EMACOP project: characterising the wave energy resources of hot spots in Brittany for on-shore WEC

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Abstract: **The French national EMACOP project (Énergies Marines Côtières et Portuaires) aims at characterising wave power nearby on-shore structures such as breakwater or jetty. This paper presents the application of the open source non-hydrostatic wave-flow model SWASH to wave propagation and transformation on two hot spots in Brittany (France). The numerical simulations were performed with the SWASH model in two-dimensional mode for dominant incident wave conditions and three tide levels. The results of wave simulations presented here allows us to characterise wave energy resources and define WEC's promising positions on both sites.**

Keywords **— Wave power; Resources; WEC; Brittany; Emacop**

I. Introduction

The energy transition undertaken in France includes an important development in marine renewable energies. In this respect, the French research project EMACOP (Énergies MArines, COtières et Portuaires) aims at studying and promoting the development of marine energy systems in ports or coastal structures in France, in particular at characterizing wave power nearby on-shore structures. This article fits in the framework of the task " wave power devices on existing structures " of the EMACOP project (http://www.emacop.fr/). The approach is extended to evaluation of nearshore potential of each site. A initial work was done to identify and characterise the wave energy potential of 22 sites along France's coastlines in order to select the most relevant sites [1].

Here, we present the characterisation of wave energy resources, using numerical simulations for two hot spots in Brittany (Esquibien and Saint-Guénolé), which are selected and could be equipped with on-shore Wave Energy Converters (WEC). Wave transformation processes from offshore to the coastal structures are taken into account using the non-hydrostactic wave-flow SWASH model, an open source tool solving the non-linear shallow-water equations, developed at Delft University of Technology [2]. The SWASH model allows discrete waves analysis and takes refraction, breaking wave, diffraction, reflection and spectral harmonic transfers into consideration.

This article presents the simulated nearshore wave transformation in the Esquibien and Saint-Guénolé sites, the numericals models setup, and the results obtained with the SWASH model. The two models were built using grids centred on the breakwaters. Their vast spatial domains are essential to understanding physical phenomena influencing the wave propagation such refraction, reflection and diffraction. A JONSWAP spectrum was used as input to simulate an incoming swell.

Moreover, spectrally-derived wave parameters (Hm0, Tp, direction of wave propagation, directional spreading) are introduced from numerical database HOMERE developed by

Ifremer [3]. Results from SWASH contribute to a better understanding of waves transformation processes on both spots. The results of wave simulations as water surface elevation, wave height, and wave power level clearly allow to characterise wave energy resources of both sites and define WEC's most promising positions.

II. SWASH: A Non-Hydrostatic Wave Flow Model

A. Features of SWASH

SWASH (an acronym of Simulating WAves till SHore) is an open source code developed at Delft University of Technology [2] (more information can be found at http://swash.sourceforge.net/). SWASH is a non-hydrostatic wave-flow model and is intended to be used for predicting transformation of dispersive surface waves from offshore to the shore for studying the surf zone and swash zone dynamics, wave propagation and agitation in ports and rapidly varied shallow water flows.

SWASH is a relatively new time-domain wave propagation model based on the nonlinear shallow water (NLSW) equations including non-hydrostatic pressure. It employs an explicit second order finite difference method for staggered grids whereby mass and momentum are strictly conserved at the discrete level.

The philosophy of the SWASH code is to provide an efficient and robust model that allows a wide range of time and space scales of surface waves and shallow water flows in complex environments to be applied. It should be emphasized that SWASH is not a Boussinesq-type wave model.

Conceptually, the vertical structure of the flow is part of the solution. In fact, SWASH may either be run in depth-averaged mode or multi-layered mode.

The model has been validated with a series of analytical, laboratory and field test cases. Overall, the level of agreement between predictions and observations is quite favourable, particularly since that a wide range of wave conditions and topographies were modelled.

SWASH accounts for the following physical phenomena: wave propagation, frequency dispersion, shoaling, refraction and diffraction, nonlinear wave-wave interactions, wave breaking, bottom friction, and provides the following output quantities: surface elevation, significant wave height, pressure at bottom, velocity in z-direction, etc.

B. Governing Equations

The SWASH model is a time domain model for simulating non-hydrostatic, free-surface and rotational flow. The governing equations are the non-linear shallow water equations including a nonhydrostatic pressure term. The two-dimensional, depth-averaged shallow water equations are shown as follows:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \zeta}{\partial x}+\frac{1}{h}\int_{-d}^{\zeta}\frac{\partial q}{\partial x}dz+c_f\frac{u\sqrt{u^2+v^2}}{h}=\frac{1}{h}\left(\frac{\partial h\tau_{xx}}{\partial x}+\frac{\partial h\tau_{xy}}{\partial y}\right)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \zeta}{\partial x}+\frac{1}{h}\int_{-d}^{\zeta}\frac{\partial q}{\partial x}dz+c_f\frac{u\sqrt{u^2+v^2}}{h}=\frac{1}{h}\left(\frac{\partial h\tau_{yx}}{\partial x}+\frac{\partial h\tau_{yy}}{\partial y}\right)$$

where t is time, x and y are located at the still water level, ζ(x, y, t) is the surface elevation measured from the still water level, h = ζ + d is the water depth, or total depth, d(x, y) is the still water depth, u(x, y, t) and v(x, y, t) are the depth-averaged flow velocities in x− and y−directions, respectively, q(x, y, z, t) is the non-hydrostatic pressure, g is gravitational acceleration, c_f is the dimensionless bottom friction coefficient, and τ_{xx}, τ_{xy}, τ_{yx} and τ_{yy} are the horizontal turbulent stress terms. A full description of the numerical model, boundary conditions, numerical scheme and applications are given in [2].

III. Numerical Simulations

A. Spots Localisation

Fig. 1: Esquibien and Saint-Guénolé spots in Audierne bay (west coast of Brittany, France; http://cms.geobretagne.fr/)

The hot spots of Esquibien and Saint-Guénolé located in west coast of Brittany (France) present a good ressource of wave energy conversion with respectively an annual wave power of 6.9 and 21.1kW/m established in [1]. The length of useful structures, which could be equipped with WEC are about 340 and 250 meters, with the bathymetry of 2m (CD).

