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The turbulent wake of a monopile foundation

C. Rogan*, J. Miles**, D. Simmonds, G. Iglesias

School of Marine Science and Engineering, Plymouth University, Plymouth PL4 8AA, UK

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ABSTRACT

An experimental programme is presented, examining the turbulent wake of a monopile foundation in a current. Velocity was recorded across an extensive domain downstream of a model monopile in a 0.5 m deep basin, using an acoustic Doppler velocimeter array. The distribution of turbulent kinetic energy (*TKE*) is examined across the entire domain. Tests were undertaken using several combinations of pile diameter ($D = 0.1$ and 0.2 m) and mean flow velocity ($\overline{u_0} = 0.08–0.24$ m/s), representing typical prototype conditions at a scale of 1:50. It is shown that turbulence can be predicted using the distance downstream (x) and off axis (y), the pile diameter, and the mean flow velocity. Two new parameters are introduced to simplify assessment of proposed structures. Relative Excess Turbulence (*RET*) is the extra turbulence generated by the pile, normalised by the ambient turbulence. Turbulence Recovery Length-scale (*TRL*) is the distance downstream (normalised by D) required for *RET* to fall below a given threshold. Results show that *RET* decays exponentially with distance downstream. Across the wake, *RET* fitted a Gaussian function with peak values at the wake centreline. *TRL* is estimated at 40 for an *RET* threshold of 1.0 and 400 for an *RET* threshold of 0.1.

1. Introduction

Monopile foundations are by far the most common design for offshore wind turbines, comprising 91% of all European installations completed in 2014 [9]. They are well suited to shallow and transitional water depths, due to their simplicity of installation. At existing installations, piles are typically around 5 m in diameter. The UK is currently the world leader in terms of offshore wind installed capacity, with further growth in the sector forming a key component of the government's renewables 2020 strategy [7,8].

As installations move into deeper water and turbine diameters increase, the greater horizontal loads and bending moments will necessitate the use of ever larger piles [5]. There are plans for turbines of 6 MW capacity, in as much as 30 m of water depth. Such installations will require monopiles of up to 7.5 m diameter [2]. With a greater number of ever larger monopiles anticipated in the coming years, it is important that we understand their impact.

The flow structure close to the base of a monopile has already been extensively studied [6,10,25,27]. Three distinct flow structures can be identified close to the base of the pile. A horseshoe vortex forms at the upstream face, contraction of streamlines occurs as the flow accelerates around the sides of the pile, and lee wake vortices are formed immediately downstream of the pile.

These flow structures lead to enhanced bed scour and the formation of a scour hole around the pile. This is of great concern to the structural integrity of the foundation. Much work has been done to quantify the depth of the scour hole [24,26,31], and its rate of development [19].

In addition to the flow structures described above, the monopile's presence will cause increased turbulence in the flow downstream. Elevated turbulence enhances the carrying capacity of the flow, leading to increased sediment transport [4,14]. This increases the distance that scoured sediments can be transported downstream of the pile.

The environmental impacts of suspended sediments are numerous. Increased turbidity can affect the productivity of plankton [15], as well as influencing the behaviour of predatory fish [1] and marine mammals [30]. These are related to economic concerns, as any changes could impact on fisheries. Sediment transport regimes also govern sedimentation processes downstream [32].

Techniques exist for estimating the turbidity downstream of existing monopiles, by analysing satellite images [11]. Turbid wakes have been observed transporting sediment for hundreds of metres

* Corresponding author.
** Corresponding author.
E-mail addresses: crogan04@qub.ac.uk (C. Rogan), j.r.miles@plymouth.ac.uk (J. Miles), d.simmonds@plymouth.ac.uk (D. Simmonds), gregorio.iglesias@plymouth.ac.uk (G. Iglesias).

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downstream of monopiles [28].

Ideally, numerical modelling would be used to predict the likely impact of a proposed wind farm on sediment transport during the planning phase. However, the flow structures governing the increased turbulence are typically on the same scale as the monopile. These cannot be resolved by existing sediment transport models, which typically have cell sizes on the order of hundreds of meters in order to cope with the large regions of interest [16].

This paper presents the results of a series of laboratory experiments, performed at a scale of 1:50, examining the wake structure downstream of a monopile foundation. In particular, the influence on turbulence of flow velocity, pile diameter and location relative to the pile were measured. Two new parameters are introduced to simplify turbulence assessment of planned monopile structures in terms the relative position and flow velocity.

Empirical relationships are presented predicting the turbulent characteristics of the wake. These have been validated to show that turbulence in the wake of a monopile can be described by a small number of parameters. These parameterisations will allow the monopile's influence on turbulence to be implemented in regional sediment transport models.

