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Vortex shedding and evolution induced by a solitary wave propagating over a submerged cylindrical structure

G.A. Zarruk [a,*], E.A. Cowen [a], T.-R. Wu [b], P.L.-F. Liu [a,b]

[a] School of Civil and Environmental Engineering, Hollister Hall, Cornell University, Ithaca, NY 14853-3501, USA
[b] Graduate Institute of Hydrological and Oceanic Sciences, National Central University, Jhongli City, Taoyuan County 32001, Taiwan

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ABSTRACT

The shedding and evolution of the vortical structures generated by a solitary wave propagating over a submerged cylindrical structure are investigated experimentally and numerically. The cylindrical structure consists of two concentric cylinders and represents a simplified model for an offshore submerged intake structure typically used in coastal power plants. Flow visualization by dye injection is used to identify the dominant vortical structures near the structure. The flow visualization results show an unexpected flow reversal that causes shedding of secondary vortical structures. The experimental results are used to check a three-dimensional volume of fluid-large eddy simulation (VOF-LES) numerical model. The VOF-LES model is then used to further study the flow structure. A total of six dominant vortical structures generated by the wave motion are identified, followed by two more generated by the flow reversal. In summary, this paper provides the vorticity evolution for a complex fluid–structure interaction problem and a three-dimensional numerical simulation tool has also been validated, which can be extended to study more complex geometries and wave conditions.

1. Introduction

Coastal power plants require large quantities of cooling water to dissipate the emitted condenser heat. The cooling water is typically supplied by a coastal intake structure. A velocity cap is commonly installed on the top of the offshore intake (Zheng and Alsaffar, 2000). Many of these types of intake structures have been constructed along the California and Florida coastline in the USA, and other locations worldwide. As shown in Fig. 1, the vertical intake structure with the velocity cap on top is connected to a buried pipe that conveys the flow to the on-shore pump intake. The intake and cap are attached by support columns and other components, such as trash bars and inlet screens. Ultimately, the structure and its components are designed to withstand wave forces and to generate a sufficiently slow intake horizontal velocity to protect fish from entrainment and impingement (Dixon, 2007; Fritz, 1980; Hanson et al., 1977).

As a part of the structural design process, engineers must estimate the wave forces on the structure. For a submerged cylindrical structure, this is typically done by using the Morison's equation (Morison et al., 1950), an approach that requires a good approximation of the flow kinematics and an estimate of the drag and inertia force coefficients for the submerged body. Although linear wave theory is the simplest way to obtain the force coefficients, it assumes that the waves have

* Corresponding author. Present address: Australian Maritime College, University of Tasmania, Maritime Way, Newnham, Tasmania 7248, Australia.
E-mail address: gazarruk@utas.edu.au (G.A. Zarruk).

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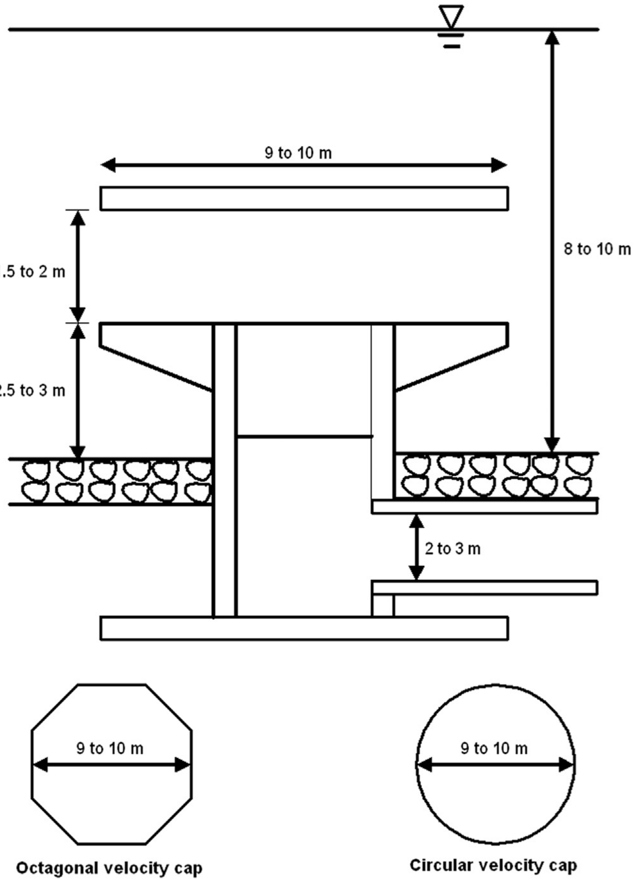

Fig. 1. Typical intake structure.

relatively small amplitudes and it does not represent the large waves found in common engineering practice or the flow structure around intakes.

Another approach is to use a nonlinear wave theory, for which several methods are available. Examples are the Stokes finite amplitude wave theory and cnoidal wave theory. A more common approach, and the one recommended by Morang (2008), is to calculate the flow kinematics on the basis of nonlinear stream function theory (Dean, 1965) and obtain the force coefficients from experimental observations. These theories are comprehensively described in the work of Chakrabarti (1987). This approach provides a better approximation of the wave environment but not of the flow structure.

A common limitation of the above design methods is that they consider only the inline force and ignore the lift force. Submerged objects in oscillatory flows will experience a significant lift force that is a function of the Keulegan–Carpenter number and is strongly coupled to the vortex shedding regimes (Justesen, 1989, 1991). Similar to the inline force, the lift force can be estimated from the flow kinematics (Williamson, 1985; Sumer and Fredsoe, 1997) and experimental observations. However, only a limited amount of experimental or numerical information is available to properly estimate the lift force for a submerged cylindrical structure under wave attack.

Given the insufficient amount of empirical information about the flow structure around submerged structures in oscillatory flows, most of the information used during the design process is derived from work on slender cylinders or rectangular obstacles (Sumer and Fredsoe, 1997; Chang et al., 2001, 2005; Lin and Huang, 2010). Thus, the hydrodynamics around the structure are not properly represented. This shortcoming is compounded by the three-dimensional nature of the vortices shed around an intake structure under wave attack. It is expected that several large vortical structures will be shed around the structure. Each of them affects the force coefficients to a different degree depending on when and where it is shed and on the structure of the near-wake region (Carberry et al., 2001). This situation drives engineers to employ conservative values for the force coefficients during the design stage. They are typically multiplied by a safety factor of about 1.5. As a result, offshore intakes are designed conservatively to maintain stability under wave attack.

Proper knowledge of the flow structure around a submerged intake structure under wave attack is a first step toward optimizing its design. However, reproducing and analyzing the flow around an intake structure is not simple. There are designed features and secondary flows (e.g., screens, inflow) that increase the complexity of the problem, and consequently that of any experimental or numerical effort to describe the dominant flow structures. It is therefore considered