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MODELLING THE IMPACT OF TIDAL FARMS ON FLOOD RISK IN THE SOLWAY FIRTH ESTUARY

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ABSTRACT

The available tidal energy resource within estuaries is quite significant in the UK but these areas are usually prone to flooding. The objective of this study is the assessment of flood risk due to tidal farms in estuaries through its application to a real case, the Solway Firth.

A numerical model has been developed to represent the hydrodynamic conditions of the estuary during an extreme event. The results from this model for the maximum velocities indicate the suitable locations for the tidal farms. Two different cases with parallel and staggered configurations of tidal farms have been introduced. The comparison of the results for the maximum water levels between the situations with and without the farms allow us to draw conclusions about changes of flood risk due to the farm and contrast the impact of two different arrangements of turbines. The values of the energy extracted in both configurations will also be investigated.

INTRODUCTION

Methods for extracting tidal energy fall broadly into two categories; those using the tidal variation in height through barrages and tidal pools, and those extracting energy from the tidal stream through various designs of turbines. Tidal turbines are under active investigation in a number of contexts, particularly for use in deep water environments; in contrast their application in shallower estuarine environments has not been investigated to the same extent. An example of the latter can be found in the work carried out by Fallon et al [1].

Estuarine sites present significant advantages, in particular shorter distances to cable to shore and the fact of the sites being sheltered from offshore waves. However individual turbines would be relatively small, and so to achieve GW scale installation will require the development of farms of 100's of turbines. Therefore, prior to their deployment, it is necessary to study the consequences from the blockage effects induced by large arrays of turbines in order to avoid aggravating the damages caused by coastal flooding. In this regard, an analysis of the effects of different arrays of turbines in the hydrodynamic conditions of the Severn Estuary was presented by Ahmadian and Falconer [2].

In order to assess the flood risk induced by tidal farms in estuaries, the Solway Firth area has been selected as a case study from a group of estuaries in the UK under the criteria of suitability for tidal energy extraction and presence of flood risk. The water velocity and elevations fields have been calculated in the estuary in the cases with and without turbines by means of a numerical model.

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NUMERICAL MODEL

A numerical model, Mike 21 Flow Model FM, has been used to simulate the hydrodynamic behaviour of the flow in the estuary. This model is a two-dimensional (2D) system based on an unstructured mesh. A cell-centred finite volume method is applied for the spatial discretization of the governing equations, consisting of the 2D incompressible Reynolds averaged Navier-Stokes equations subject to the assumptions of Boussinesq and of hydrostatic pressure (See equations 1, 2 and 3). For the time integration both a low order method (first order explicit Euler method) or a higher order method (second order Runge-Kutta method) can be applied. [3]

Continuity equation:

$$\frac{\partial h}{\partial t}+\frac{\partial h\bar{u}}{\partial x}+\frac{\partial h\bar{v}}{\partial y}=hS \qquad (1)$$

Momentum equations:

$$\frac{\partial h\bar{u}}{\partial t}+\frac{\partial h\bar{u}^2}{\partial x}+\frac{\partial h\bar{v}\bar{u}}{\partial y}=f\bar{v}h-gh\frac{\partial \eta}{\partial x}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial x}$$
$$-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial x}+\frac{\tau_{sx}}{\rho_0}-\frac{\tau_{bx}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial s_{xx}}{\partial x}+\frac{\partial s_{xy}}{\partial y}\right)$$
$$+\frac{\partial}{\partial x}(hT_{xx})+\frac{\partial}{\partial y}(hT_{xy})+hu_sS \qquad (2)$$

$$\frac{\partial h\bar{v}}{\partial t}+\frac{\partial h\bar{u}\bar{v}}{\partial x}+\frac{\partial h\bar{v}^2}{\partial y}=f\bar{u}h-gh\frac{\partial \eta}{\partial y}-\frac{h}{\rho_0}\frac{\partial p_a}{\partial y}$$
$$-\frac{gh^2}{2\rho_0}\frac{\partial \rho}{\partial y}+\frac{\tau_{sy}}{\rho_0}-\frac{\tau_{by}}{\rho_0}-\frac{1}{\rho_0}\left(\frac{\partial s_{yx}}{\partial x}+\frac{\partial s_{yy}}{\partial y}\right)$$
$$+\frac{\partial}{\partial x}(hT_{xy})+\frac{\partial}{\partial y}(hT_{yy})+hv_sS \qquad (3)$$

