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The Tidal Garden concept: Numerical modelling of tidal stream turbines in channels for optimal energy extraction.

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Abstract— **The Tidal Garden concept results from the combination of existing tidal power solutions. The aim of the present article is to evaluate its performance and potential as a new cost-effective and efficient tidal energy arrangement.**

I. CONTEXT

The last decade has seen a revival of tidal power solutions development as the world is seeking cost-effective and efficient renewable power options. Today, the tidal energy landscape is formed by two main categories:

Tidal range barrages (such as La Rance tidal power plant [1]) or lagoons (such as the future Swansea Bay tidal power plant [4]); the associated technologies are mastered but require high tidal ranges to be efficient and economically feasible;

Open-sea tidal stream turbines (such as the technology developed by OpenHydro and used by EDF in the tidal demonstration project deployed off the coast of Brittany [2]); the tidal stream resource – strong tidal currents – is very localized and located on sites where offshore conditions imply heavy structural designs and difficult Operation & Maintenance access.

The idea to combine a tidal basin with tidal stream turbines fostered the proposition of the "Tidal Garden" concept – or "Marélienne" in French [5]. The concept consists in a coastal basin, outlined by breakwaters and linked with the open sea through a number of open channels equipped with arrays of tidal stream turbines; the increased flow speed in the channels allows higher energy production than with tidal turbines placed in open waters and subject to the natural tidal flow. The goal will be to maximize energy production by generating velocities as high as possible during as long as possible, while maintaining the tidal range within the basin close to the site's natural conditions to avoid or reduce the impact on the intertidal zone. The optimization parameters are: the basin geometry and equipment, the possible use of sluice gates, the dynamic control of turbines.

The Tidal Garden concept thus completes the tidal energy landscape with a solution for nearshore installations on sites with average tidal conditions.

II. GOALS

Numerical modelling is used to study the hydrodynamics of such a coastal basin and to assess tidal energy extraction possibilities by this conceptual arrangement. Note: the Tidal Garden concept also brings economical and environmental advantages [3]; however the present paper will focus on modelling and hydrodynamics.

Indeed, for a given site, hydraulic design tools are necessary to help define the best Tidal Garden layout, and simulate its energetic performance and potential impacts. EDF-CIH has thus developed a 2-level approach:

- A 0D model: the aim of this simple approach is to rapidly define a pre-optimized layout of Tidal Garden scheme, and simulate the sensitivity of hydraulic and power performance to the main controlling parameters: number of channels connecting the tidal basin and the open sea, tidal range characteristics, number of tidal stream turbines, operating mode of tidal stream turbines (dynamic control of turbines).
- A 2D numerical model based on the Telemac© software system, which is used to study hydrodynamic effects of filling and emptying the basin and the impact of tidal stream turbines in the channels and which takes into account site-specific effects (e.g. detailed bathymetry, spatial variability of tidal flows,...) on the hydraulic and generation performance of a project.

The present paper focuses on the 2D model and aims at a/ describing the work achieved so far, along with b/ the first results obtained on a generic test site and c/ presenting ongoing developments.

III. DESIGN PARAMETERS OF A TIDAL GARDEN INSTALLATION

A standard basin is basically designed as a semi-circular dyke breached with channels. The flow in and out of the channels is guided by adding converging/diverging sections at the channel extremities. Rows of tidal turbines are erected inside each channel to extract energy from the accelerated flow. The impact of this extraction is taken into account in the simulation by adding a drag force in the surroundings of the turbines.

The main parameters that need to be defined are the following:

- Geometry: area/shape of basin (yields length of dyke), the number, orientation, length and width of channels, converging/diverging entries of channels, Strickler coefficient.
- Turbines: drag force due to each turbine, the spacing between turbines (of a same row and between rows). Note: Relation between number of turbines per row and channel width (25m per turbine), and between number of rows and channel length (100m – 5 times the turbine diameter - between 2 rows). Sensibility analyses will be needed.

A power extraction coefficient is used for computing the power output of each turbine; however it does not influence the flow calculation. All parameters related to turbine technology are based on EDF past experience and on recent studies for Paimpol-Bréhat tidal stream turbine demonstration project.

The combination of geometrical parameters and turbine spacing yields the installed capacity/total number of turbines.

Given the numerous parameters, the “right” selection of parameters is not straightforward; hence the use of the 0D model, for a multi-criteria analysis on a large number of configurations.

IV. IMPLEMENTATION IN TELEMAC2D

The geometry and turbine placement are prepared using a dedicated Matlab code. The geometry is then imported in BlueKenue for the mesh generation.

Tidal conditions are imposed on the liquid boundary using TELEMAC integrated tidal model and J.-M. Janin’s tidal database.

