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Effect of scour depth on flow around circular cylinder in gravity current

J.H. Jung [a], H.S. Yoon [b,*]

[a] Department of Naval Architecture and Ocean Engineering, Pusan National University, 2, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 609-735, Republic of Korea

[b] Global Core Research Center for Ships and Offshore Plants, Pusan National University, 2, Busandaehak-ro 63beon-gil, Geumjeong-gu, Busan 609-735, Republic of Korea

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ABSTRACT

We investigated the effect of scour depth on the flow around a circular cylinder in a gravity current. In order to simulate the gravity current flow past a circular cylinder placed above a scour, we solved the incompressible Navier–Stokes and concentration transport equations based on the finite volume method. Vorticity fields, hydrodynamic forces, and pressure distributions on the cylinder and streamlines with regard to scour depth are examined to investigate the effect of scour depth on the flow over the cylinder. As the scour depth increases, the first maximum at the impact stage and mean drag during the quasi-steady state stage subsequently decrease. In particular, the first maximum drag at the impact stage is almost 2.5 times greater than the mean drag during the quasi-steady state stage, regardless of the scour depth. For a smaller scour depth, a root mean square (RMS) lift value of approximately zero reveals that no periodic vortex shedding occurs, indicating that the scour effect on vortex shedding is significant. However, as the scour depth increases, the RMS lift increases, resulting in an increase in the strength of the vortex shedding. For a larger scour depth, Kármán vortex shedding occurs near the cylinder. However, due to the existence of the scour, only negative vortices separated from the top side of the cylinder move farther downstream, resulting in a single vortex row on the smooth bed.

1. Introduction

Due to its interesting flow features and practical applications, flow over circular cylinders has been investigated extensively, both experimentally and numerically, for over a century beginning with the discovery of Strouhal (1878). Williamson (1996) successfully conducted a comprehensive review of the characteristics of the flow around circular cylinders with respect to Reynolds numbers (Re). Another interesting phenomenon is the flow around a cylinder near a wall, since this configuration is strongly linked with automobiles, submarines, and subsea structures moving near or placed on a wall. When a cylinder is located near a wall, it is expected that different flow mechanisms around the cylinder near the wall occur in comparison with those around an isolated cylinder. Early research was conducted by Taneda (1965), who carried out flow visualizations at a Reynolds number of 170. He considered gap (G) to diameter (D) ratios, G/D, of 0.1 and 0.6, and found that for $G/D=0.1$, only a single row of vortices was shed from the cylinder. For $G/D=0.6$, a regular double row of vortices was shed. Bearman and Zdravkovich (1978) investigated the effect of the gap ratios (G/D) on the flow around a circular cylinder in the range of $0 \le G/D \le 3.5$. They found that for all values of $G/D \le 0.3$, strong regular vortex shedding was suppressed, and the pressure distributions on the cylinder became asymmetric when G/D approached zero. This result indicates that force coefficients strongly depend on G/D. After these studies, many researchers have focused on this problem of identifying flow characteristics of a circular cylinder near a wall due to the physical importance of this configuration (Lei et al., 1999, 2000; Price et al., 2002). However, there are still some controversial aspects related to the occurrence and suppression of the vortex shedding phenomenon and hydrodynamic forces with respect to gap ratios. Lei et al. (1999) pointed out two kinds of the controversial issues such as an influence of rod- and wire-mesh-generated boundary layers on the lift forces and the identifying the critical gap ratio at which the vortex shedding is suppressed from a hot wire measurement. In addition to the statement of Lei et al. (1999), Huang and Sung (2007) also reported a controversial issue for a mechanism of vortex shedding suppression. This is due to the complexity of the problem, and to various flow conditions in experiments and numerical simulations.

In ocean engineering, the aforementioned flow problem is also important because many submarine structures and cables (e.g., power cables, crude oil transportation, and running water transportation) are placed on the sea floor. However, an additional issue

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* Corresponding author.
E-mail address: lesmodel@pusan.ac.kr (H.S. Yoon).