B. Numerical Models Setup

1) Bathymetry: Nautical charts published by SHOM n° 7147 (port of Audierne) and n° 6645 (Penmarc'h cap) were reproduced in the two numericals domains using a grid size of 1m by interpolation with "Blue Kenue", a software tool of Canadian National Research Council (*http://www.nrc-cnrc.gc.ca/eng/solutions/advisory/blue_kenue_index.html*).

The bathymetric grid is an important input grid and must be large enough that it completely covers the computational grid of SWASH. The resolution of bathymetric grid is not necessarily the same as that of the computational grid.

The bottom grid size selected of Esquibien model is 3000m in the x-direction and 3400m in the y-direction, and the bottom grid size of Saint-Guénolé model is 2600m in the x-direction and 1500m in the y-direction.

2) Numerical and Physical Parameters: Numerical simulations of both sites were carried out by the SWASH model using one vertical layer which is enough concerning wave transformation and with an initial time step of 0.015s.

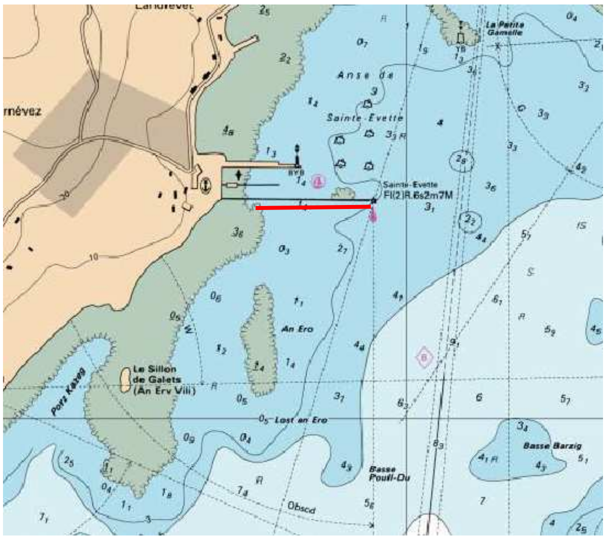

Fig. 2: Esquibien site (www.data.shom.fr)

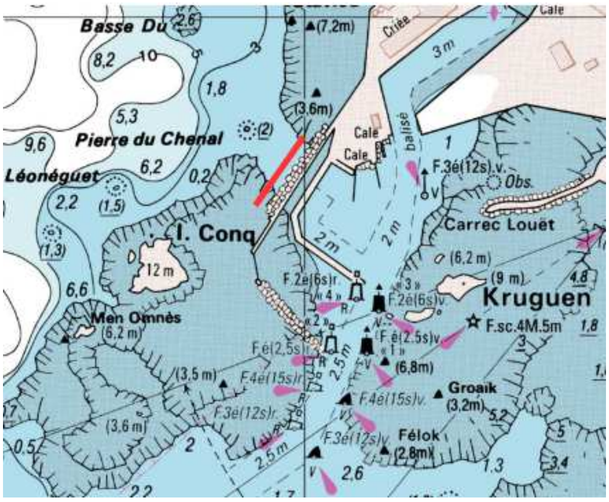

Fig. 3: Saint-Guénolé site (www.data.shom.fr)

The calculation time step is automatically adjusted in the calculation depending on the CFL condition, with a maximum CFL value of 0.5 in this case.

For numerical, the non-hydrostatic pressure in the shallow water equations is included. The Keller-box scheme is mainly used for accurate wave propagation with one layer calculation [4]. A default Manning's bottom friction value of 0.019 is used and the time duration of the numerical simulations is 40 minutes in the two numerical models runs.

C. Esquibien Model Setup

The computational domain of Esquibien model is a horizontal grid with a cell size of 4m in the x-direction and 2m in the y-direction. The computational domain size is 1600m (x-direction) and 2100m (y-direction). Around the domain, the sponge layers are specified at the north edge of the domain (width of 200m), the west edge (width of 100m) and the east edge (width of 100m) to absorb wave energy at open boundaries where waves are supposed to leave the domain freely. So, they prevent from reflecting at open boundaries [5].

The wave boundary conditions at the south edge of the domain simulate incoming random swells, as indicated in Tables I and II. This is done using a JONSWAP spectrum, a directional spreading of 24.9 degrees with different combinations of significant wave heights Hm0, peak periods Tp, wave directions and still water depths.

The simulation of Esquibien model takes about 4 hours on 8 cores of Intel Xeon processor with MPI parallel computing.

1) Estimation of Esquibien Wave Climate: The model input parameters are the significant wave height, wave peak period and wave direction (Hm0, Tp, θ) and the water levels. At this site, waves generally arrive from the south-southwest (200°N) since the dominant west swells (270°N) are refracted by the upwave bathymetry. The three selected water levels represent 80% of the tidal regime, from an 18-year tidal simulation (Saros cycle). The corresponding levels are 1.45m (low tide), 3.07m (mid-tide) and 4.75m (high tide).

The choice of (Hm0, Tp)-couples was based on the analysis of the wave parameters at Esquibien, point W458N4796 extracted from the 19-year (1994-2012) HOMERE database, distributed through the French PREVIMER project (*http://www.previmer.org/en/produits/hindcast_sea_states_homere*). The statistical analysis of the 19-year wave hindcast, (160 000 hourly data) has produced a occurrence table of each couple (Hm0, Tp) expressed in hours/year to ease the choice of these couples (see Table I).