Regular head losses (in the channels and over the sea bottom) are modelled in TELEMAC2D with friction defined by a Strickler coefficient: this coefficient is defined as a function of depth and of the bottom type (e.g. the channels are assumed to be paved with concrete).

The DRAGFO routine is customized to implement turbine drag and energy extraction. Drag is a function of current speed, diameter and drag coefficient of the turbines. The classical drag force formula is encoded:

$$F_{drag} = 0.5\ \rho\ S_u\ C_d\ V^2, \qquad (1)$$

with ρ the water density, S_u the sweep area of a turbine (m²), C_d the drag coefficient and V the flow speed. In a first attempt, drag was added on each mesh nodes where turbines are installed; this resulted in diverging results. In order to avoid these numerical discrepancies, drag is allocated as density zones around the turbine rows (as shown in Fig. 2).

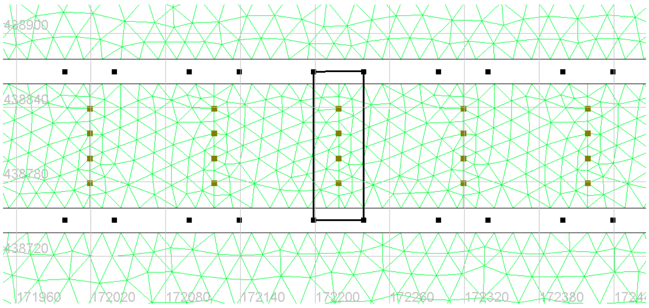

Figure 1. Mesh area around a row of turbines where drag force is applied.

The DRAGFO routine also computes the power output of each turbine, at each time step, using equation (2):

$$P = 0.5\ \rho\ S_u\ C_p\ V^3, \qquad (2)$$

with C_p the turbine capacity factor which depends on turbine performance.

A result file is generated at the end of calculations to extract the time series of flow speed, water depth and power output at each turbine location (node).

It is considered that under 0.5m/s of flow speed, tidal turbines do not extract energy from the flow and drag is disregarded. Control of the turbines is important to maximize power generation. Start and stop sequences are managed during the drag calculation by adding time and flow speed constraints.

Configurations with sluice gates, temporarily isolating the basin from the sea and artificially increasing the head (and thus flow velocity) for better energy extraction are also tested. A customised CORPOR routine is used to this effect: an artificial porosity imposed on mesh zones barring the channels allows closing and opening the channels at will. The initial implementation consisted in closing the full length of the channels; however, this resulted in water filling the channels from both ends when the porosity was removed. The modified mesh zones were thus limited to a fraction of the channel length and a linear evolution of the porosity with time was implemented. Although this method results in some water flowing through the closed channels, the water level in the basin is kept sufficiently constant over the closure period. In terms of control, the sluice gates can be opened for a given head or after a given time.

The duration of simulations can be adjusted: a period of 12 hours 24 min can be simulated in order to get results during a complete semi-diurnal tidal cycle while calculations covering a 14-day period allow the study of the tide amplitude influence on the energy extraction and, by extrapolation, the evaluation of production over a complete year. It takes around 30 min to run the first type of simulation and 150 min to run the second type (on a dual processor (3.3-GHz) standard PC configuration).

V. APPLICATION TO A TEST SITE

To test the implemented model, a Tidal Garden installation is conceived: the mesh used for this study covers a domain of 40 by 50km located on the French side of the English Channel, where the mean and spring tide amplitudes are respectively 6.3m and 9m. The dyke is a 5.6km-radius semi-circle with a changeable number of channels, forming a 50km² basin. This geometry is represented on **Error! Reference source not found.**3. Bathymetry is modelled to achieve acceptable depths in the channels: from 50m in the open ocean, a nearshore slope raises the bottom to 20m in the channels and emerged heights at the land boundaries (lower side of the mesh on the figure below). It does not exactly reproduce the real shore, so the results shall be considered theoretical. The length of finite element edges varies from approximately 3km on the open ocean boundaries to 10m in the channels.

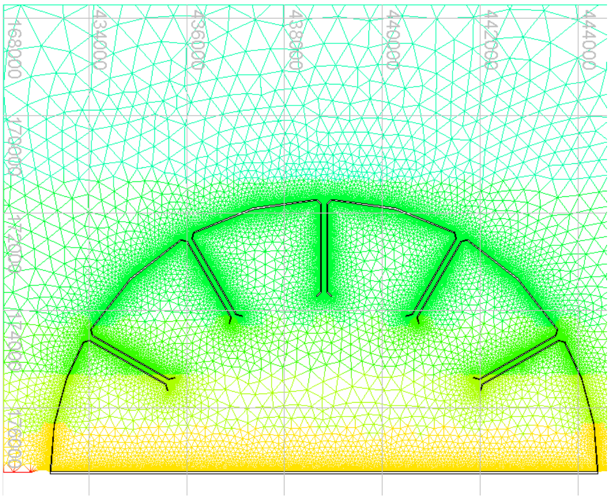

Figure 2. Modelled test site with 5.6km-radius dyke and 5 channels.

