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Nonlinear Simulation of 3-D Freak Waves Using a Fast Numerical Method

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This paper presents nonlinear simulation of 3-D freak waves by using the QALE-FEM (Quasi Arbitrary Lagrangian-Eulerian Finite Element Method) based on the FNPT (Fully Nonlinear Potential Theory) model. A snake wavemaker is adopted to generate 3-D freak waves based on the directional energy focusing principle. The effects of nonlinearity and seabed slopes on freak waves are investigated. Both overturning and nonoverturning freak waves are considered. Some results are compared with those in the public domain and good agreement is achieved.

INTRODUCTION

Freak waves (also called rogue waves) are extremely large water waves in the ocean, and they may occur in both shallow and deep water. Despite their low possibility of occurrence, they potentially pose severe hazards for mariners and man-made structures. Many incidents considered to be caused by freak waves have been reported, in which a lot of lives (about 542 during 1969–94) were lost (Lawton, 2001). The freak waves are now considered a real threat to human activities in the ocean and have thus attracted great attention.

Due to the complexity of the real sea condition which involves winds, currents and waves, the physical mechanism of freak wave generation is still an open question. However, based on previous research (e.g. Baldock et al., 1994; Kharif et al., 2003), one of the possible mechanisms of freak wave generation may be due to energy focusing, i.e. the wave energy concentrates in a small spatial area during a short time and generates an abnormally large wave. There may be many reasons for such an energy focusing, mainly including spatio-temporal (dispersive) focusing (i.e. frequency and/or directional focusing) of transient wave groups (e.g. She et al., 1997; Johannessen and Swan, 2000; Brandini et al., 2001; Fochesato et al., 2007; Grilli et al., 2009), wave-current interaction (e.g. Lavrenov et al., 2006), geometrical focusing due to seabed topography (Grilli et al., 2001; Guyenne et al., 2006) and nonlinear modulation instability (e.g. Zakharov et al., 2006). A good review can be found in Kharif et al. (2003).

Many efforts have been made to understand the generation of freak waves and their behaviours by performing laboratory experiments. In those experiments, the freak waves are generated by using a wavemaker. For 2-D problems, the motion of the wavemaker is mainly specified by one of the following ways: (1) using a sine function with linearly variable frequency with the largest frequency at the start (Touboul et al., 2006); (2) using a sum of a number of sine or cosine wave components with different frequencies (Baldock et al., 1996; Grue and Jensen, 2006); and (3) using signals composed of normal random waves and the freak wave (Kriebel, 2000; Clauss, 2002). The third way is the closest to the reality that freak waves always appear together with other random waves. So far, the laboratory research on 3-D freak waves is still rare. She et al. (1997) and Johannessen et al. (2000) studied the properties of 3-D freak waves by focusing directional waves of single frequency or of multiple frequencies, which are generated by a snake wavemaker.

Alternatively, freak waves have also been studied by numerical modelling and theoretical analysis. Kharif et al. (2003) summarised various levels of approximation, which consist of linear, weakly nonlinear and strongly nonlinear models, such as the energy balance equation, the wave-action balance equation, the nonlinear Schrödinger equation and the nonlinear KdV equation. More recently, Ducrozet et al. (2006) extended a high-order spectral method (HOS) to treat fully nonlinear freak waves, and Fuhrman and Madsen (2006) used a high-order Boussinesq equation to simulate 3-D freak waves.

In addition to the different orders of approximation, the FNPT (Fully Nonlinear Potential Theory) model is also employed to investigate freak waves. The problems formulated by the FNPT model are usually solved by a time marching procedure, similar to that suggested by Longuet-Higgins and Cokelet (1976). In this procedure, the key task is to solve the boundary value problem by using a numerical method, such as the boundary element method (BEM) or the finite element method (FEM). The BEM has been attempted by several researchers in simulating freak waves. Only a few publications are cited here, and more references may be found in the cited papers. Touboul et al. (2006) simulated 2-D freak waves under the action of winds using a boundary integral equation method (BIEM) and a mixed Euler Lagrange (MEL) time marching scheme. Grilli et al. (2001) developed an efficient higher-order BEM to study the overturning waves due to the seabed topography, and Guyenne et al. (2006) followed their work. Using this numerical model, Brandini et al. (2001) performed the simulation of 3-D freak waves resulting from the spatio-temporal (dispersive) energy focusing of transient wave groups. On the basis of the BEM model, Fochesato and Dias (2006) developed a fast BEM method by introducing a fast multipole algorithm (FMA). This method reduces the computing complexity for the BEM method from $O(N_b^2)$to nearly $O(N_b)$, where N_b is the number of boundary nodes. It could be considered the fastest method at the time to simulate related free-surface problems. Using the fast BEM method, Fochesato et al. (2007) and Grilli et al. (2009) studied freak waves similar to those in Brandini et al. (2001).

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