TABLE I
OCCURENCE OF THE (HM0, TP) COUPLES IN HOURS/YEAR

Hm0 (m) \ Tp (s)		5–7	7–9	9–11	11–13	13–15	15–17
5.5	6.5	0.0	0.0	0.2	5.0	21.6	28.7
4.5	5.5	0.0	0.1	3.9	41.0	78.0	73.3
3.5	4.5	0.0	6.5	43.0	130.0	203.1	107.3
2.5	3.5	2.9	75.1	139.7	316.8	351.9	123.8
1.5	2.5	95.8	306.7	423.0	782.7	493.9	116.9
0.5	1.5	243.3	862.2	1348.6	1228.4	360.0	111.1
0	0.5	20.3	169.5	155.7	62.6	18.5	6.9

The examination of the previous table has allowed the selection of 10 couples (Hm0, Tp) for the boundary conditions of the SWASH model (see Table II).

TABLE II
THE 10 (HM0, TP) COUPLES SELECTED TO REPRESENT ESQUIBIEN WAVE CLIMATE.

Hm0 (m) \ Tp (s)	8	10	12	14
3		X	X	X
2	X	X	X	X
1	X	X	X	

To sum up, the Esquibien wave climate estimation is based on 30 simulations: 10 wave couples (Hm0, Tp) selected for 3 different tidal levels (low, mid and high tides).

With a computation time of about 4 hours per simulation, the model runs took around 120 hours (5 days).

2) Output Points Selection for the Wave Power and Directional Spectra Calculations: An in-deep examination of the Esquibien site characteristics allowed us to extract 9 relevant output points, as shown on the bathymetry illustration (Fig. 4). These output points have been chosen based on two criteria: alignment in front of the breakwater and water depth. Points 1, 2 and 3 lie in 3m-depth, points 4, 5 and 6 in 5m-depth and points 7, 8 and 9 in 10m-depth. Points 3, 6 and 9 allow to examine the depth influence on wave energy resource over a specific energetic area.

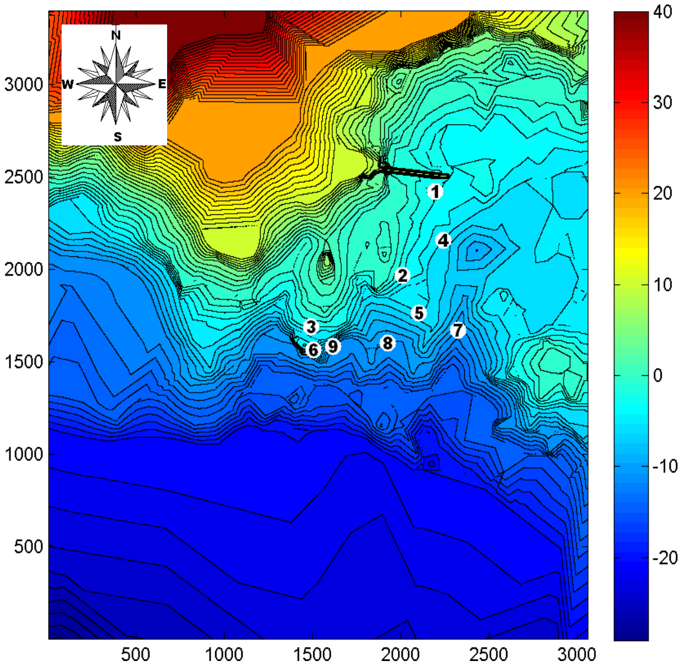

Fig. 4: Esquibien bathymetry map and location of the 9 output points

D. *Saint-Guénolé Model Setup*

The computational domain is an horizontal grid with cell size of 3m in the x-direction and 3m in the y-direction. The domain size is 1600m (x-direction) and 1300m (y-direction). Around the domain, the sponge layers are specified at the north edge of the domain (width of 100m), the south edge (width of 100m) and the east edge (width of 200m) to absorb wave energy at open boundaries.

The wave boundary conditions at the west edge of the domain simulate incoming swells, as indicated in Table III. This is done using a JONSWAP spectrum, a directional spreading of 24.9 degrees with different combinations of significant wave heights Hm0, peak periods Tp, wave directions and still water depths.

The simulation of the Saint-Guénolé model takes about 1.5 hour due to the smaller computational domain.

1) Estimation of Saint-Guénolé Wave Climate: The model input parameters are the significant wave height, wave peak period and wave direction (Hm0, Tp, θ) and the water levels. Waves in Saint-Guénolé propagate from the west direction (270°N) and the three water levels, low, mid and high tide have been conserved for thoses simulations.

Similarly to what has been done for the Esquibien site, the choice of the (Hm0, Tp)-couples results from the analysis of HOMERE database at point "Emacop06" lying about 25m. Since the computation was less demanding, a greater numbers of simulations were performed. The 16 couples (Hm0, Tp) shown in Table III were used for the SWASH runs.

TABLE III
THE 16 (HM0, TP) COUPLES SELECTED TO REPRESENT SAINT-GUÉNOLÉ WAVE CLIMATE.

Hm0 (m) \ Tp (s)	8	10	12	14
5			X	X
4		X	X	X
3	X	X	X	X
2	X	X	X	X
1	X	X	X	

To sum up, Saint-Guénolé wave climate estimation relies on 48 simulations: 16 (Hm0, Tp)-couples associated to 3 water levels (low, mid and high tides). With a computation time of about 1h30min per simulation, the 48 runs represent about 72 hours of computation.

2) Output Points Selection: The examination of the Saint-Guénolé site allows us to select, as displayed in Fig. 5, 8 output points. 5 points are located perpendicularly to the breakwater from points 1 to 5 (1m to 10m-depth) and 3 others (points 6, 8 in 10m-depth and point 7 in 5m-depth) are placed over an offshore shoal, with potential high wave resource.