The first results show that, for a constant cumulative width of channel (600m), an installation with 5 channels generates the highest flow speeds compared to configurations with smaller numbers of channels. Because of current tidal turbine technology limitations, a flow velocity of at least 4m/s is necessary to produce more than 2MW per turbine. Without any tidal turbines, a flow speed of 4m/s is reached but energy extraction by the tidal turbines has an impact on the flow speed in the channel: speeds decrease to 3m/s during the flood and under 2m/s during the ebb; at these speeds, the energy production would drop significantly. Flow speeds in the 5-channel configuration are higher because of the smaller width of each channel. However, this flow constriction has a direct impact on the tidal amplitude in the basin, which is to be considered for environmental reasons.

According to these results, the channel width needs to be reduced in order to raise flow speeds and the energy output of the installation. A configuration with 3 channels, 10 rows of tidal turbines per channel and 3 tidal turbines per row is then tested to validate the interest of a reduced width (75m per channel). Fig. 3 shows that flow speed in the channels without the tidal turbines reaches nearly 5m/s during the flow and 3m/s during the ebb. Once the tidal turbines are in place, flow speed is maintained at 3.5m/s during the flow and 2.5m/s during the ebb.

In terms of controls, sensibility studies on the control parameters of the turbines (shut-off velocity, start sequence timing) have shown that it is more efficient to limit the number of generating tidal turbines to maintain a higher flow speed (around 4m/s) instead of working with all tidal turbines at lower flow speeds.

In order to increase the flow speed even more, a configuration with 5 channels (50m width), 20 rows per channel, 2 turbines per row and sluice gates in each channel is simulated. Once the basin is filled, the sluice gates are maintained closed until a 2-meter head between basin and sea is reached. According to Fig. 4, the water level in the basin is efficiently maintained constant during the gates closure. Flow speeds reach 5.6m/s during the flood and more than 4m/s during the ebb in the case without turbines; when turbines are activated, the velocities reach respectively 4m/s and 3m/s (see Fig. 5).

In terms of performance and energy output, 3 configurations have been compared and are presented in Table I:

- All cases are based on a 50km^2 basin with a mean tidal amplitude of 7.5m; the channels are not equipped with sluice gates;
- Cases A and B present the same total channel width (300m), but case A is equipped with twice as many turbines;
- Cases B and C present approximately the same number of turbines (respectively 90 and 72), but case C has a narrower total channel width (160m vs. 300m).

The obtained results show that a significant amount of electricity can be generated by a Tidal Garden installation; however, the load factor remains below 25% (estimated load factor for a standard tidal power plant); furthermore, the highest load factor is obtained for the site yielding the highest tidal range impact.

For all the configurations studied, the use of sluice gates allows to significantly increase the power output, up to two fold, as well as the load factor. This higher production leads to a different evolution of the tidal range inside the basin: as with traditional tidal range plants, the high-tide slack periods will last longer, thus increasing the risk of sedimentation. Determining the balanced trade-off between power output and environmental impact will require further studies, in both hydrodynamics and sediment transport.

TABLE I

Cases		**A**	**B**	**C**
Total aperture	m	300	300	160
Number of channels & rows/channel	-	5/20	3/10	2/12
Number of tidal turbines per row	-	2	3	3
Installed power	MW	400	180	144
Annual electricity production	GWh	**424**	**245**	**290**
Load factor	-	0.12	0.16	0.23
Maximum impact on tidal range	m	3.9	1.4	5.1

VI. FUTURE WORK

The first results obtained highlight the complexity of optimising a Tidal Garden installation due to the large number of parameters. Some considerations also need to be more precisely defined (e.g. acceptable limits of the basin tidal range evolution). Economical considerations shall also be included to guide the optimisation process (e.g. should the number of turbines be reduced to achieve higher load factor?). Additional technical aspects to be studied are: optimisation of geometrical parameters (e.g. converging/diverging sections), turbine and sluice gate control methods; sediment transport modelling and siltation risk evaluation; turbine wake and turbulence dissipation.

