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The hydrodynamic forces on a circular cylinder in proximity to a wall with intermittent contact in steady current

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ABSTRACT

We present a three-dimensional Large Eddy Simulations (LES) study on the hydrodynamics of a circular cylinder close to a wall. Intermittent gaps between the cylinder and wall, forming spanning and non-spanning sections along the span are considered. This geometry setting represents an idealized model of pipelines laid on an uneven seabed. As compared to that of the corresponding spanwise-uniform cylinders, the drag coefficient on spanning sections is generally smaller, while the drag on non-spanning sections is slightly larger. Large amplitudes of the sectional forces are observed, partially due to the variations of the gap flow under the spanned sections. Flow deflection from the non-spanning section to the spanning section induces changes in local force and pressure distributions. Despite these changes, the mean force on the cylinder with intermittent contact as a whole is shown to be reasonably estimated by pro rata of forces from spanwise-uniform cylinders over the parameter space considered in this study.

1. Introduction

The research on hydrodynamics around a horizontal circular cylinder near a plane boundary has been largely driven by pipeline engineering in the offshore oil and gas industry, which has been well documented in the monographs by Sumer and Fredsøe (1997) and Zdravkovich (1997), as well as research papers by Sarpkaya (1976), Bearman and Zdravkovich (1978, 1985), Kozakiewicz et al. (1995), Lei et al. (1999) and Price et al. (2002), among others. Most of the studies considered a wall-cylinder configuration with planar two-dimensional cross-sections, and the bed wall was either treated as smooth or smooth with grain roughness. While the flat-wall assumption is advantageous in separating the wall effects from the effects of diverse seafloor profiles (due to scour processes or the presence of rocky seafloor, for instance), the pipeline and seabed contacts are unlikely to be uniform. Field observations on subsea pipelines show variation in both as-laid embedment (e.g. Westgate and White (2015)) and in the changing through-life contact due to self-burial processes after installation (e.g. Leckie et al. (2015)). However, the effect of these gap features on the hydrodynamics is not well-known, yet it is believed to be important especially when a small diameter pipe is considered, such as subsea cables.

In fact, many pipelines have to cross seafloor areas characterized by rocks, valleys and hills, in the presence of frequent severe storm events. This paper forms part of a wider research effort being undertaken by the University of Western Australia (UWA) using both physical and numerical testing of pipe behavior over artificially-created rocky seabed. The work includes lateral resistance of pipes on rocky seabed (Griffiths et al., 2017), the effect of seabed roughness on enhanced boundary layer thickness and the validity of existing hydrodynamic force models for small diameter cables (Cheng et al., 2016). In this paper, the effects of intermittent contact on hydrodynamic forces are investigated using a numerical approach.

The hydrodynamic characteristics on a circular cylinder subjected to steady current includes the drag coefficient C_D, lift coefficient C_L, and the oscillation frequency of the forces (such as due to vortex shedding), which are defined as,

$$C_D = \frac{F_x}{0.5\rho U_\infty^2 DH}, C_L = \frac{F_y}{0.5\rho U_\infty^2 DH}, St = \frac{f_s D}{U_\infty}, \quad (1\text{-}1)$$

where F_x and F_y are the forces in the in-line and cross-flow directions, respectively, ρ the density of the fluid, U_∞ the unaffected incoming fluid velocity outside the wall boundary layer, D the diameter and H is the length of the cylinder. The f_s are normally referred to the vortex shedding

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frequency in the classic von Kármán vortex sheet, which can be measured by the dominant frequency in the lift force. However, for a pipe close to a wall as it will be seen later, it is noticed that the unsteadiness of the forces is not necessarily due to vortex shedding. The root-mean-square (*rms*) values of C_D and C_L, which describe the oscillation amplitude of the forces, are also important in characterizing the hydrodynamic features.

For a wall-free circular cylinder, the hydrodynamic forces and Strouhal number are mainly influenced by the Reynolds number (*Re*),

$$Re = \frac{U_\infty D}{\nu}, \tag{1-2}$$

where ν is the kinematic viscosity of the fluid. However, wall-proximity complicates the problem in the sense that it introduces a wall boundary layer. There is no surprise that the forces on a cylinder near a wall are also dependent on the distance (e) between the wall and the cylinder, normally defined as gap ratio,

$$G = \frac{e}{D}. \tag{1-3}$$

But for avoidance of confusion in this paper, G is henceforth referred to as the cylinder elevation above the far-field seabed and it is independent of the configuration of local seabed contact under the cylinder.

From the observations by Leckie et al. (2015) it is recognized that a circular cylinder close to a plane boundary can experience global lowering relative to the far-field elevation of the plane bed, with local gaps under the cylinder occurring as deformations in the bed surface. These observations contrast with observations from other pipelines where embedment occurs due to sedimentation of the local seabed above the far-field bed elevation (Leckie et al., 2016) in the absence of significant pipeline lowering. In this work, the approach is adopted of treating the horizontal cylinder as variable in elevation above the bed, with and without contact generated as localized increases in bed elevation against the pipe as shown in Fig. 1.

