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Experimental investigation of the wave-induced flow around a surface-touching cylinder

M. Mattioli *, A. Mancinelli, M. Brocchini

Dipartimento Ingegneria Civile, Edile e Architettura (DICEA) – Sezione Idraulica e Ambiente, Università Politecnica delle Marche, Via Brecce Bianche, 60131 Ancona, Italy

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ABSTRACT

The wave-induced flow around a circular cylinder near both a rigid wall and an erodible bed is experimentally investigated using Particle Tracking Velocimetry (PTV). The aim of this study is to gain quantitative information on the local mean flow, the vorticity dynamics and the evolution of the erodible bed. The flow is characterized in terms of the Keulegan–Carpenter (KC), Reynolds (Re) and Ursell (U_r) numbers. The effects of changing these parameters over the ranges $1 < \mathrm{KC} < 31$, $3 \times 10^3 < \mathrm{Re} < 2.6 \times 10^4$ and $1.5 < U_r < 152$ are investigated. For KC < 1.1 the flow does not separate. When KC increases, the flow becomes unstable and large-scale vortical structures develop. The dimensionless intensity ($|\Gamma^*|$) depends non-monotonically on KC, with a local maximum at KC = 17, and the dimensionless area of the same macrovortex (A^*) follows a somewhat similar law. Although the dimensionless boundary layer thickness (δ^*) exhibits some discontinuities between KC regimes, it decreases with KC at $x/D = 0.5$, as $x/D = 1$ weakly depends on KC and can be regarded as constant ($\delta^* = 0.7$) and then, increases with KC when moving away from the cylinder. These findings are used to interpret the physics governing the flow around a cylinder touching a wall and are compared with available results from the literature (Sumer et al., 1991). The evolution of the scour mechanism occurring over an erodible sandy bed is also investigated. The validity of some empirical formulas in the literature is also tested on the basis of the available dataset. The empirical relationships of Cevik and Yuksel (1999) and Sumer and Fredsøe (1990) for the dimensionless scour depth (S/D) agree well with our results. The dimensionless scour width (W_s/D) is predicted well by Sumer and Fredsøe's (2002) empirical equation for KC < 23, whereas Catano-Lopera and Garcia's (2007) formula is more accurate for higher values of KC.

1. Introduction

The flow around a cylinder near a planar surface has been extensively studied over the last three decades because of its importance in many engineering applications, including the design of underwater pipelines, flow past tunnels, and the enhancement of heat transfer in heat exchangers. One of the most important manifestations of this problem is found in the oil and gas industry, where most offshore hydrocarbon products are transported to shore by underwater pipelines that lay on either rigid or erodible seabeds. Understanding the flow that waves induce around these pipelines is critical in assessing the loads that they experience and in identifying necessary measures to ensure stability and safety. However, the wavy

* Corresponding author.
E-mail address: matteo.mattioli@univpm.it (M. Mattioli).

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flow that occurs around a circular cylinder touching a surface remains poorly understood. This work studies this type of flow with a specific focus on the analysis of the pipeline–seabed interaction.

Placing a pipeline near a seabed significantly alters the local environment. As a result, a pressure gradient may occur between the upstream and downstream sides of the pipeline, forming vortices in the neighborhood of the pipeline. Piping underneath the erodible seabed and stagnation eddies may combine to generate a scour hole under the pipeline (Sumer and Fredsøe, 2002). The degree of piping is also a function of the local water depth h: for increasing Froude numbers $\mathrm{Fr} = U_0/\sqrt{gh}$, where U_0 represents the amplitude of mean free-stream velocity, i.e., for decreasing water depths, the flow velocity in the gap between the pipe and the bed increases, leading to increasing scour depths. The effect of water depth on scour may be important when the water depth becomes small, such as in the case of a river crossing. The physics governing the hydrodynamics around a cylinder placed far from a wall are completely different from the physics governing the hydrodynamics around a cylinder touching a wall, and the vortex shedding is significantly different between these two scenarios. The wall first influences the flow as a solid boundary inhibiting normal velocities, and then as a surface along which a boundary layer grows (Bearman and Zdravkovich, 1978; Rao et al., 2011).

Some of the first investigations of this type of flow examined the forces on a cylinder near a plane boundary in a sinusoidally oscillating fluid (Sarpkaya, 1976, 1977). A good description of the flow around a wall-free cylinder in oscillatory flows has been provided by Williamson (1985), and more recently, by Sumer et al. (1991), Sumer and Fredsøe (1997) and Tatsuno and Bearman (1990). These studies have provided a fundamental contribution to our understanding of complex pipe–flow interactions in various flow regimes.