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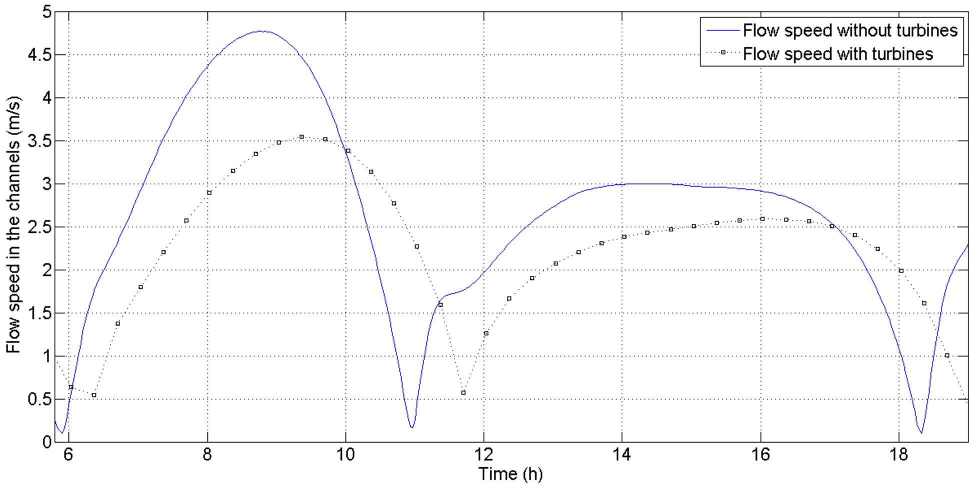

Figure 3. Flow velocity (average of the 3 channels), with and without turbines.

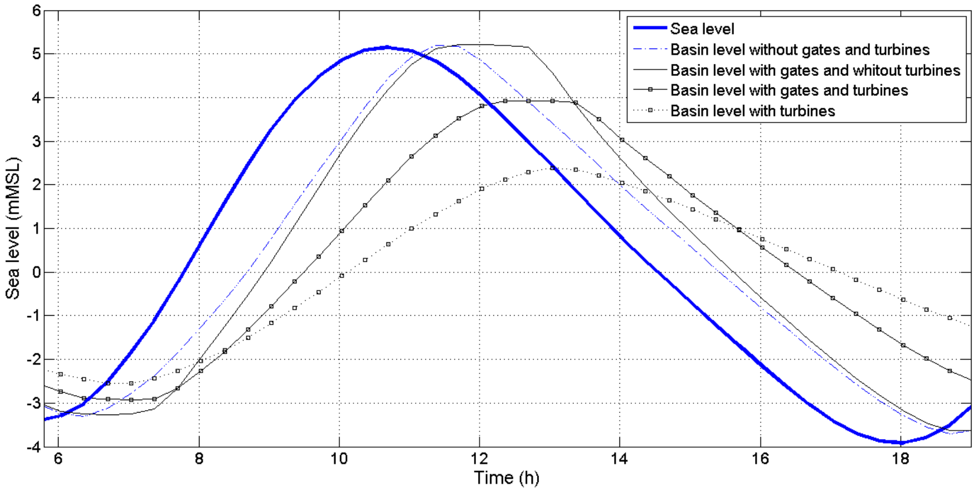

Figure 4. Achieved basin levels with different configurations.

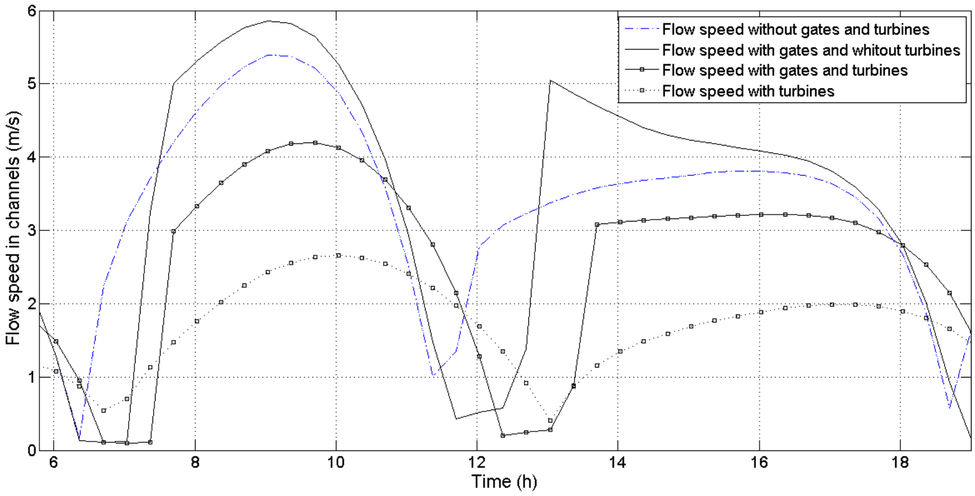

Figure 5. Achieved velocities (average of 5 channels) with different configurations.