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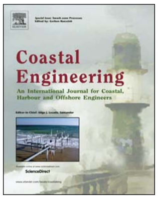

Current and wave effects around windfarm monopile foundations

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ABSTRACT

Laboratory measurements were undertaken to investigate wave and current velocities in the vicinity of a wind turbine monopile foundation, in order to inform environmental impact assessments and to quantify flow variability in the region of the power take off cable. Flow measurements were made up to 15.5 pile diameters (D) downstream of the pile. Measurements were also taken around the perimeter of the pile (~0.75 D from the pile centre) at the approximate representative height of the power cable.

In current-only tests, the mean flow was reduced immediately downstream of the pile, but returned to within 5% of background levels by 8.3 D downstream of the pile centre in representative conditions. A new parameterisation of the velocity recovery is given. The turbulent eddy shedding frequency was well predicted by the Strouhal number. Turbulence peaked at 1.5 D from the pile centre, and the subsequent decay was parameterised. Velocity magnitudes at the side of the pile were up to 1.35 times greater than background flow rates, in line with potential flow theory. Velocities in the wake region were much less than predicted by potential flow theory, corresponding with increased turbulence.

Tests with waves indicated that oscillatory velocities reduced immediately down-wave of the pile, but returned quickly to background levels (by 1.65 to 3.5 D of the pile centre). The general near-pile distribution of the orbital velocity maximum was well represented by potential flow theory. Orbital velocities were reduced immediately up-wave and down-wave of the pile. At the side of the pile in wind sea conditions, the velocity increased up to 1.66 times the background level. This increased to 1.85 times in swell conditions.

For orthogonal currents and waves, a velocity parameter was calculated as the mean current plus wave orbital velocity, resolved. With the mean current direction as a reference, the maximum flow was observed at the side of the pile. At 0.75 D from the pile centre, the flow was enhanced by up to 1.2 times the no–pile case. Spectral peaks in the velocity were evident at both wave frequency and at the Strouhal frequency, immediately down current from the pile.

1. Introduction

Offshore wind turbines have become an important contributor to renewable energy generation. The foundations of monopiles are known to modify flows, and generate complex three dimensional localised flow structures [14,20,22]. The pile-induced flow modifications affect scour generation, need to be considered for cable design, and may impact on local ecosystems.

Flows passing a vertical cylinder are accelerated as they pass around it. This flow enhancement may be demonstrated theoretically by potential flow models (e.g. [1,27]). In these models, the flow in the radial direction U_r is given by:

$$U_r = U_\infty\left(1-\frac{R^2}{r^2}\right)\cos\theta \tag{1}$$

where U_∞ is the flow strength away from the pile's influence, R is the radius of the pile, r is the distance from the pile centre, and θ is the angle around the pile from the upstream stagnation point. The flow in the tangential direction U_θ is given by:

$$U_\theta = -U_\infty\left(1+\frac{R^2}{r^2}\right)\sin\theta \tag{2}$$

The magnitude of the flow is given by:

$$U = (U_r^2 + U_\theta^2)^{1/2} \tag{3}$$

These predictions do not include the generation of vortices, or turbulence in the wake region, and may therefore misrepresent the flow. For offshore monopiles, three key mechanisms of turbulence generation are recognised [14]. These include lee wake vortices, horseshoe vortices and (vertical) counter-rotating vortices (Fig. 1).

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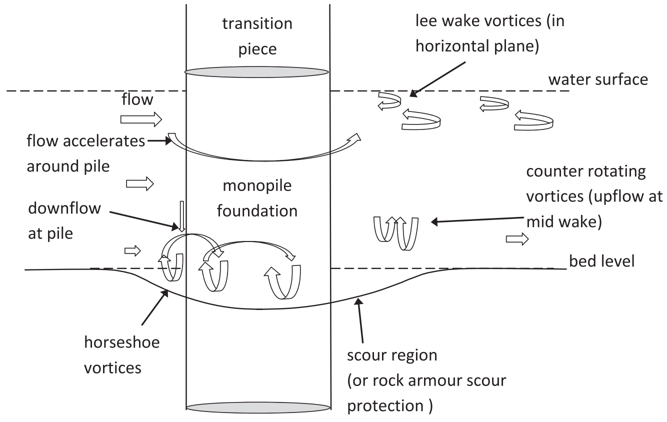

Fig. 1. Flow processes near windfarm monopile foundations.

Lee-wake vortices are well documented (e.g. [1]). They may be symmetrical and stationary at very low Reynolds number (Re around 30), or shed as vortex pairs in a von Karman vortex street at higher Reynolds number. For Re > 2000, the wake is essentially turbulent, but still has traces of periodic structure remaining. The frequency of eddy shedding (f_s) may be predicted using the Strouhal number (S), the flow velocity away from the pile (U_∞) and the pile diameter (D) as:

$$f_s = \frac{SU_\infty}{D} \tag{4}$$

The Strouhal number (S) is a function of the pile Reynolds number (Re_D):

$$S=0.\ 198\left(1-\frac{19.\ 7}{Re_D}\right) \tag{5}$$

The pile Reynolds number varies with flow velocity, pile diameter and fluid viscosity ν:

$$Re_D = \frac{U_\infty D}{\nu} \tag{6}$$

Horseshoe vortices are formed near the bed. These are generated by a downflow on the upstream side of the pile. The horseshoe vortices affect the region around the perimeter of the pile, near the bed [2,22,5].

