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Extreme wave loads on submerged water intakes in shallow water*

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Abstract: This paper provides new guidance concerning the hydrodynamic loads on submerged intake structures located in shallow water under breaking and non-breaking waves. Results from a series of experiments conducted in a large wave flume at 1:15 scale to study the hydrodynamic forces exerted on a generic intake structure located on a sloping seabed in shallow water below breaking and non-breaking irregular waves are presented. Based on analysis of the experimental data, empirical relationships are developed to describe the peak loads in terms of characteristic wave parameters such as significant wave height and peak wave period. The distribution of the peak loads across different parts of the intake structure is also described. Drag and inertia force coefficients for the horizontal forcing on the intake structure and for the main structural sub-components are derived and presented. It is shown that the well-known Morison equation, with appropriate drag and inertia force coefficients, can provide reasonable estimates of the moderate horizontal loads, but the peak loads are less well predicted.

Key words: wave force, water intake, drag force, inertia force, coastal engineering

Introduction

Submerged water intake structures are commonly used to draw-in water for cooling and to support various processes at industrial facilities such as desalination plants, power generating stations, smelters and refineries. A typical submerged water intake structure features a vertical intake pipe protruding several meters above the seabed, set below a solid horizontal plate known as a velocity cap (see Fig.1). The velocity cap, which is typically supported above the mouth of intake pipe on three or more columns, serves to promote horizontal flow into the inlet, prevent vortex formation and help protect local fish species[1]. In many coastal areas, submerged water intakes are located in depths less than 10 m and are exposed to forcing from breaking waves during storms. Estimating wave-induced forces and moments on these structures for design purposes is challenging, particularly when they are located in the surf zone. This is due to the non-linearity of the orbital velocities under large breaking and non-breaking waves in shallow water, and the complexity of the interaction between the unsteady flow and the intake structure[2]. Large waves breaking in the surf zone can exert induce substantial horizontal and vertical forces on submerged intake structures–loads that are difficult to predict with acceptable certainty[3-5].

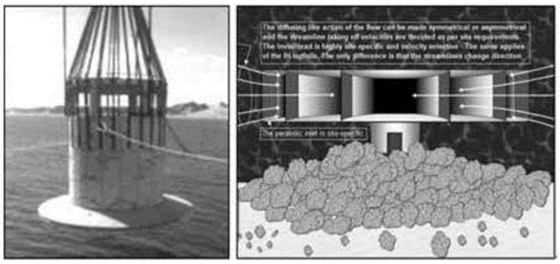

Fig.1 Typical submerged intake structures with solid velocity caps (source: www.google.com)

There has been considerable research over many decades concerning the hydrodynamic forces on objects, and particularly cylinders, in oscillatory flows. However, relatively few studies have focused on intake structures, and even fewer have considered open

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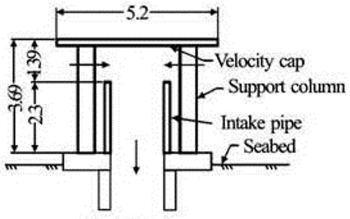
intake structures with velocity caps exposed to highly nonlinear oscillatory flows. Mogridge and Jamieson[6] used experimental methods to investigate the loads on a submerged capped intake structure due to breaking and non-breaking waves, and found linear correlations between the wave heights and the induced horizontal forces. Nakota and Houser[7] used physical hydrodynamic modelling to investigate the loads on a submerged velocity cap due to non-breaking regular waves. More recently, Pita and Sierra[8] described several different types of intake structure, defined the principal design parameters, and described their recent experience with design, manufacture and installation of such structures. Raju et al.[9] used a sophisticated numerical model (OpenFoam) to estimate wave forces on a caisson-type water intake structure located on the seabed, and compared their predictions with results from laboratory experiments conducted with regular waves.

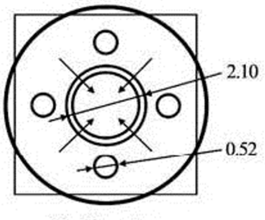
In 1950, Morison et al.[10] proposed the Morison equation (also known as the MOJS equation after the original authors), in which the hydrodynamic force on a submerged cylinder due to oscillatory flows is expressed as a summation of drag and inertia forces. Over the years, many researchers have conducted experiments to determine the most appropriate force and inertia coefficients for various situations (smooth and rough cylinders, low, medium and high Reynolds number, single and multiple cylinders, etc.). For example, Zdravkovich[11] investigated the effects that two cylinders spaced at varying distances had on the recorded forces and presented drag coefficient data dependant on the relative spacing. Sarpkaya[12] tested a circular array of tubes surrounding a central pipe in oscillatory flow and found that force coefficients vary with the Keulegan-Carpenter (KC) number, which represents the ratio between the amplitude of the water particle orbits and the cylinder diameter. Sarpkaya[12] found that the inertia coefficient increased with increasing KC, while the drag coefficient decreased. Burrows et al.[13] published force coefficient data for a submerged cylinder in random waves, and used the Morison equation to predict the wave-induced forces on the cylinder. Sparboom et al.[14] studied cylinder groups in breaking and non-breaking wave conditions and found that the wave force for all cylinder group configurations (for cylinders in close proximity) increased with increasing wave height and wave period. Despite this previous research, the relationship between the wave conditions and the resulting hydrodynamic loads on realistic intake structures remains unclear, and no simple methods are available to predict wave loading on realistic intake structures.

This paper describes a research study in which physical scale model experiments were conducted to determine the hydrodynamic loads exerted by breaking and non-breaking irregular waves on a typical submerged intake structure comprised of a circular intake pipe protruding vertically above the seabed and located below a solid horizontal velocity cap supported by four circular columns. The design of the intake structure is shown in Fig.2. At prototype scale, the circular intake pipe has an external diameter of 2.1 m and protrudes 2.3 m above the seabed. The four support columns each have an external diameter of 0.52 m and a length of 3.1 m, while the velocity cap has a diameter of 5.2 m and a thickness of 0.2 m. The projected area, A, of the intake pipe in the vertical plane is 4.85 m^2, while the projected area of the four circular columns is 6.48 m^2. The projected area of the velocity cap in the vertical plane is 1.0 m^2, while the projected area of the velocity cap in the horizontal plane is 21.2 m^2.

The experiments were conducted in a 2.0 m wide by 97 m long by 2.9 m deep wave flume, at a geometric scale of 1:15. Scaling laws derived from Froude scaling principles have been used to estimate prototype quantities from the data measured in physical model. The wave-induced loads on the entire structure and on the different parts of the intake (intake pipe, columns, velocity cap) have been determined for a range of water depths in irregular and regular wave conditions.



(a) Elevation



(b) Plan view

Fig.2 Design of the typical submerged intake structure considered in this study (m)

1. Physical model experiments

1.1 *Scaling considerations*

The intake structure shown in Fig.2 was modeled at 1:15 scale according to scaling laws derived from similarity of the Froude number (Fr) in the model and prototype. This implies that all model lengths were reduced by a factor of 15, all velocities and durations were reduced by a factor of 3.87, all forces were reduced by a factor of 3 375, and all moments were reduced by a factor of 50 625. Since wave mo-