Tatsuno and Bearman (1990) carried out experiments at Keulegan–Carpenter numbers between 1.6 and 15 ($\mathrm{KC}=U_0T/D$, where T represents the period of fluid oscillations and D is the cylinder diameter) and at Stokes numbers between 5 and 160. They found that above a threshold Keulegan–Carpenter number, some asymmetry appears in the flow separation and the associated vortex development behind the cylinder. The two vortices that develop in a half cycle differ in strength and may convect in different directions.

Sumer et al. (1991) found that, for small values of KC, the flow does not separate. When KC is increased further, up to 4, separation begins in the form of symmetric, attached vortices, while for $4 \leq \mathrm{KC} \leq 7$, the symmetry between the two vortices breaks down. For $\mathrm{KC} > 7$, the so-called vortex-shedding regime sets in (Sumer and Fredsøe, 1997). The effects of the proximity to the wall have been studied by Sumer et al. (1991), who performed a series of experimental visualizations of the flow for different values of Re and KC, with $\mathrm{Re}=U_0D/\nu$, where ν is the kinematic viscosity of water. These authors found that (i) the vortical flow regimes undergo major changes when the gap-to-diameter (e/D) ratio is below $O(1)$; (ii) the transverse vortex street, observed for a free cylinder for $7 < \mathrm{KC} < 13$, disappears for $e/D < 1.7$; (iii) the shedding frequency increases as e/D decreases; and (iv) when the cylinder is placed on the wall, a vortex pair forms upstream/downstream of the cylinder in each half-period. This vortex pair moves away from the cylinder, as the oscillation progresses. Although Sumer et al. (1991) identified some crucial issues for the analysis of the flow around a pipeline, a detailed quantitative knowledge of the vorticity dynamics is still lacking. Summarizing available knowledge to date, at least three questions remain regarding wall interference:

i) How do vortex structures evolve with a pipeline touching a wall? How does the intensity of the vorticity vary as a function of KC?
ii) What are the main features of the turbulent boundary layer along the wall?
iii) How does the flow change along the wall during the different wave phases?

The present work complements that of Sumer et al. (1991), in the sense that it extends their study of the flow around a near-wall cylinder to the case of wave-induced flows for the value of $e/D=0$. We aim to provide a quantitative description of flow properties of interest, including (i) the boundary layer structure, (ii) the vorticity dynamics for different values of the governing parameters (i.e. KC, Re and U_r numbers, U_r being the Ursell number $U_r=HL^2/h^3$, where H is the height and L the length of the incident wave and h the water depth), (iii) the intensity and size of the dominant vortical structures.

The present study is only the first step in a wider research effort into the role of the complex turbulent flows generated around a cylinder placed horizontally across the flow and touching a planar surface. In the present two-dimensional analysis, the flow is only characterized by spanwise vortices shed from the cylinder and by other turbulent structures generated by the interaction of the latter with the wall; however, the flow may exhibit three-dimensional character. These three-dimensional vortices, as shown by Nehari et al. (2004) and Scandura et al. (2009), cause axial modulation of the spanwise vorticity, but this issue is not examined here.

This study also investigates the scour formation around a submerged cylinder placed on an erodible seabed. The initial embedment of the cylinder was fixed to $e/D=0$ for all the tested waves. All of the experiments were carried out for at least 1.5 h, even if the equilibrium scour depth was reached within 60 min for most of the tests. The temporal history of the bed morphology was directly measured at fixed time steps. Three distinctive regimes were observed: (i) no scour regime for $\mathrm{KC} < 4$, (ii) scour with small ripples for $4 < \mathrm{KC} < 15$, and finally, (iii) scour with large ripples for $15 < \mathrm{KC} < 31$.

The paper is organized as follows. Section 2 describes the experimental set-up for the rigid-wall configuration, while Section 3 describes the data analysis procedures. Then, Section 4 summarizes the experimental results obtained for different values of KC subdivided into the classes identified by Sumer et al. (1991): (i) $\mathrm{KC} < 4$, (ii) $4 < \mathrm{KC} < 7$, (iii) $7 < \mathrm{KC} < 15$, (iv) $15 < \mathrm{KC} < 24$ and (v) $\mathrm{KC} > 24$ with Re ranging from 3.0×10^3 to 2.6×10^4 and U_r ranging from 1.5