Where η is the surface elevation, h is the water depth, u and v are the velocity components in the x and y directions (the overbar indicates the depth-averaged values), g is the gravitational acceleration, ρ_0 is the reference density of water, s_{ij} are the components of the radiation stress tensor, p_a is the atmospheric pressure, τ_{bx}, τ_{by} are bottom stresses, τ_{sx}, τ_{sy} are wind or ice stresses, T_{ij} are the lateral stresses including those due to viscous friction, turbulent friction and differential advection, S is the discharge from point sources and u_s, v_s are the velocity components of the water discharged into ambient.

Turbines are represented in the model as an increased resistance to the flow and their effect is introduced in the governing equations by the axial and transverse components of the drag force (Eqs. 4 and 5) [4].

$$F_d = \frac{1}{2}\rho\alpha C_d A_e v^2 \tag{4}$$

$$F_l = \frac{1}{2}\rho\alpha C_l A_e v^2 \tag{5}$$

Being α a correction factor, C_d and C_l the drag and lift coefficients respectively, A_e the effective area of the turbine and v the velocity of the flow incident into the turbine.

APPLICATION TO THE SOLWAY FIRTH

The Solway Firth estuary can be seen in Figure 1. The domain of the model covers the area between the open boundary, defined by Abbey Head and St Bee´s Head, and the convergence of the rivers Esk and Eden. The bathymetry of the estuary has been obtained from the BODC dataset ´Celtic Seas Bathymetry´ [5], with a resolution of 30 arc seconds in latitude and 1 arc minute in longitude.

Figure 1.- Solway Firth area (source: Digimap Ordnance Survey)

The boundary conditions in the open sea limit consist of water elevations under the scenario of the 200 years return period event, formed by the highest astronomical tide plus an atmospheric surge, as indicated by the Environment Agency for the design of flood defences [6]. The average flows of the main rivers in the estuary (Urr, Nith, Lochar, Annan, Esk, Eden, Wampool and Waver) have been used as sources at specific points in the contour of the domain according to the values provided by Gurbutt et al [7]. Wind conditions have also been included in the model following the monthly values provided by Carlisle airport. The rest of parameters in the model can be seen from table 1. The model has been calibrated against observed measurements of the current speed on 30th April 1977 at the station with coordinates (54º 44' N, 3º 53' W) [5].

Table 1. Model parameters

Simulation period	9/02/2013, 10h - 13/02/2013, 14h
Time step	900 sec
Elements (approx.)	13500
Max. mesh size	1 km^2
Bed roughness (1/n)	22 $m^{1/3}/s$
Smagorinsky Coeff.	0.28

TIDAL FARMS

The location of the farms was defined in terms of the results for maximum velocities in the estuary. These results showed two potential places for the installation of the farm however one of them has not been considered due to its shallowness.

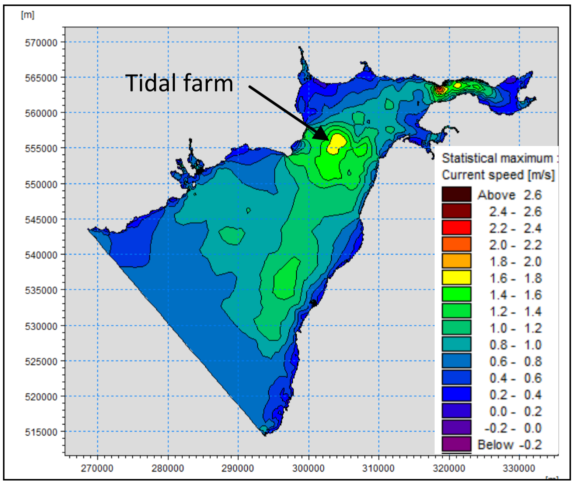

Figure 2.- Maximum current speed in the Solway Firth over the period of the simulation