Counter rotating vortices in the vertical plane, downstream of the pile were observed to form in models with scour protection by Petersen et al. [14]. These give a net upward directed flow in a line downstream of the centre of the pile, in the lower part of the water column, balanced by a downward flow to the sides of the centreline.

In oscillatory flows, the Keulegan-Carpenter (KC) number gives a measure of the orbital excursion compared to pile diameter [22]. The KC number is given by:

$$KC = \frac{U_m T}{D} \tag{7}$$

where u_m is the maximum orbital velocity calculated from linear theory. The importance of flow separation increases with the KC number. Sumer et al. [22] identify that for wave cases with KC < 6, no horseshoe vortex occurs. With increasing KC, the size and lifespan of the horseshoe vortex increases. The importance of diffraction increases with the ratio D/λ [21]. As KC increases, non-linear effects become important at gradually lower values of D/λ.

The interaction between the flow and bed material leads to enhanced bed shear stress and the formation of scour around the pile base [23,24]. The depth of scour has been observed to be up to 1.4 pile diameters in the field [28], although there is variability in this depending on the sediment type (see [29]). Scour may lead to concerns about structure stability, and in some cases, rock armour scour protection is put in place. When applied, the horizontal extent of this scour protection typically has a diameter of 2 D to 4.5 D [10,9].

Flow velocity has been shown in numerical models to be modified further downstream than is indicated by the size of the scour hole [16,17]. Rogan et al. [18] and Rogan et al. [19] give a detailed study of the downstream impacts of turbulence, indicating that pile induced turbulence can remain for up to 80 pile diameters downstream of the pile. The change in mean flow may lead to larger scale variations in bedforms, as has been observed in the field at Scroby Sands windfarm, UK [15].

The design of monopile foundations is such that power cables are routed to the seafloor near the base of the pile. There are different design approaches for the cabling, depending on whether scour protection is applied, and the specific design preferences of the installer [26,3]. The cable may be routed through a ‘J-tube’ that brings the cables to the structure base on the outside of the pile. Alternatively, cables may be routed inside the foundations, and leave through a port in the base of the foundation. Each monopile may require one or two cables, depending on the cable layout of the windfarm. The cable typically leaves the pile above the level of the bed, at about ~2 m above undisturbed sand level and at a downward angle of ~45°. This structure takes the cables across the deepest scour region (E.ON, *pers comm*). The diameter of the cable is small compared to the pile diameter (e.g. the inter-pile cable diameter is ~13.9 cm for the UK Rampion wind site). Beyond the J-tube/port, a free hanging section of cable (catenary section) crosses the remaining scour region, and is then routed into a trench in the seafloor (substrate permitting) (E.ON, *pers. comm.*). The free section of the catenary cable is susceptible to hydrodynamic forcing from different sources, including loading from the mean flow, variability in loading due to monopile foundation induced turbulence, and vortex induced vibration of the cable itself. Furthermore, surface wind wave and swell driven oscillations may affect the flow velocity near the cable. The time varying nature of the flow gives rise to the potential for cyclic stress fatigue and cable failure.

Predictions of tidal currents and wave orbital velocities may be obtained on a large scale from oceanographic measurements and model predictions. However, the local modification of flow, as a result of the inclusion of the pile in the system, means that these velocity predictions do not necessarily accurately represent the velocity near the pile. Numerical models [17] and laboratory experiments [19] have illustrated that the monopile leads to considerable modification of parameters such as the near-pile velocity and bed shear stress. This paper documents new laboratory measurements of currents and wave orbital velocities in the vicinity of a model monopile and downstream of the pile, with the aim of offering guidance parameters describing flow modifications. This is necessary in order to inform both environmental impact assessment and cable design.

2. Method

2.1. The COAST basin

Physical model experiments were carried out in the Plymouth University (UK) COAST basin. The basin is 15.5 m long, 10 m wide and 0.5 m deep. Pre-installed internally threaded anchor points on the basin floor allowed a scale model monopile to be securely attached. Fig. 2 shows the general basin set up during the experiments. The dimensions of the basin components are indicated in Fig. 3.

An integral pump system generates currents across the basin. Pumped flow upwells through basin floor grids into a narrow (turbulent) pool. The currents were driven through a flow straightener block at the upstream side of the basin, to reduce turbulence in the flow as far as possible. The block was formed from multiple parallel pipes that were horizontal and in-line with the flow. The individual pipes were approximately circular, of diameter 12 mm, and length 0.3 m. The straightener block extended over the full water depth (0.5 m). The pump driven flows were calibrated using Acoustic Doppler Velocimeter (ADV) measurements.