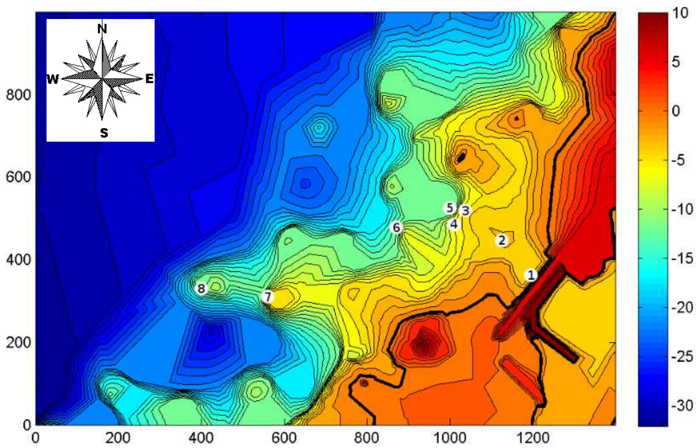

Fig. 5: Saint-Guénolé bathymetry map and location of the 8 output points

IV. RESULTS OF ESQUIBIEN NUMERICAL SIMULATIONS

A. *Results of a Typical Simulation*

The SWASH results were analysed with MATLAB and the tools of the librairies WAFO (Wave Analysis for Fatigue and Oceanography, *http://www.maths.lth.se/matstat/wafo/*) and DIWASP (DIrectional WAve SPectra toolbox, *http://www.metocean.co.nz/support/resources/*). The model outputs exploited were the water surface elevation, the significant wave height, the directional spectra with DIWASP and the wave power per unit crest length from the US Electric Power Research Institute (EPRI) formula [6]:

$$P=\frac{\rho g^2}{4\pi}\int_0^\infty \frac{S(f)}{f}\left[\left(1+\frac{2k_f d}{\sinh(2k_f d)}\right)\tanh(k_f d)\right]df$$

The presented example uses the following wave conditions: significant wave height Hm0=2m, peak period Tp=12s, wave direction θ=200°N and a high tide water level of 4.75m. The SWASH simulations outputs are treated to produce maps of relevant wave parameters.

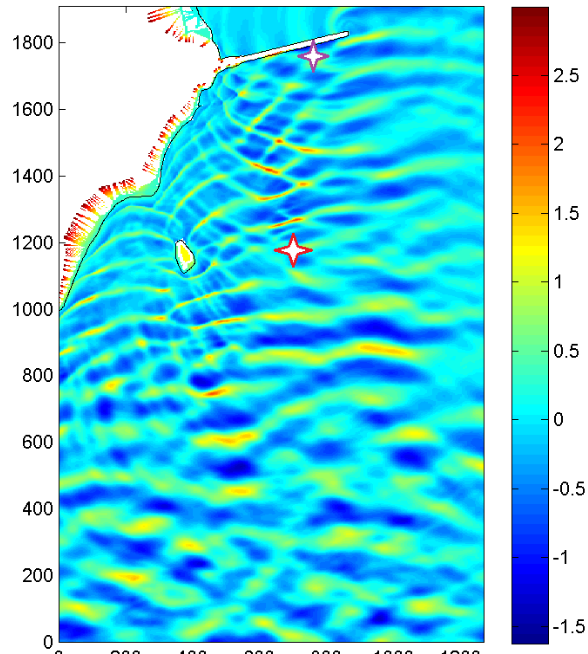

Fig. 6: Water surface elevation for the reference simulation (Hm0=2m, Tp=12s, wave direction θ=200°N and a high tide water level of 4.75m)

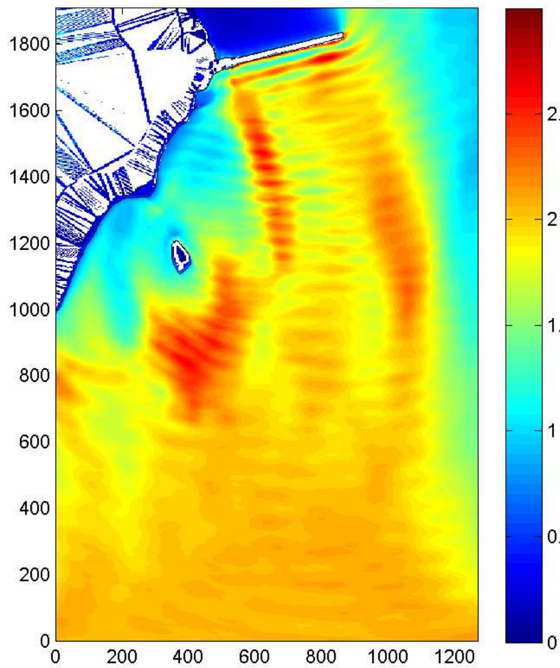

Fig. 7: Significant wave height for the reference simulation

The SWASH simulation provided elevations times series at the 9 output points. The WAFO tool was used to produce wave power per unit crest length at these points (Table IV).

TABLE IV
WAVE POWER PER UNIT CREST LENGTH AT EACH OF THE 9 OUTPUT POINTS FOR THE REFERENCE SIMULATION

Output point	1	2	3	4	5	6	7	8	9
P (kW/m)	16.3	15.8	26.3	21.4	16.3	21.8	10.4	22.1	21.7

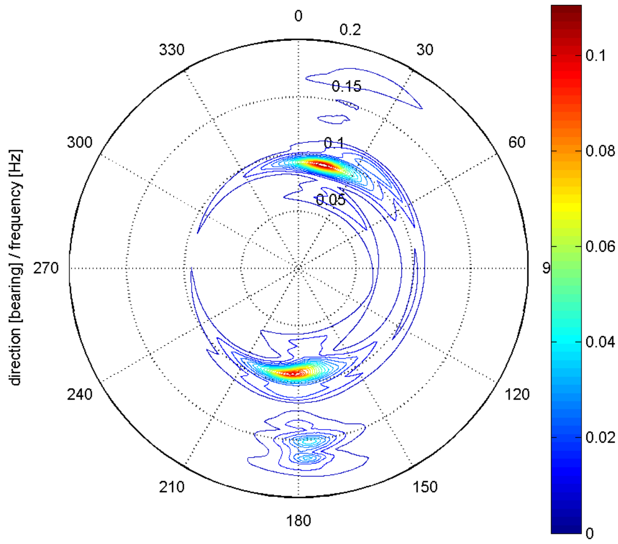

Fig. 8: Modeled directional spectra at point 1 with DIWASP (see Fig. 4 and purple spot on Fig. 6) for the reference simulation