A tidal farm consisting of 17x17 turbines have been included under parallel and staggered configurations. Each turbine, based in the MRL design [8] has dimensions of 7.8 m in diameter and 39 m in length. The size of the turbine is related to an approximated capacity of 0.5 MW, assuming a power coefficient of 0.4 for a 2m/s flow. The lateral spacing between turbines is 46.8 m while the longitudinal spacing has been set equal to 117 m. The drag force exerted by each turbine to the flow is defined by a constant drag coefficient of 0.5, according to theoretical values extracted from previous studies [9].

RESULTS

In order to assess the effect of the tidal farms on the flood risk levels in the estuary, the results for the maximum water levels during the simulation have been analysed and compared in the situations with and without the turbines, as shown in Figure 3.

In both configurations, the maximum water levels are generally increased slightly in the outer and the upper part of the estuary and decreased above the farm in the inner area. Differences are in the order of cm in both cases therefore it does not appear to have a significant influence on flood risk. When comparing the results between both configurations the parallel case shows a higher reduction in the maximum water levels in the inner area next to the farm and a higher increase in the upper part but the differences with the staggered configuration are small.

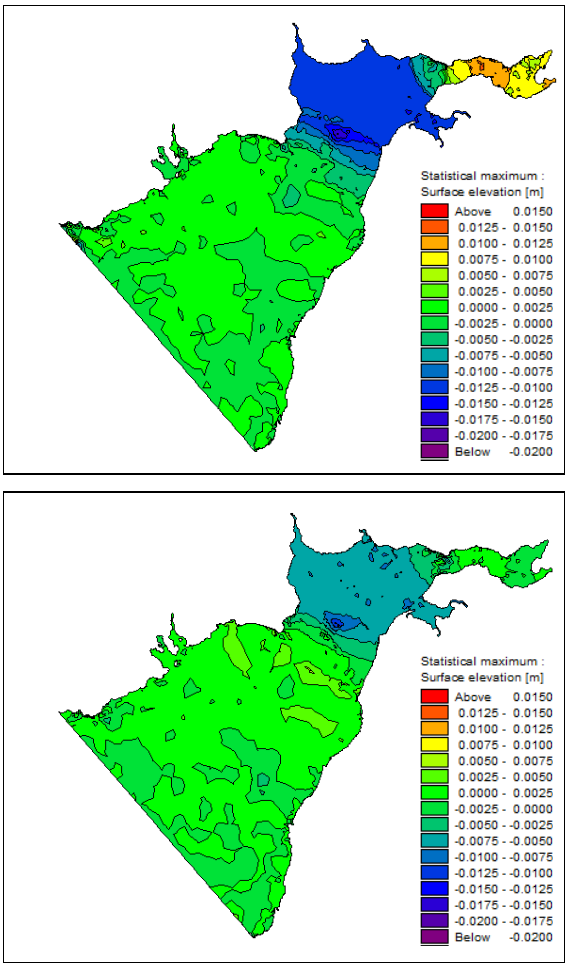

Figure 3.- Differences in the maximum water levels between the simulation without tidal farms and with the parallel and the staggered configurations (top and bottom images, respectively)

Regarding the energy extracted by the farms, a parallel research is being conducted to determine the power coefficient of the MRL design in detail. This coefficient will be used to calculate the power output taking into account the results from this study about the velocities within the turbines. In this sense, previous research has demonstrated that the extracted energy would be higher in the staggered configuration than in the parallel one. [10]

CONCLUSIONS

From the analysis of the maximum water levels in the estuary during the extreme event it can be seen that the effect of tidal farms is not significant for flood risk. Changes in the inner part of the estuary consist of a reduction of water levels next to the farm and an increase in the uppermost area. These changes are smoother for the staggered case while in the outer part the increase is almost imperceptible in both cases. Nevertheless, the implications of having a higher number of turbines cannot be ignored. Therefore, further work will focus on the effects on maximum water levels in a situation with an increased number of turbines.

The analysis of the energy extracted by each layout will also be addressed in future stages of the research.

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