a good agreement between experimental and numerical results: time series of free surface elevation at different gauges, time series of mean free surface inside the water chamber, amplification factor, phase lag, free surface position and velocity vectors for the wave crest and the wave trough positions of mean free surface inside the chamber. This finding suggests that the new integrated tool has the potential to become a useful tool to support ocean and coastal engineering projects, for implementation of coastal/harbour structures taking into account the real bathymetry and offshore wave climate, for wave propagation from offshore to the structure (and inside the OWC device), for wave-structure interactions, for nonlinear phenomena and for interactions between hydrodynamics and aerodynamics of a OWC-WEC, due to its capacity to effectively reproduce the main phenomena involved in this type of study.

## ACKNOWLEDGMENTS

The authors acknowledge the financial support of project ref. PTDC/ECM-HID/1719/2012 by FCT, Portugal.

## REFERENCES

Booij N., Ris R.C., Holthuijsen L.H. (1999). *A third-generation wave model for coastal regions 1. Model description and validation*. Journal of Geophysical Research, Vol. 104(C4), pp. 7649-7666.

Brito Melo, A., Neumann, F., Didier, E., Sarmento, A. (2007). Full-scale data assessment in OWC Pico Plant. Proc. International Offshore (Ocean) and Polar Engineering Conference - ISOPE, Lisbon, Portugal, pp. 447-454.

Falcão, A.F.O. (2000). The shoreline OWC wave power plant at the Azores. Proc. 4th European Wave Energy Conference, Aalborg.

Falnes, J (2007). *A review of wave-energy extraction.* Marine Structures, Vol. 20(4), pp. 185-201.

Flater, D. (1998). XTide Manual: Harmonic tide clock and tide predictor. E.U.A.

FLUENT (2006). User Guide FLUENT version 6.3.26.

Fortes, C.J.E.M., Reis, M.T., Poseiro, P., Capitão, R., Santos, J.A., Pinheiro, L.V., Craveiro, J., Rodrigues, A., Sabino, A., Silva, S.F., Ferreira, J.C., Raposeiro, P.D., Silva, C., Rodrigues, M.C., Simões, A., Azevedo, E.B., Reis, F. (2014). HIDRALERTA Project – A Flood Forecast and Alert System in Coastal and Port Areas. Proc. IWA World Water Congress & Exhibition 2014, Shaping our Water Future, 21-26 September, Lisbon.

Josset, C., Clément, A. H. (2006). *A time-domain numerical simulator for oscillating water column wave power plants*. Renewable Energy, Vol. 32, pp 1379-1402.

Lara, J.L., Ruju, A., Losada, I.J. (2011). Reynolds averaged Navier–Stokes modelling of long waves induced by a transient wave group on a beach. Proc. Royal Society A 467, pp. 1215–1242.

Lynett, P., Liu, PL-F. (2004). Modelling wave generation, evolution and interaction with Depth-Integrated, Dispersive Wave equations. COULWAVE Code Manual. Cornell Univ. Long Inter. Wave Modelling Package.

OpenFOAM Foundation (2011). OpenFOAM, The Open Source CFD Toolbox User Guide, Version 2.1.0.

Simões, A. (2006). The Sea Wave Climate at the Islands of Macaronesia. A Study at the Azores. CLIMAAT Project Report.

Teixeira, P.R.F., Didier, E., Paixão Conde, J.M. (2009). Numerical analysis of OWC-wave energy converter. Proc. Jornadas Portuguesas de Engenharia Costeira e Portuária, Funchal, Madeira, Portugal (CDRom).

Tolman, H. L. (1999). User manual and system documentation of WAVEWATCH-III version 1.18. NOAA/NWS/NCEP/OMB technical note 166, 110 pages.

Whitcomb, T. (2012). Navy global forecast system, NAVGEM: Distribution and user support. Proc. 2nd Scientific Workshop on ONR DRI: Unified Parameterization for Extended Range Prediction.