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Study on hydro-kinematic characteristics of green water over different fixed decks using immersed boundary method

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ABSTRACT

An immersed boundary method is applied to simulate the green water over a fixed deck by combining a level set method for the free water surface capturing. An efficient Navier-Stokes equation solver of second-order accuracy adopting the fractional step method at a staggered Cartesian grid system is used to solve the incompressible fluid motion. The numerical model is validated by comparing extensively the wave elevation and pressure with the experimental data for two types of fixed decks, which suggests that the developed immersed boundary method coupled with the level set method is very promising to predict green water problems due to its accuracy and efficiency. Furthermore, the cross-sectional velocity distribution over the deck, which is an important parameter in the industrial application, is computed and compared to the analytical Ritter's solution. It is found that Ritter's solution is much more conservative than the numerical simulations, which confirms the safe application of the simplified analytical solution in the current design practise. Volume of green water over the deck that affects the stability of deck is also tracked. The numerical results reveal that the amount of green water over both the two types of fixed decks shows a linear relationship with the relative wave height. This important finding may be very helpful for the prediction of deck elevation under a certain wave condition to reduce the occurrence of green water event.

1. Introduction

Green water impact is a hazardous event in ocean and coastal engineering that could cause local damage and global failure of marine vessels and offshore platforms. In high sea states, when big waves impact at ships and platforms, a part of the water runs up along the vertical surface of the structure, collapses onto the frontal deck violently and quickly washes over the whole deck. As the wave breaks and overtops on a marine structure, the flow becomes multi-phased and sometimes chaotic in the fluid area close to the structure, which makes the green water problem more complicated and challenging.

For simple cases, some analytical solutions have been derived for the green water problem in the past. For instance, a simplest solution to green water with the assumption of a frictionless dry flat bed was proposed in Ritter (1892), in which the free surface profile for a collapsing rectangular column of fluid over a horizontal bed was described. This analytical solution has been widely used in the industry for green water predictions. However, experimental and analytical study in Lauber and Hager (1998) on the dam break indicated that the front velocity of a dam break flow reduces as time increases, which disagrees with the constant front velocity shown in the analytical solution of Ritter (1892). In recent years, a semi-analytical solution was developed in Yilmaz et al. (2003) for a dam break flow to simulate the green water problem. The result indicated that a jet-like water profile can be formulated at the forefront of the flow. However, the analytical solution is still too simple to fully elucidate the physics of green water over a deck.

French (1969) carried out the early experiments to investigate the vertical force due to the regular wave slamming on a horizontal plate. An impulsive force was captured in the experiments. Another experiment was conducted in Denson and Priest (1971) to identify the influence of relative wave height, relative plate clearance, relative plate width and relative plate length on the pressure distribution under a thick horizontal plate. A potential flow model was also developed in Lai and Lee (1989) to predict the vertical forces caused by large amplitude waves on decks. Their numerical results were consistent with the experimental results in French (1969). In addition, Kaplan (1992) extended the hydrodynamics theory for ship slamming to study the wave action on a deck slab by representing the time varying vertical forces as the combination of a hydrodynamic impact force and a drag force. The

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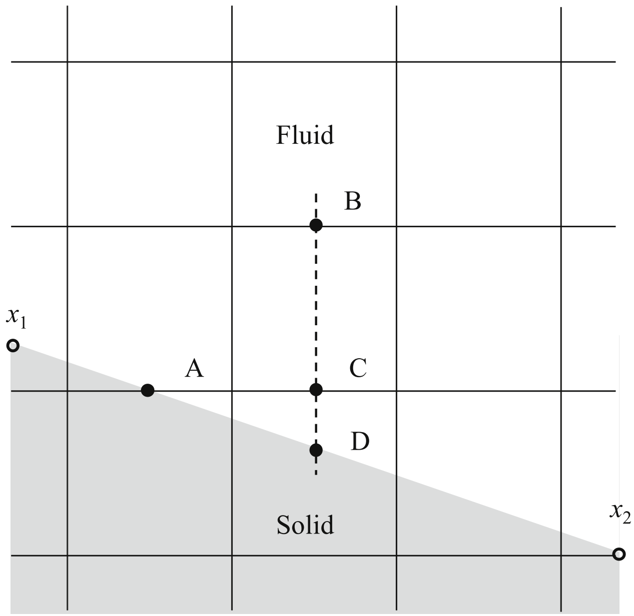

Fig. 1. Illustration of the location and determination of imposed forcing component.

time history of vertical forces indicated that the force magnitudes are considerably large, but a discontinuity appears at the instant of complete submergence of the structure. Cox and Scott (2001) and Cox and Ortega (2002) conducted the experimental study on the green water over a fixed deck in a narrow wave flume. In Cox and Scott (2001) it was found that free surface and volumetric overtopping exceedance probability follow the exponential distributions. Cox and Ortega (2002) experimentally revealed that the wave collapsing into a thin deck exhibits the velocities that exceed 2.4 times the maximum crest velocity in the case without the deck.

