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Numerical simulation of flip-through impacts of variable steepness on a vertical breakwater

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ABSTRACT

This paper focuses on the analysis of the flow field and pressures generated by flip-through impacts on a vertical breakwater. A multiphase Navier–Stokes model is used as a numerical wave tank to analyse the influence of interface steepness on pressures and forces generated in the real configuration of a breakwater caisson. The numerical simulations consist in a solitary wave propagating over a reef and impacting a caisson breakwater placed over a porous rubble mound. After careful validation, the model allows us to make an in-depth investigation of three flip-through impacts with different incidence angles at impact (least steep, medium steep and steepest flip-through impact). The main characteristics of flip-through impacts are identified for the three cases: no air entrapped, presence of an ascending jet with large accelerations and large pressures. The focusing phase before impact introduced by Lugni et al. [30] is only observed for the steepest case. The understanding of the process of this extreme impact is improved by analysing velocities and accelerations for the three cases. Pressures and forces are shown to be directly linked to the flip-through impact inclination at impact. The flow field and pressure variations inside the porous rubble mound are also analysed in this study.

1. Introduction

Wave impacts on breakwater caissons may generate high and variable pressures in space and time. The prediction of pressure distributions has been the main objective of several empirical studies [32,14,47,39,10]. Other authors applied CFD models to study the problem of wave impact or wave interaction with breakwater caissons [21,29,28,37,50]. So far, most published works aim to give a conservative envelope of the maximum horizontal and uplift forces submitted to the caissons, which is essential for breakwater design. But there is still a lack of knowledge of the impact dynamic at the wave scale.

Focusing on the wave impact dynamics, two phases can be distinguished on the pressure signal generated onto breakwater caissons: first, an impulsive component characterized by a very high magnitude and a short duration, followed by a longer part influenced by the pressure peak value. Impulsive forces have been identified as one of the main causes of coastal structure failure in Takahashi et al. [46]. They are generally associated to storm waves but tsunami bores are also susceptible to produce such violent impacts ([43,20,24,36]). Many researchers (e.g., [27,52,38,17,22,5,26,1]) highlighted that these impulsive pressures depend strongly on the wave shape at impact.

In general, vertical obstacles may be submitted to three breaking wave impact types: a very aerated impact corresponding to a broken wave; a second one presenting enclosed air between the wall and the wave; and finally, a last kind of wave impact where there is neither air pocket nor mixed air, also called flip-through impact. Bagnold [3] first stressed the influence of entrapped air observing that pressures were greatest when the amount of air trapped by the wave was small. Mitsuyasu [33] and Chan [6] emphasized the sensitivity of peak pressure due to very small changes of parameters such as the kinematic of the breaking wave or the amount of entrapped air. Laboratory experiments were carried out in Hull and Müller [22] obtaining similar pressure values for several breaking waves with a variable amount of entrapped air, the pressure peak being slightly higher for large air pockets which was contradictory to what was shown by Bagnold [3]. However, when the wave impacts without air trapping (flip-through), even higher pressure peaks can be generated as reported by Cooker and Peregrine [8] and Cooker and Peregrine [9].

The flip-through impact (hereinafter referred as FTI) is generated when the convergence of the wave crest and trough flow at the wall is strong enough to give birth to a small scale ascending jet associated to accelerations orders of magnitude larger than in other parts of the wave. It is generated by near-breaking waves presenting very steep

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faces when meeting the wall. It is therefore an intermediate case between slosh impacts and the developed plunging breaking wave which traps air at the wall. Hattori et al. [17] have illustrated the importance of the FTI in terms of loading on structures. In this experimental study, several flip-through cases were tested concluding that the most severe impact is produced by a near-breaking wave with a very steep face. Lugni et al. [30] highlighted the existence of extreme pressures for the FTI. High upward accelerations of the characteristic jet were measured during the laboratory experiments. Lugni et al. [30] identified three main steps characterising the flow evolution of a FTI: *Wave advancement* is the step when the wave approaches the wall; it is followed by the *focusing* stage, in which wave front and trough move toward each other, generating high vertical flow accelerations; finally, the characteristic upward moving jet is suddenly produced at the beginning of the *flip-through* stage. upward moving jet is suddenly produced [5] found that low-aerated breaking waves generate higher pressure values than wave impacts enclosing a large amount of air (high-aerated). The low-aerated impacts are defined by containing little if any enclosed air between the wave interface and the structure, and they may, therefore, be considered as close to FTI. An experimental and numerical FTI on a seawall placed over an impermeable slope was investigated in Bredmose et al. [4]. The potential-flow model used for these simulations was able to reproduce well the FTI until the stage of jet formation. However, the nature of this model does not allow to simulate the formation of droplets and interaction of fluids observed after the phase of jet formation. Scolan [44] computed FTIs with a potential-flow model using a desingularized technique. High pressure variations and extreme accelerations of the upward moving jet were reached in a very short time.