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arises from these applications called "scour" (Whitehouse, 1998; Sumer and Fredsbe, 2002). If a seabed is erodible, a seepage flow occurs in the sand immediately below the submarine structure, resulting from a large pressure difference between the upstream and downstream sides of the submarine structure. When this pressure difference exceeds a certain threshold that depends on sand properties, the discharge of the seepage flow increases, and a mixture of sand and water break through the gap under the submarine structure. This process is called "piping." After this stage, a small tunnel occurs and enlarges, which is called "tunnel erosion." This stage is followed by a lee-wake erosion stage in which a well-organized vortex alternately sheds immediately behind the cylinder and sweeps the sea bed. Eventually, the bed shear stress along the bed under the submarine structure becomes constant, and then the scour process finally reaches a steady state called the "equilibrium stage." During and after the scour process, scour poses a great threat to the stability of a submarine structure. For this reason, many researchers consider the scour instead of the plane boundary wall in steady current and wave conditions for practical relevance (Sumer et al., 1989; Sumer and Fredsoe, 1990; Liang and Cheng, 2005a). However, since submarine structures above the scour are exposed to gravity currents such as turbidity currents as well as currents and waves, we should consider the gravity current flow past a circular cylinder. Such a gravity or turbidity current forms when a dense fluid moves into a lighter fluid in a horizontal direction under the action of a gravitational field. This occurs infrequently and unpredictably (Simpson, 1997) and is usually triggered by earthquakes, collapsing slopes, and other geological disturbances within a specific area such as submarine trench slopes of convergent plate margins, continental slopes and submarine canyons of passive margins. Kneller et al. (1999) reported that gravity currents can reach heights of up to O (100 m) and velocities in the range of O (1–10 m/s). If the gravity current meets a submarine structure, it would be destructive to the structure. Therefore, it is important to estimate the hydrodynamic forces induced by the gravity current and the associated time scales for their interaction (Gonzalez-Juez et al., 2009a). However, transient interactions between a cylinder and the gravity current have not received much attention in the past, whereas the flow characteristics of gravity currents in the absence of obstacles have been widely investigated by many researchers (Kneller et al., 1999; Blanchette et al., 2005; Meiburg and Kneller, 2010). Experimental studies of a transient interaction of the gravity current with a circular cylinder were conducted by Ermanyuk and Gavrilov (2005a, b). They measured the drag and lift acting on a square and circular cylinder placed above a wall in a gravity current flow. They defined an impact, a transient, and a quasi-steady stage based on the flow characteristics associated with the hydrodynamic forces acting on the cylinder. Their results yielded a limited explanation for the relation between transient forces and flow structures. Gonzalez-Juez et al. (2009a) have played a leading role in our understanding of gravity current flows past cylinders, and provided detailed information on flow features based on numerical simulation. They investigated the unsteady drag and lift generated by the interaction of a gravity current with a bottom-mounted square cylinder. Gonzalez-Juez et al. (2009b) focused on effects of the gap size on forces acting on a cylinder. They found a distinctive characteristic of the interaction between the gravity current and the cylinder compared with constant density flows past circular cylinders. In a continuation of the study by Gonzalez-Juez et al. (2009b) Gonzalez-Juez et al. (2010) employed two-dimensional (2-D) and three-dimensional (3-D) Navier–Stokes simulations to quantify the force load on a cylinder for Reynolds numbers ranging from 2000 to 45,000. They suggest that 2-D simulations accurately capture the impact stage, but can overpredict the force and friction velocity fluctuations during the transient stage. Also, the maximum drag at the impact stage can be up to three times as high as the mean drag during the quasi-steady state stage. Gonzalez-Juez et al. (2009b, 2010) explored a range of gap widths, $G/D=0.067$ to 1.33, that correspond to values typically generated through scouring (Sumer and Fredsoe, 1990; Liang and Cheng, 2005a). These two studies considered the plane boundary wall instead of the scour. Sumer et al. (1989) reviewed effects of regular and irregular waves, and pipe positions, on the hydro-elastic vibrations of a marine pipeline placed above a scoured trench for two values of the Keulegan–Carpenter number (KC), 10 and 40. Reynolds numbers were also considered, ranging from 2.0×10^4 to 7.0×10^4. Their observations revealed that the response of a pipe placed above a scoured trench is significantly different from that of a pipe placed near a flat bed. Although there is a significant difference in the hydrodynamic characteristics between the plane boundary and the scour, little attention has been given to gravity current flows interacting with circular cylinders above the scour. We are still unaware of any fundamental investigation into the scour effect on submarine structures in a gravity current flow. Therefore, our objective in the present study is to assess the effect of scour depth on a cylinder in a gravity current, and to explain physical mechanisms that generate forces on the cylinder according to scour depth based on the two-dimensional simulation.

In general, the Reynolds number at which the gravity currents may occur in nature is in the range of 10^7 to 10^9, while one is from 10^3 to 10^4 for laboratory experiments (Gonzalez-Juez et al., 2009a). According to the work of Gonzalez-Juez et al. (2010), results from two- and three-dimensional simulation show that an important physical mechanism depend only slightly on the Reynolds number, and Gonzalez-Juez et al. (2009a) found that two-dimensional simulations for gravity currents interacting with obstacles on a wall can predict unphysical force fluctuations at high Reynolds number ($Re=O(10,000)$). For this reason, we considered the moderate Reynolds number of 6000 based on a gravity current height (h) and a buoyancy velocity (u_b) to compare the existing experimental measurements and numerical simulations with the present results like as the studies of Gonzalez-Juez et al. (2009b, 2010). Note that Reynolds number of 6000 corresponds to $Re_D=558$ based on a diameter of cylinder (D) and a current front speed (V). Williamson (1996) reported that three-dimensionality of a vortex shedding from a cylinder begins to develop at $Re \approx 194$. Therefore, our simulation may not capture three-dimensional flow features owing to the limit of two-dimensional simulation. However, Bailey et al. (2002) found that when the cylinder approaches the bottom wall, the vortex formation is increasingly two dimensional, and Lei et al. (2000) assumed that the three-dimensional effect would not severely contaminate the results according to the gap ratio at a Reynolds number above 260. Therefore, many researchers have studied constant density or gravity current flows around circular cylinders near a wall by using two-dimensional simulation at a Reynolds number above 260 (Gonzalez-Juez et al., 2009b, 2010; Huang and Sung, 2007; Lei et al., 2000).

In addition to three dimensional effects, for the Re_D of 558, it may exceed a threshold value for transition to turbulence in the near wake of a cylinder, while the boundary layer on the surface of the cylinder is laminar (Williamson, 1996). Therefore, we considered a sufficiently fine grid to resolve all of the scales of fluid motion by direct numerical simulation. Moreover, Perry et al. (1982) pointed out that results for a flow around a cylinder from the two-dimensional simulation have the same qualitative features for the fully turbulent phase-averaged results, and Gonzalez-Juez et al. (2009b) successfully showed that their two-dimensional simulations at $Re=6000$ reveal the dominant physical mechanisms of a gravity current interacting with a circular cylinder according to gap ratio. Based on the above discussion, we concluded that our consideration for the numerical approach is suitable to