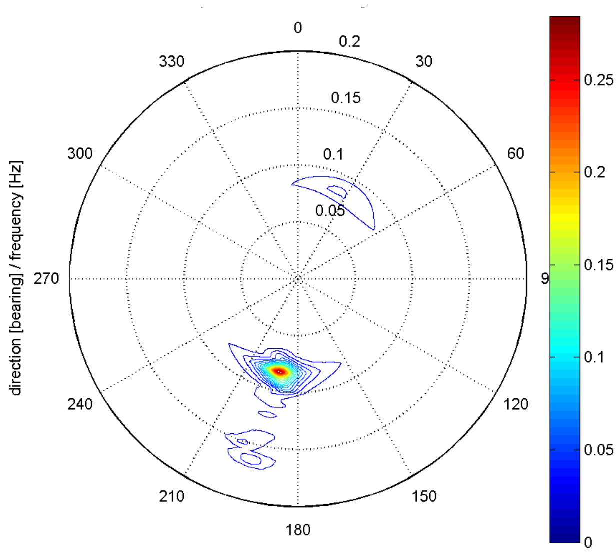

Fig. 9: Modeled directional spectra at point 2 (see Fig. 4 and red spot on Fig. 6) for the reference simulation

The Hm0 map presents the main wave energy hot spots as the shoaling area in front of “île aux vaches”, corresponding to points 3, 6 and 9. In the western part of the map, close to point 4 and even closer to the breakwater (point 1), the significant wave height reached up to 2.7m. In the eastern part of the map, Hm0 less than 1.5m are observed in about 6m-depth. In this area, the water depth rapidly decreases to 3m near the breakwater which causes the waves to refract toward the breakwater.

1) Reflection Phenomena (point 1): At the tip of the breakwater, and at regularly spaced distance, corresponding to half the wave length, important wave height variations are evident. They are due to wave interferences responsible for the well-known standing wave phenomena characterised by nodes and anti-nodes at fixed locations. The obtained spectrum at point 1 (see Fig. 8) shows that the reflected wave keeps its peak period of 12s.

The available power is computed from the water surface elevation spectra, given the probabilities of occurrence of the various tidal levels and incoming waves conditions. It provides thus the total yearly energy in the form of heave at the point of interest. However, it should be noted that energy extraction devices are not all making exclusive use of heave at a single point.

In addition, the location at Esquibien is the scene of reflection and shoaling effects that distribute the incoming energy into several categories, namely incident and reflected waves, and primary free wave and harmonic bound waves at the sum and difference frequencies. When considering heave only, the incident and reflected waves may add or cancel as a function of the location, dominant wave direction and wavelength. A thorough design analysis will thus require to know how the energy can be split between those characteristics.

2) Partitioning Analysis of Directional Spectra: To answer that question, this partioning analysis was carried out on the directional spectra for three tidal level conditions. This partitionning used a watershed algorithm ([7], [8]), and resulted in 2 to 6 partitions depending on the location and conditions.

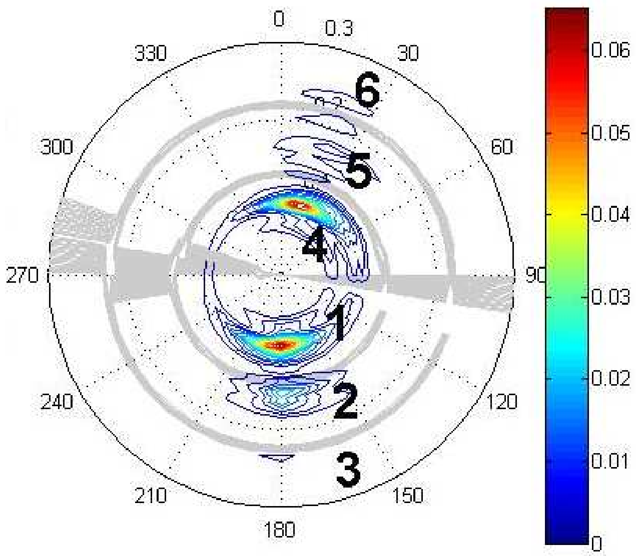

Fig. 10: Results of partitioning at point 1 for a 2m incoming Hm0 at high tide

The characteristics of the partitions of Fig. 10 are given in Table V. From their directions, partitions 1-3 can be identified as incident, and partitions 4-6 as reflected. The incoming wave system is at period 12s, and thus partitions 1 and 4 can be characterised as primary (free) waves, partitions 2 and 5 as harmonic, sum of frequencies (bound) waves, and partitions 3 and 6 as superior order harmonics. When designing an energy extraction system, two points should be kept in mind:

- Extraction of the incident power will decrease in proportion to the available reflected power, unless the extent of the extraction system is narrow enough for waves to get around it and reflect,
- Bound waves energy is difficult to extract, though some systems may benefit from the changes that they induce in the shapes of the primary waves.

TABLE V

SPLIT-OUT EVALUATION OF THE POTENTIAL WAVE ENERGY FOR A 2M INCOMING AT HIGH TIDE (TOTAL WAVE POWER OF 22.37KW/M).

Wave parameters	Incident waves systems			Reflected waves systems		
	Syst 1	Syst 2	Syst 3	Syst 4	Syst 5	Syst 6
Hm0 (m)	1.27	0.69	0.23	1.24	0.51	0.26
Tp (s)	12.63	6.24	4.10	12.42	5.77	4.08
P (kW/m)	8.83	2.58	0.29	8.35	1.39	0.38

It can be seen from Table VI that the incident free wave power, the only part that can be straightforwardly extracted, only amounts to one third to one half of the total observed power in a directional spectrum. Yet, since components from opposing directions may cancel, directional spectra usually exhibit more power than point heave spectra, as can be seen when comparing the two first columns of the table.

