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Laboratory study on the effects of hydro kinetic turbines on hydrodynamics and sediment dynamics

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ABSTRACT

The need for hydrokinetic turbine wake characterisation and their environmental impact has led to a number of studies. However, a small number of them have taken into account mobile sediment bed effects. The aim of the present work is to study the impact of the presence of a horizontal-axis three-bladed turbine with the flow and a mobile sediment bed. We use a series of laboratory experiments with a scaled modelled turbine installed in a flume with a mobile sandy bed at the bottom. Acoustic instruments were used to monitor flow, suspended sediment and bed behaviour. Results show a velocity decrease of about 50% throughout the water column and no flow recovery after a distance of 15 rotor diameters. Clearly visible ripples in the absence of the model turbine were replaced by horseshoe-shaped scour pit in the near wake region, and a depositional heap in the far wake. Suspended sediment differences were recorded in the streamwise direction with a possible effect of the wake as far as 15 rotor diameters. These results imply potentially important effects on the efficiency of turbine arrays, if the flow were to be lower than expected, on turbine foundations and modify coastal sediment transport.

1. Introduction

Energy from renewable sources is widely available from water, geothermal heat, sun, wind, biomass and wave-tidal sources. However, their use remains extremely difficult due to conversion processes, limited efficiencies, infrastructure, land availability, systems reliability and environmental impact [1]. In the marine sector, the growing interest in hydro kinetic turbines and tidal stream turbines toward commercial developments requires improved understanding of the implications of array deployments. In particular, the characterisation of the wake of a device is critical for engineering, development and environmental reasons. For hydro kinetic and tidal stream turbines, which aim to extract energy from river and tidal currents, the spacing between turbines in future arrays and thus optimal array design fundamentally depends on the knowledge of the wake recovery length. Environmental effects may include changes to both physical and ecological processes. Examples of such effects are the turbid wakes 30–150 m wide and up to 10 km long which have been observed downstream of offshore wind farm arrays [2,3]. Deployments of tidal stream turbines (TST) could produce similarly large wakes, even though the underpinning mechanisms would be more complicated due, in part, to the combination of a support structure and the moving turbine.

Improved understanding of turbine (hydro kinetic and tidal stream) wakes is fundamentally underpinned by direct measurements both at reduced scales in laboratory flumes and at full scale in the field. These measurements can be, in turn, used to inform and validate the numerical models required to predict the wide-scale implications of turbine deployments (e.g., [4]). Following from their intended purpose, marine tidal stream turbines are expected to be deployed in coastal and shelf seas and in particular in locations with relatively high tidal currents. One implication is that the tidal boundary layer would typically cover the entire water column, another key implication is that wakes generated by TST may then interact with the seabed in these relatively shallow environments.

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Although laboratory experiments have investigated wakes due to mesh discs [5] and model turbines (e.g. [6,7]), the focus has commonly been on determining the wake recovery length rather than on investigating the impact on environmental physical processes (e.g., [8,9]). Assessing such impacts (on hydrodynamics, waves, turbulence and sediment transport for example) is, however, critical for successful commercial deployments of turbines and has been recognised as a key research gap [10]. Recent experiments have further characterised the wake behaviour in shallow turbulent flow above a fixed bed (e.g. [11]), and investigated near-wall effects and bed shear stress due to scaled turbines above a smooth fixed bed (e.g., [12]). Nevertheless, studies about the complete two-way interactions between the seabed and the presence of the TST remain very scarce.

Deployment of turbines above mobile beds, whether in rivers, estuaries, or the coastal ocean, may lead to a range of issues linked with sediment transport. Generating turbid wakes (e.g. [2,3]), may limit light availability with important ecological consequences. Increased erosion leading to scour can be expected in the near wake of a turbine, although the fate of the eroded sediment is not fully known and the effect on adjacent and nearby turbines is uncertain. Alternatively, other areas may be subjected to net deposition, which may have important ecological and geomorphic implications. The seabed, and changes to it, may also have an important impact on the flow and TST efficiency via the control of bed roughness on the vertical velocity profile. Existing studies that have included artificial roughness (e.g. [5]), have focused on local scour generated by model turbines in laboratory experiments [13], and have measured the interaction between three model turbines and a mobile bed with two-dimensional bedforms [14]. Nevertheless, studies encompassing all elements of the triad of hydrodynamics, sediment bed dynamics and suspended sediment dynamics are still lacking.