For a circular cylinder above a plane wall, the general trend is that the mean drag coefficient $\overline{C}_D$ increases with increasing G, until it asymptotes to the value of an isolated cylinder at large G (>2.0). Zdravkovich (1985) correlated the critical G with the thickness of the boundary layer (δ, the distance from the wall to a point where the velocity reaches 99% of U_∞). It was also found that $\overline{C}_D$ peaks at about $G = 0.5$–0.6 at about 1.2 times that on an isolated cylinder (Lei et al., 1999; Roshko et al., 1975; Zdravkovich, 1985) and drops to less than 50% at zero G. The mean lift coefficient $\overline{C}_L$ is normally larger than 0 due to that the proximity of a wall moves the stagnation point on the cylinder downwards close to the wall. The variation of $\overline{C}_L$ with G is characterized by two peaks. One is at close-to-zero G, when the suction pressure on the cylinder surface dominates; another one at around $G = 0.1$, where the stagnation pressure dominates (Sumer and Fredsøe, 1997). However, for a turbulent boundary layer generated by trip-wires (Lei et al., 1999; Zdravkovich, 1985), the cylinder experiences a negative lift for G between 0.3 and 1.3. For Strouhal number, St, it increases with decreasing G, until the vortex shedding is fully suppressed. The reported critical G for this change in vortex shedding behavior differs significantly among studies and falls into a wide range between 0.2 and 0.9 (Buresti and Lanciotti, 1979; Taniguchi and Miyakoshi, 1990), depending on factors including *Re*.

For a partially buried cylinder, both hydrodynamic forces and the flow features have been reasonably researched (Jacobsen et al., 1989; Cokgor and Avci, 2001; Gao et al., 2011; Akoz, 2012). Due to its natural process, the hydrodynamic loading is usually studied concurrently with the bed-form evolution and the pipe–soil interaction (Xu et al., 2010; Gao et al., 2003). For a cylinder buried in an impermeable bed, the reduction in the force coefficient were found to be substantial, especially for the in-line force (Jacobsen et al., 1989). Probably as expected, the force coefficients decreased with increasing burial ratio for the steady current (Cokgor and Avci, 2001). As reported by Akoz (2012), rotational flows were observed close to the wall in the upstream of a partially buried circular cylinder and the starting point of flow separation in the upstream is strongly dependent on the burial ratio and *Re*. We note that no clear vortex shedding in the wake of the cylinder from the detailed PIV measurement (Akoz, 2012), which is consistent with Bearman and Zdravkovich (1978).

An et al. (2011) studied a partially buried cylinder in a permeable seabed subjected to combined oscillatory flow and steady current through two-dimensional (2D) numerical simulations. Different embedment depths besides the cylinder were considered for the first time. In agreement with Jacobsen et al. (1989), the in-line force reduces due to the reduction in exposed area normal to the flow. Interestingly, although seepage flow was found to be a few magnitudes smaller than the undisturbed inlet flow, it played a role in enlarging the in-line force.

Available research on hydrodynamics on a cylinder above an uneven wall is relatively rare. The unevenness of a seabed may lead to free spans of submarine pipelines, which are crucial for the structural behavior and safety (Ronold, 1995), partially due to the change in hydrodynamic loading and the dynamic features of free spanning pipelines (Furnes and Berntsen, 2003). Jensen et al. (1990) experimentally investigated a pipeline placed on a frozen-scoured bed to study the hydrodynamics. The seabed profiles were taken from five characteristic stages of the scour process in currents. It was demonstrated that both $\overline{C}_D$ and $\overline{C}_L$ quickly reach the equilibrium values at an early stages of the scour process. The $\overline{C}_D$ was found to be about 20% smaller in the case of the scoured bed than that from plane wall boundary for $0.4 \leq G \leq 0.7$, but $\overline{C}_L$ becomes negative due to the strong suction in the gap side. Sumer and Fredsøe (1997) reported that if the cylinder is placed in a trench or partially

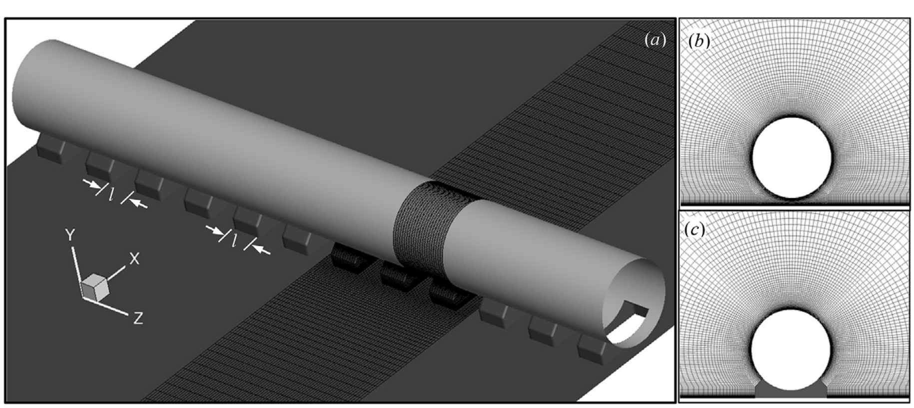

Fig. 1. (*a*), Three-dimensional view of the cylinder (light grey) seated on a wall (dark grey) with staggered gaps. Part of the used mesh is given for the wall, the wedge and the cylinder surface. The pipe elevations above the far-field seabed shown here is 0.1*D*. The meshes used are shown for spanning section (*b*), and non-spanning contact section (*c*). The inlet flow is in *x*-direction, from bottom left to top right in (*a*) and from left to right in (*b*) and (*c*).