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A numerical study of the effects of the longitudinal baffle on nickel ore slurry sloshing in a prismatic cargo hold

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The nickel ore slurry sloshing in a rolling partially loaded prismatic cargo hold with a longitudinal baffle is investigated. A numerical model based on the volume of fluid (VOF) method and the non-Newtonian Herschel-Bulkley and Bingham equations is proposed to study the dynamic behavior of nickel ore slurry sloshing. The numerical model is solved by using the finite volume approximations and the dynamic mesh technique is utilized to handle the cargo hold's motion. After taking grid and time step independence study, the numerical results are compared with experimental data. Comparisons show good agreement in the cases investigated. Further, the relationship between the moment amplitude induced on the hold boundary and the excitation frequency is checked numerically. The ratio of baffle height to the initial cargo depth has been changed in the range of $0.0 \leq h_B/d \leq 1.2$. The variation of the sloshing-induced moment and the deformation of the free surface under different baffle heights have been obtained and discussed. To clearly understand the sloshing behavior of nickel ore slurry, the sloshing of liquid water has also been carried out. Meanwhile, the dynamic viscosity of the nickel ore slurry is monitored. The critical baffle height with regard to the sloshing-induced moment and the elevation difference of the free surface at two sides of the cargo hold has also been presented and discussed.

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1. Introduction

A combination of the water content, dynamic energy produced by the waves and the vessels engine along with the material itself would cause the granular bulk cargo to liquefy [1]. When the liquefaction of the bulk cargo occurs, it behaves like a fluid. Owing to its high density and viscosity, the movement of the cargo in a carrier's hold would dramatically weaken the stability of the carrier, even cause it to capsize under some rough seas. In the last two decades, more than 800 seamen lost their lives on bulk carriers [2]. From 2001 to 2010, more than 23 ships carrying solid bulk cargoes sunk in China [3]. The probable reason lies in the cargo liquefaction and the cargo shift effect. To ensure shipping safety, some measures should be taken in advance to minimize the movement of the liquefied cargo. For example, a longitudinal baffle is recommended to be mounted in the cargo hold. Considering the effectiveness, it is a priority to investigate the effects of the vertical baffle on the sloshing of the liquefied granular bulk cargo. However, due to its complexity the study in this field has not been fully developed. Several recent studies are summarized as follows.

Koromila et al. [4] carried out several model tests to investigate the liquefaction of granular materials in a rectangular container under roll and sway motions using shaking table facilities. When the sand cargo was investigated, there existed a critical moisture level, below which the mixture would not flow. Besides, the impact of liquefaction process on a bulk carrier's stability was investigated. It is concluded that alternate or inhomogeneous loading is safer than homogeneous loading when the liquefaction occurred. Similarly, Guan et al. [5] carried out 6-DOF platform experiments using a cargo hold model. The liquefaction process of nickel ore with 35.0% water content was analyzed and the dynamic heeling moment was measured. It is concluded that the liquefaction process can be divided into three stages. Owing to the characteristic of the liquefied nickel ore, the formation of the list would be facilitated when a ship is sailing in a rough sea. Chen [6] conducted several tests using a bulk cargo hold model considering different excitation modes. The mechanical properties of the liquefied cargo with different water contents were compared. It is pointed out that there existed a phase lag between the liquefied cargo and the ship's roll motion, which is the main reason that causes a ship to capsize. Spandonidis and Spyrou [7] used molecular dynamics method to simulate the dynamic behavior of granular materials in a two-dimensional rectangular tank without considering the water content. In their study, the particles were treated as discrete interacting objects and the tilting and linear vibration was added. It was observed that the material with the smaller particle size and the higher density tended to flow more easily. The movement of mass center was also recorded under various excitations. The simulation results are in good agreement with experimental data.

In the case of Newtonian fluids, there has been a considerable amount of work on liquid sloshing. Faltinsen and Timokha [8] have offered a textbook to deal with the overall aspects of sloshing. The book addresses mostly the problems concerning in marine and some land applications related to sloshing. Rebouillat and Liksonov [9] presented a paper to review the recent studies devoted to the problem of modeling the solid–fluid interaction in partially filled liquid containers. The sloshing phenomenon and the numerical approaches adopted to predict the sloshing wave amplitude, frequency, pressures exerted on the walls and the effect of sloshing on the stability of the container were described and discussed in the paper. Gardarsson and Yeh [10] studied the hysteresis behavior in sloshing of shallow water in horizontally excited tanks experimentally. The ratio of depth to tank length is set to 0.038 in the experiments. And the experimental investigation was extended to sloshing in a tank with sloping beaches. When considering a baffle mounted in a tank, Akyildiz and Unal [11] studied the pressure variations in both baffled and unbaffled rectangular tank numerically and experimentally. They revealed that the effects of the baffle are most pronounced in shallow water and accordingly the pressure response is reduced by using the baffles. Jung et al. [12] analyzed the variation of pressure and the free surface elevation with respect to the baffle height in a three-dimensional tank based on the finite volume and the volume of fluid (VOF) methods. The computation was validated by the experimental results. Akyildiz [13] solved the complete Navier–Stokes equations using finite difference approximations and the volume of fluid technique, the effect of the vertical baffle height on the liquid sloshing was studied. They denoted that the block effect of the baffle on the liquid convection is predominant to the tip vortex. Chao and Lee [14] concluded that the liquid motion and the dynamic pressure distribution above the baffle are more active than those below the baffle by carrying out the