TABLE VI

INCIDENT AND REFLECTED WAVE POWER (KW/M) AT LOW TIDE, MID-TIDE AND HIGH TIDE

Water level	Total power (1D)	Total power (2D)	Incident free	Reflected free
Low tide (1.45m)	10.16	13.43	4.89	4.99
Mid-tide (3.07m)	16.72	19.58	9.41	7.15
High tide (4.75m)	16.30	22.37	8.83	8.35

Overall, the results indicate that the wave energy depends on the couple (Hm0, Tp) and on the water level that induced variations of the breakwater exposition.

At low tide, the "île aux vaches" shoal shelters the breakwater as it both focuses and dissipates energy through wave breaking. The breakwater is less exposed as shown in the following maps of water surface elevation and significant wave height for the simulation at low tide (see Fig. 11 and 12).

At high tide, the refraction weakens and some areas become shoaling zones and make the breakwater more exposed [9].

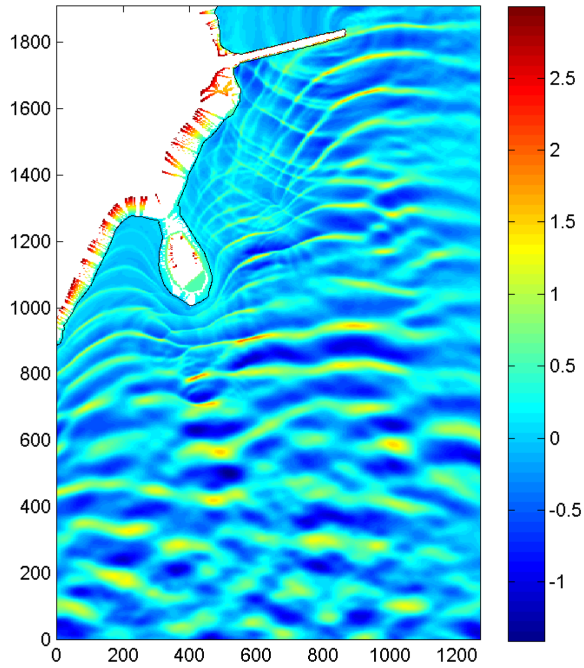

Fig. 11: Water surface elevation for the simulation at low tide (Hm0=2m, Tp=12s, wave direction θ=200°N and a low tide water level of 1.45m)

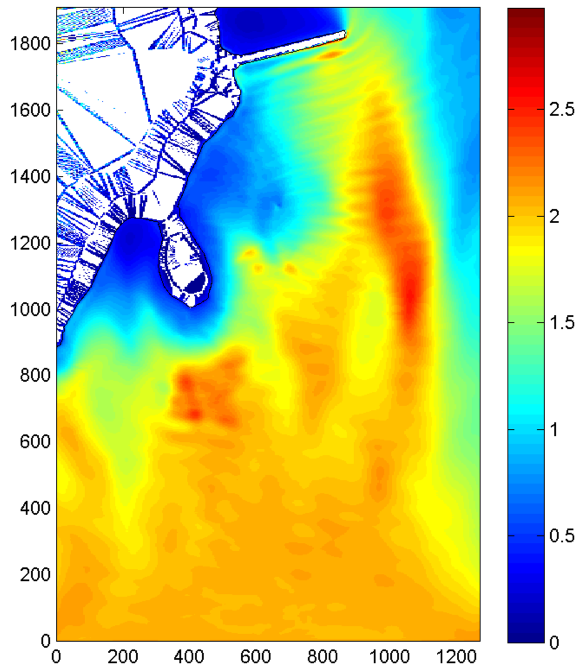

Fig. 12: Significant wave height for the simulation at low tide (Hm0=2m, Tp=12s, wave direction θ =200°N and a low tide water level of 1.45m)

B. Results of Wave Energy Resource

The results of the 30 simulations at the 9 output points (see Fig. 4) have been gathered. The missing wave power data has been extrapolated based on the obtained information.

Below is an example of the results at ouput point 4, located at 100m in front of the breakwater tip, in 5m depth (Fig. 4). The green cases in the 3 following wave power tables (Tables VII, VIII and IX) correspond to the results of the model simulations and the neighbouring data that was extrapolated. The yearly energy output has then estimated by multipying the wave power values by the occurrences corresponding to Table I that provides 3 intermediate yearly energy tables.

Considering the water levels, a sum has been applied with the following weight coefficients: low tide (0.3), mid-tide (0.4), high tide (0.3), in order to put together the 3 energy tables into a global yearly energy table (see Table X). To illustrate the importance of considering three water level, note that for the wave class (2.50m – 3m50), the wave resource is increased by about 1.5 from low to mid tide but remains roughly identical from mid to high tide (see Table VII, VIII and IX). If only the mid tide water level was considered the resource would be spuriously biased high.

TABLE VII
WAVE POWER (KW/M) AT LOW TIDE (WATER LEVEL 1,45 M) AT POINT 4

	Tp (s)	5	7	9	11	13	15
Hm0 (m)		7	9	11	13	15	17
5.5	6.5					15.27	8.33
4.5	5.5				23.43	19.06	14.70
3.5	4.5			28.00	24.64	22.86	21.07
2.5	3.5		16.94	21.40	25.85	26.65	27.47
1.5	2.5	6.46	10.63	14.80	17.50	19.34	21.36
0.5	1.5	0.77	2.77	4.77	5.90	7.02	

TABLE VIII
WAVE POWER (KW/M) AT MID-TIDE (WATER LEVEL 3,07 M) AT POINT 4

	Tp (s)	5	7	9	11	13	15
Hm0 (m)		7	9	11	13	15	17
5.5	6.5					58.14	51.41
4.5	5.5				56.05	53.92	51.78
3.5	4.5			43.89	47.24	49.70	52.16
2.5	3.5		21.49	29.96	38.43	45.48	52.54
1.5	2.5	4.19	10.11	16.02	21.33	25.86	30.38
0.5	1.5	0.76	2.66	4.57	6.23	7.89	