This study aims to address this gap and present for the first time an investigation of the interaction between the sediment triad flow, suspended sediment and bed [15], and a modelled turbine using experiments in a flume. We use a set of different acoustic instruments to give a wide covering area of observations for different variables. This will show that the wake due to the scaled turbine has an impact as far as 15 times the diameter of the rotor in the streamwise direction and over the width of the flume. The next Section 2 explains the experimental setup used in this study. Section 3 describes the effects of the modelled turbine on the flow and the sediment bed. The results are discussed in Section 4 in terms of hydrodynamics, wake recovery and the sediment bed. Finally, the main findings are highlighted in the conclusion Section 5.

2. Experimental methods

A series of laboratory scale experiments were carried out in the Total Environment Simulator at the University of Hull, United Kingdom, which was set up as an 11 m long and 1.6 m wide flume in order to quantify the potential impact of TST on near-bed hydrodynamics and sediment dynamics (bed and suspended). The effect of a modelled turbine (or rotor) was determined from a comparison between measurements in absence of the rotor and measurements with the rotor installed.

2.1. Scaled laboratory measurements

The interactions between horizontal axis turbines and the triad of hydrodynamics, bed dynamics and suspended sediment dynamics were determined by considering a model three-bladed horizontal axis rotor of diameter $D = 0.2$ m (Fig. 1). The rotor was mounted in a shaft of 8 mm diameter which in turn was attached to a housing of 32 mm diameter with a 25 W DC motor. This allowed the control of the rotation to a tip speed ratio of 5.5. The housing was fixed to a solid fin of 68 mm × 6mm which was mounted from a gantry above the flume. The experiments were carried out above a mobile bed consisting of a 0.1m thick layer of coarse well-sorted sand (0.41 mm median diameter). The complete particle size distribution is presented in Fig. 2. The flume was filled with freshwater to obtain 0.5 m water column depth. The pumps, which recirculated both sediment and water, were set up to create a steady current approximately 0.5 $m \cdot s^{-1}$. The water and sediment were left to flow in the flume without the rotor until it was considered that the

Fig. 1. Tidal stream turbine model used in the experiments with a 0.2 m diameter rotor.

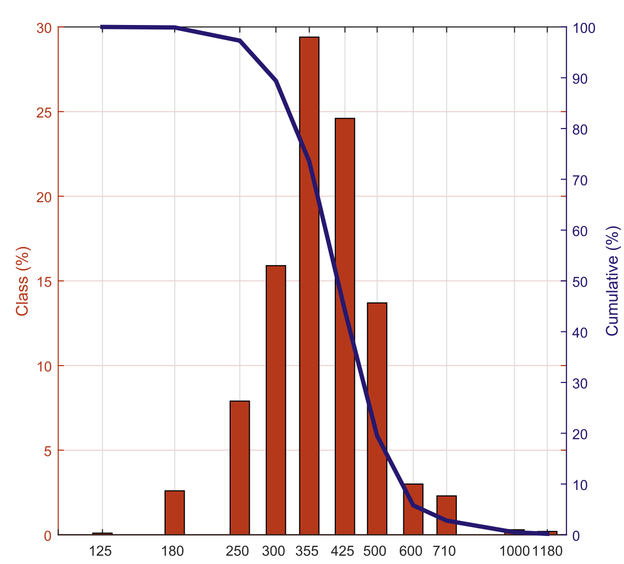

Fig. 2. Particle size distribution and cumulative curve of the sediments used in the experiment.