Based on the experiment in Cox and Ortega (2002), green water over a fixed deck was analyzed using the Smoothed Particle Hydrodynamics (SPH) method in Gómez-Gesteira et al. (2005). The numerical results of wave profile agreed well with the experimental data, in both phase and amplitude. In addition, with the incompressible SPH model Shao et al. (2006) investigated the overtopping phenomenon on a fixed deck caused by a transient wave. The results were in good agreement with the experimental and other numerical data. As the CFL condition was completely related to the fluid particle velocity, a much larger time step could be adopted in Shao et al. (2006) than that used in Gómez-Gesteira et al. (2005). Still based on the experiment in Cox and Ortega (2002), a finite element Navier-Stokes solver combining with a single-phase Volume of Fluid (VOF) technique was developed in Lu et al. (2010) to investigate the green water phenomena on a fixed deck, and a

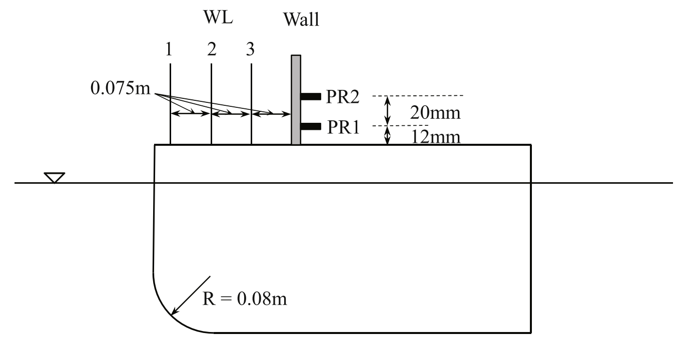

Fig. 3. Details around the deck of two-dimensional FPSO.

deck-house on a floating structure. In the recent work of Qin et al. (2017), green water on rigid deck, elastic bare deck and elastic deck with intermediate elastic supports caused by freak waves and the deck response were studied.

Besides the studies on green water over a thin deck, Greco (2001) conducted an important experimental investigation of two-dimensional green water on the deck of a fixed Floating, Production, Storage and Offloading (FPSO) vessel model without and with a solid wall. Two green water events as well as two peaks in the green water height and pressure on the solid wall were observed. An air cavity was also captured when the green water travelled along the deck. In the numerical simulation based on the potential flow model presented in Greco (2001), the free surface evolution was in reasonable agreement with the physical observation just for the lower wave steepness. Barcellona et al. (2003) carried out the experiments for stationary vessel models in head waves to study the characteristics of green water loads and water-front velocity on the deck. Both the pressure on the deck and the horizontal force on the wall show a double-peaked evolution, which is similar to those in Greco (2001). Based on the experimental work in Greco (2001), Nielsen and Mayer (2004) simulated green water on a vessel with and without motions by the use of a Navier-Stokes flow solver with the VOF scheme. The water elevation on the two-dimensional deck agreed well with the data in Greco (2001), but the extension to the three-dimensional situations indicated that the three-dimensional effect is insignificant.

More recently, Ryu et al. (2007a, b) compared the green water with the dam break flow to examine the applicability of dam break flow models to describe green water flows. The comparisons indicated that the solution of Ritter (1892) for dam break flows works well in the prediction of green water velocity despite the significant difference between these two flows. In addition, the green water over three different structures in regular head waves were presented experimentally in Lee et al. (2012), based on which a database for the validation of numerical simulations was developed. Ariyarathne et al. (2012) found the relationship among impact pressure, wave celerity, and air void in

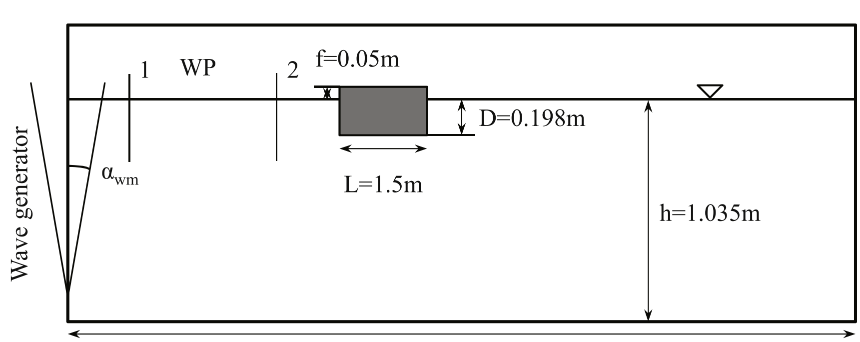

Fig. 2. Sketch of the problem of wave on a rectangular deck.