TABLE IX
WAVE POWER (KW/M) AT HIGH TIDE (WATER LEVEL 4,75 M) AT POINT 4

	Tp (s)	5	7	9	11	13	15
Hm0 (m)		7	9	11	13	15	17
5.5	6.5					165.36	194.91
4.5	5.5				105.02	126.33	147.65
3.5	4.5			46.73	74.25	87.31	100.38
2.5	3.5		18.80	31.14	43.47	48.29	53.12
1.5	2.5	2.87	9.20	15.54	21.47	23.72	25.98
0.5	1.5	0.61	2.42	4.24	5.94	7.65	

TABLE X
YEARLY WAVE ENERGY (MWH/M) AT POINT 4

	Tp (s)	5	7	9	11	13	15
Hm0 (m)		7	9	11	13	15	17
5.5	6.5	0.00	0.00	0.00	0.00	1.67	2.34
4.5	5.5	0.00	0.00	0.00	2.50	5.08	5.09
3.5	4.5	0.00	0.00	1.72	6.31	10.75	6.15
2.5	3.5	0.00	1.45	3.88	11.46	14.31	5.59
1.5	2.5	0.43	3.07	6.56	15.83	11.49	3.08
0.5	1.5	0.17	2.26	6.11	7.42	2.72	0.00

As a result, at point 4, the sum of the values displayed in Table X for the (Hm0, Tp)-couples yields a mean early energy E of 137.4Mwh/m, hence a mean wave power P of 15.7kW/m. The yearly energy E and wave power P for the 9 output points of Esquibien, presented in Table XI show power variations, P ranging from 9.3 to 20.8kW/h depending on the location.

Surprisingly, the power values at points 3, 6 and 9 are quite similar despite the large water depth differences between these 3 points (depth ranging from 3 to 10m) [10].

TABLE XI
RESULTS FOR THE YEARLY ENERGY E (MWH/M) AND WAVE POWER P (KW/M) IN EACH OF THE 9 OUTPUT POINTS

Output point	1	2	3	4	5	6	7	8	9
Yearly E (MWh/m)	99.9	81.9	135.9	137.4	123.4	174.4	83.8	176.2	181.9
P (kW/m)	11.4	9.3	15.5	15.7	14.1	19.9	9.6	20.1	20.8

V. RESULTS OF SAINT-GUÉNOLÉ NUMERICAL SIMULATIONS

A. Results of a Typical Simulation

The presented example of numerical simulation uses the following wave conditons: Hm0=2m, Tp=12 s, θ=270°N and a mid-tide water level of 3.07m.

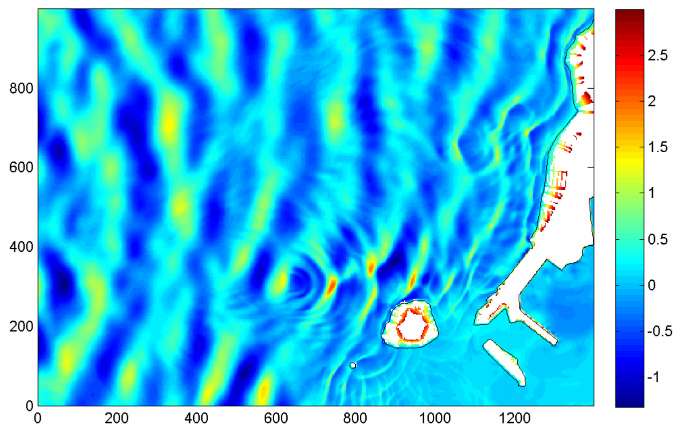

Fig. 13: Water surface elevation for the reference simulation (at t= 40min, Hm0=2m, Tp=12 s, θ=270° and a mid-tide water level of 3.07m)

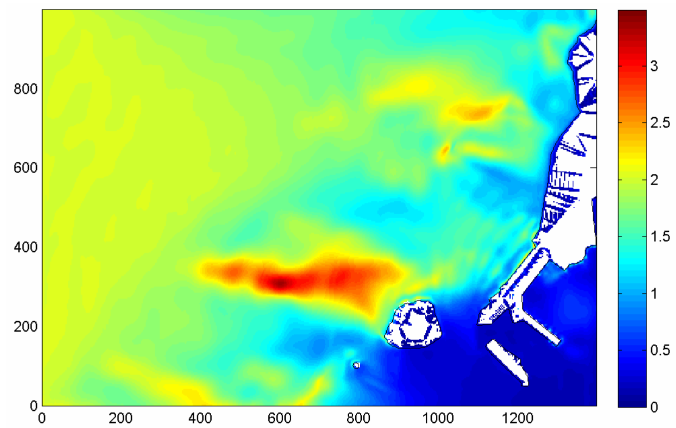

Fig. 14: Significant wave height for the reference simulation (mid-tide level)

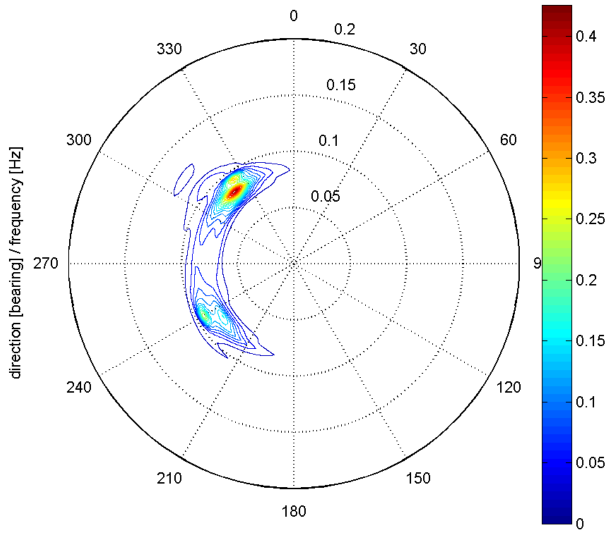

Fig. 15: Modeled directional spectra at point 7 with DIWASP (see Fig. 5) for the reference simulation