2. Materials and methods

2.1. Experimental design

The experimental programme was carried out in the Coastal basin at Plymouth University. The basin measures 10 m long by 7.2 m wide, with a water depth of 0.5 m. The pile was fixed to the floor of the basin, centred 4.5 m from the downstream tank wall and 3.5 m from the side (Fig. 1). The floor of the tank is fibre reinforced plastic, with a roughness lengthscale of <0.0001 m.

Prototype values of water depth, pile diameter and flow velocity were chosen based on typical values at existing wind farm sites [18]. provide information from several existing wind farms. Average monopile diameter is just below 5 m, with the largest quoted at 6 m. Pile diameters are expected to increase in the future as development moves into deeper water. Peak current velocities range between 0.6 and 2.0 m/s, although the higher values in this range correspond to particularly shallow sites. The experimental programme was designed to examine turbulence in the free stream flow, and so an intermediate depth prototype was considered more appropriate. This was confirmed by examination of proposed sites in the channel region, using the ANEMOC offshore wind farm database [3].

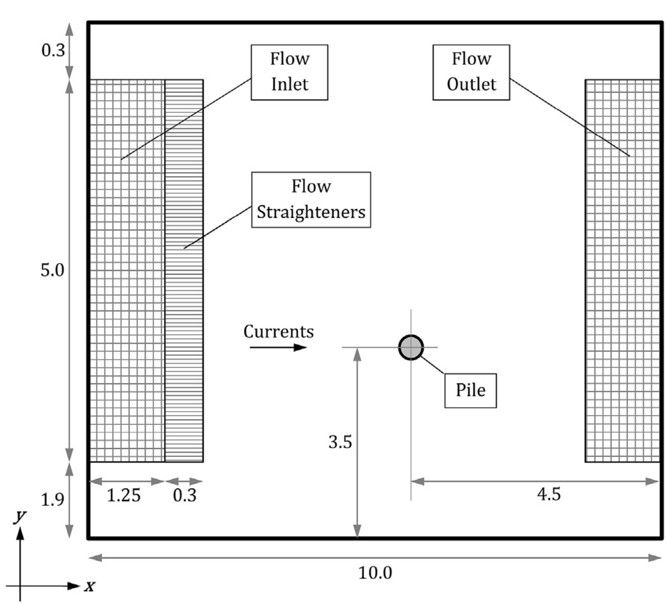

Fig. 1. Plan view of the Coastal basin. Not to scale. All dimensions in metres.

Prototype values were converted to model scale by applying Froude similitude at a scale of 1:50 to derive appropriate scale factors (λ). Measurements were made at four model velocities ($\overline{u_0}$ = 0.08, 0.14, 0.18 and 0.24 m/s), and two model pile diameters (D = 0.1 and 0.2 m), in water depth d of 0.5 m (Table 1). Froude similitude is achieved between the model and prototype, with Froude numbers ranging between 8×10^{-2} and 2×10^{-1}.

Measured water temperatures were around 20 °C throughout the experimental program, with a corresponding kinematic viscosity of approximately 10^{-6} m^2/s. For the current experimental program, model Reynolds numbers range from 8×10^3 to 5×10^4; flow is fully turbulent.

To allow comparison of results with different prototype scales, x and y positions were normalised by the pile diameter to yield x^* and y^*:

$$x^* = \frac{x}{D} \tag{1}$$

$$y^* = \frac{y}{D} \tag{2}$$

2.2. Data

Three components of velocity were measured using a Nortek Vectrino profiler Acoustic Doppler Velocimeter (ADV), referred to here as ‘ADV1’. ADVs are very suitable for experimental measurements of this kind and are widely used, [13,22]. Nikora and Goring [21] provide a summary of their operation.

Detailed velocity measurements were made downstream of the model pile under steady flow conditions, with the goal of parameterising the wake structure. Velocity time series data were recorded using ADV1 positioned along transverse and longitudinal wake profiles (Fig. 2). At each location, 500 s of velocity time series data were recorded at a sample frequency of 64 Hz, for each flow condition. The instrument was positioned vertically to record point velocity within the free stream, 35 cm from the tank floor.

The longitudinal profile extended 2.7 m downstream of the pile centre, with nine measurement positions spaced logarithmically along its length. Table 2 summarises the eight transverse profiles, aligned perpendicular to the mean flow. Values of x and D were chosen so that the eight profiles converged to four in the x^* domain. Each profile extended 50 cm either side of the wake centreline.

Velocity time series data from ADV1 was used to calculate Turbulent Kinetic Energy per unit volume (TKE), using Equation (3).

$$TKE = \frac{1}{2}\rho\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) \tag{3}$$

where u, v and w are the components of velocity in the x, y and z

Table 1
Prototype vs Model parameters.

Parameter	λ	Prototype	Model
d	50	25 m	0.5 m
D	50	5–10 m	0.1–0.2 m
$\overline{u_0}$	$\sqrt{50}$	0.6–1.6 m/s	0.08–0.24 m/s
Re	–	2×10^6–2×10^7	8×10^3–5×10^4