Former results obtained on FTI studies were confirmed by Kaminski et al. [23] and Hofland et al. [19] who carried out large scale experiments concluding that the most extreme type of impact in terms of peak pressure corresponds to the FTI case. But based on the same laboratory experiments, these authors also pointed out that strong slosh impacts close to FTI may generate intense and long pulsating loads on vertical walls. The literature showed that the limit between slosh impacts and FTIs is not always clearly defined. Cooker and Peregrine [9] defined first the term ”FTI” as corresponding to an impact for which the interface accelerates and finally “flips through” between the wall and the wave crest. Lugni et al. [30] added that the fluid accelerations are on the order of 100–1000*g*. Kaminski et al. [23] and Hofland et al. [19] tried to differentiate slosh impact from FTI. These authors stated that the difference between these two types of impact resides on the position of the wave crest when wave trough fills up the impacted zone. In the case of the FTI (Fig. 1(a)), the wave crest is near the vertical obstacle and moves toward the trough converging to a point (focusing), while in the slosh impact (Fig. 1(b)), the wave trough flow goes up at the wall before the wave crest arrives. We will follow the initial definition of FTI given by Cooker and Peregrine [9], implying a flip through interface motion and the generation of large acceleration in the rising jet compared to the wave acceleration field. So for us there will be non-focusing and focusing FTI.

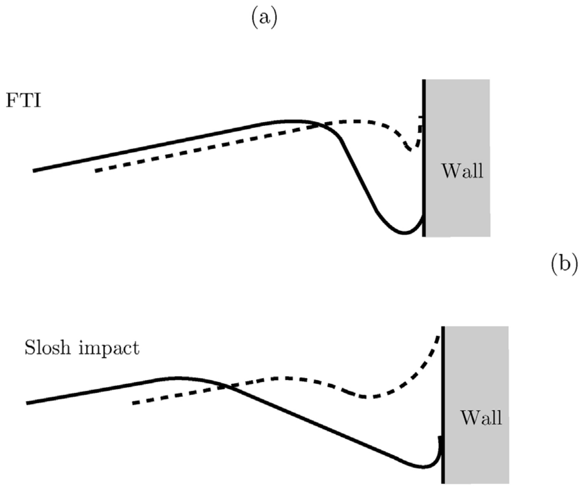

Fig. 1. Water interface and position of the wave crest and through at the beginning (–) and at the end of impact (- -) – (a): FTI; (b): slosh impact.

But behind definition inaccuracy, a gap in the knowledge may also be identified. It is still not clear how the pressure field vary for apparently very similar FTI. A related gap is linked to the structure stability and the type of impact (i.e. a longer or a quicker FTI?) which may produce the largest sliding. To answer these questions, one also have to take into account more realistic obstacles than the simple vertical wall almost always considered. In the present paper, we propose a numerical study of extreme non-aerated impacts of FTI type at wave scale in a realistic configuration (i.e. a vertical breakwater) involving a porous basis. The objective of this study is to: (1) give some answers to the question of pressure variability within the FTI class by analysing in detail the influence of the local interface inclination; and (2) document the whole pressure and flow field including the one in the breakwater rubble mound. A numerical model is used as a numerical wave tank to analyse this pressure variability, as well as the fluid dynamic. Solitary waves of a fixed height are used to generate different impact magnitudes. Pressure variations are caused by local interface changes in the wave impact obtained by slightly translating the caisson of the breakwater studied.

The paper is organized as follows. The numerical experiments are described in Section 2. The ability of the numerical model to simulate flows through a porous medium and FTIs is also shown. In Section 3, the influence of the interface inclination angle on pressure distributions is analysed. All the results obtained in this paper are discussed in Section 4. Finally, in Section 5, the conclusions of the study are drawn.

2. Methodology

2.1. Description of the numerical experiment

Numerical simulations are carried out to analyse the pressures on a breakwater caisson submitted to FTI. The set-up of the simulations is described in Fig. 2. A solitary wave of 7 m height is propagated over a constant slope (1/8) where the breakwater caisson ($h_c = 13$ m) is fixed. The third order solution of Fenton [12] is used to impose the free surface position and fluid velocity in the numerical domain at $t = 0$. Initial water depth is set to $y/h_c = 1$. Three different wave impacts are generated by slightly varying the caisson position: $x/h_c = 15.3$ for the *I1* impact, $x/h_c = 15.6$ for the *I2* impact and $x/h_c = 15.96$ for the *I3* impact. The aim is to study extreme cases with a different steepness of the wave front at impact (*I1*: least steep face; *I2*: medium steep face; *I3*: steepest face). The I3 case may be considered as the most extreme case of non-aerated impacts since air would be entrapped between the wave and wall when moving the caisson to $x/h_c > 15.96$.

The flow in the porous rubble mound breakwater is also solved in order to investigate the uplift force due to pressure changes under the caisson. The porosity and intrinsic permeability of the rubble mound are assumed to be constant with the following values: $\phi = 0.5$ and $k = 10^{-5}\,\mathrm{m}^2$.

2.2. Numerical model

The numerical study is performed with the THETIS code which solves the Navier–Stokes (NS) equations and uses a Volume of Fluid Technique (VOF) method to capture the interface evolution. The flow considered incompressible is composed of two phases: water and air. The incompressible version was commonly used in the literature since not air is entrapped between the wave and wall during the impacts. The continuity of fluid velocity is assumed through the interface and surface