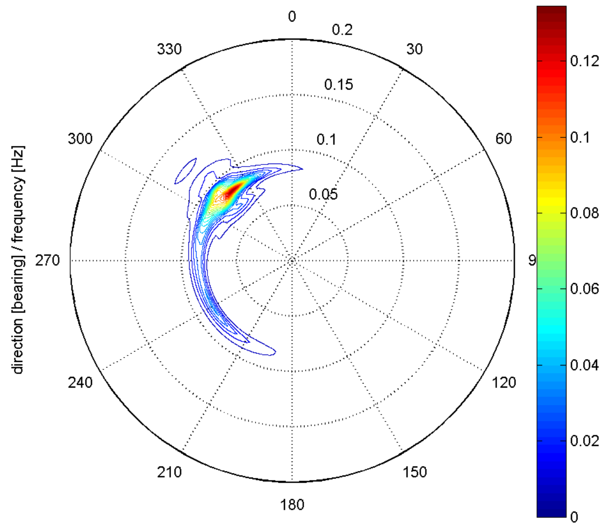

Fig. 16: Modeled directional spectra at point 5 with DIWASP (see Fig. 5) for the reference simulation

TABLE XII
WAVE POWER PER UNIT CREST LENGTH AT EACH OF THE 8 OUTPUT POINTS FOR THE REFERENCE SIMULATION

Output point	1	2	3	4	5	6	7	8
P (kW/m)	3.1	7.7	8.6	8.8	10.2	8.2	40.5	26.5

The significant wave height map (Fig. 14) shows that the wave energy is dramatically reduced by refraction and dissipation in the vicinity of the breakwater (3.1kW/m at point 1). Conversly, the wave energy focuses in front of the rocky shoal at the southwest of the breakwater, with a wave power per unit crest length of 40.5kW/m at output point 7 (see Fig. 15 and Fig. 5 for localisation).

This feature is explained by the strong bottom slope that causes the waves to refract and to shoal in that region. This area is of great interest for Wave Energy Converters (WEC) deployment, as the wave height exceeds 3m over a 400m distance. However, the wave energy is less directly in front of the breakwater with wave height of only about 1.5m and wave power per unit crest length of 10.2kW/m at point 5 (see Fig. 16 and Table XII).

At low tide, the rocky shoal shelters the breakwater as it focuses and dissipates energy through wave breaking as shown in the following map of significant wave height for the simulation of a 4m incoming Hm0 at low tide (see Fig. 17).

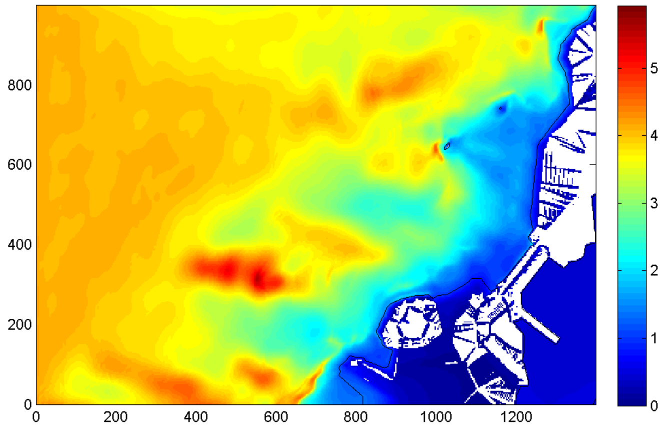

Fig. 17: Significant wave height for the simulation (Hm0=4m, Tp=14s, θ=270°N and a low tide water level of 1.45m)

B. Results of Wave Energy Resource

The data analysis has been performed with the procedure applied for Esquibien and described in the previous section. The results were put together in a single table, the missing values being extrapolated from results of available simulations.

The result for the yearly energy E and wave power P for the 8 output points of Saint-Guénolé, presented in Table XIII show power variations, P ranging from 2.4 at point 1 (located in front of the breakwater) to 33.6kW/h at point 7, placed just off the steep rocky shoal. The power values at points 2 to 6 are quite close, despite the water depth differences (2 to 10m) between these 5 points. Points 7 and 8 are the most energetic points. Their locations, near the shoal, in the southwest of the breakwater favors wave power focusing. Data from an ongoing field experiment at Saint Guénolé should allow to verify these features.

TABLE XIII
RESULTS FOR THE YEARLY ENERGY E (MWH/M) AND WAVE POWER P (KW/M) IN EACH OF THE 8 OUTPUT POINTS

Output point	1	2	3	4	5	6	7	8
Yearly E (MWh/m)	20.9	52.2	76.9	73.0	82.8	77.2	294.1	209.8
P (kW/m)	2.4	6.0	8.8	8.4	9.4	8.8	33.6	23.9

VI. CONCLUSIONS

This study has allowed to characterise the wave energy resource of Esquibien and Saint-Guénolé spots and has confirmed their high energetic potential. The SWASH models and the postprocessing libraries used are efficient tools that yield qualitative results of wave height and power, in the vicinity of breakwaters. Wave modelling is thus a precious tool for the examination of wave energy resource.

The wave power values obtained in the vicinity of the breakwater: 11.4kW/m (Esquibien) and 2.4kW/m (Saint-Guénolé), deserve to be compared to the initial wave power levels produced by a regional wave hindcast and presented in [1]: 6.9kW/m (Esquibien) and 21.1kW/m (Saint-Guénolé). The wave field from the regional model were propagated with a simplified formulation of Goda [1], which may explain the observed discrepancies.

The significant differences in wave power between both studies demonstrate the relevance of runing a high resolution deterministic model for nearshore wave resource assessment.

Further information on the wave energy resource and on the model accuracy will be available, as in-situ measurements collected with pressure sensors and wave buoys deployed at Esquibien and Saint-Guénolé sites.

Research efforts are currently conducted with a high resolution (20m resolution at the shoreline) spectral model to further consolidate the present results.

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