Numerical Study on the Effect of Transverse Baffles on the Stability of Iron Concentrate in a Cargo Hold

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Abstract—Cargo fluidization is one of the main causes of ship capsizing accidents, which has been concerned by International Association of Classification Societies. Iron concentrate is regarded as the research object, its movement in the cargo hold is simulated using discrete element method. To effectively reduce the sloshing amplitude of cargo in the cargo hold, four conditions that considering the transverse baffles are designed. The stability of cargo is analyzed in detail from the offset of cargo gravity center and the contact force on the bulkhead induced by the cargo movement. Numerical simulation results show that the installation of transverse baffles can effectively reduce the sloshing amplitude of cargo in the cargo hold. Especially, it can better restrain the variation of center of gravity of cargo in the y-direction. The study focuses on the influence of baffles with different lengths on the stability of cargo in the cargo hold, which can provide a reference for the prevention of bulk carrier accidents.

1. Introduction

Iron concentrate, a kind of fluidizable cargo, is composed of a certain proportion of fine particles and moisture content. This kind of cargo is prone to fluidization once it is continuously affected by wind and wave load and ship's own motion during maritime transportation. The formation of fluidization makes the cargo easy to tilt to one side of the cabin, increases the inclination angle of the ship, and even the capsizing of the ship under severe sea conditions [1].

Recently, lots of studies on the transportation safety of easily fluidization cargo have been made. Based on the model test of indoor shaking table, Zhou et al. [2,3] analyzed the influence of different factors on the fluidizing characteristics of iron concentrate. Results show that moisture content is the key factor affecting the fluidization of iron concentrate. Ding et al. [4] established a three-dimensional numerical model of fluidized nickel ore, and analyzed the stability of the nickel ore in a cargo hold. Results show that there is a certain phase difference between the motion of liquefied nickel ore and ship motion, but the former is relatively regular. Through the finite element software Fluent, Zhao [5] conducted numerical simulation of roll motion in the process of transportation of easily fluidization cargo. Results show that the installation of the longitudinal baffles can greatly improve the safety of cargo transportation.

So far, researchers have done a lot of study on the fluidization mechanism of easily fluidization cargo, and some effective methods to ensure the stability of cargo have been put forward, for example, adding longitudinal baffles. Considering that the installation of longitudinal baffles would affect cargo handling to a certain extent, a new two-dimensional numerical model of cargo hold is established using discrete element software PFC2D. The model focuses on the influence of different lengths of...
transverse baffles on the cargo stability under the condition of sway motion, which can provide some references for improving the safe maritime transportation of easily fluidization cargo.

2. Linear contact model

Contact behaviour, the key problem of discrete element method, is mainly determined by the selected contact model. The force-displacement law provided by the contact model is used to transfer and update the forces between particles, then the position information of particles could be updated. In PFC2D, the linear contact model is applicable to study the macroscopic characteristics of soil particles [6]. It could well transfer the force between particles. Therefore, the linear contact model is used to analyze the movement of iron concentrate in the cargo hold.

The contact model is activated immediately when there is contact between particles, i.e. the gap between particles is no more than zero. The contact forces between particles mainly include two kinds, linear force and dashpot force. The former provides linear force with linear elastic (no-tension) characteristics, while the latter is used to provide viscous characteristics, as follows.

\[ F_C = F^l + F^d \]  

(1)

Where \( F^l \) is the linear force, \( F^d \) is the dashpot force. Linear forces and dashpot forces are decomposed in normal and shear directions:

\[ F^l = -F^l_n + F^l_s \]  

(2)

\[ F^d = -F^d_n + F^d_s \]  

(3)

where \( F^l_n \) is the linear normal force, \( F^l_s \) is the linear shear force, \( F^d_n \) is the dashpot normal force, \( F^d_s \) is dashpot shear force.

In this study, the viscous behavior between particles is not considered, so the linear contact model mainly updates the linear force. With the interaction between particles, the linear normal force and the linear shear force will be updated iteratively according to the variation of the clearance between particles, as shown in Eqs. (4) and (5) below.

\[ F^l_n = \begin{cases} k_n g_s, & g_s < 0 \\ 0, & \text{otherwise} \end{cases} \]  

(4)

\[ F^l_s = \begin{cases} F^*_s, & \| F^*_s \| < F^\mu_s \\ F^\mu_s (F^*_s / F^\mu_s), & \text{otherwise} \end{cases} \]  

(5)

Where \( k_n \) is the normal stiffness of particles, \( F^*_s \) is the trial shear force, \( F^\mu_s \) is the shear strength, which are updated according to the following equations:

\[ F^*_s = (F^l_s)_o - k_s \Delta \delta_s \]  

(6)

\[ F^\mu_s = -\mu F^l_s \]  

(7)

where \((F^l_s)_o\) is the linear shear force at the beginning of the time step, \( k_s \) is the shear stiffness of particles, \( \Delta \delta_s \) is the relative shear displacement increment of particles, and \( \mu \) is the friction coefficient between particles.

3. Material property verification

Internal friction angle, an important property of soil, is mainly calculated and often obtained through direct shear test [7]. Reference [2] points out that when the particle size of iron concentrate is selected as: 7.2% with particle diameter greater than 0.5 mm, 32.6% with particle diameter greater than 0.25-0.50 mm, and 48.3% with particle diameter greater than 0.10-0.25 mm, the internal friction angle is generally about 34.5°.

3.1. Model parameter calibration

During the indoor direct shear model test, the size of the shear box is generally set as 6.18 cm * 4.00 cm [7]. Therefore, a shear box numerical model with the same size is established in this study. Reference [8] points out that when the ratio of model boundary size to particle radius is not less than 25, the influence of size effect can be ignored. To avoid the size effect, the ratio of boundary size to
particle size is greater than 25. Based on the iron concentrate particle gradation given in reference [2], parameters of the linear contact model selected are mainly set as shown in Table 1 below.

| Parameter                  | Value | Parameter         | Value |
|----------------------------|-------|-------------------|-------|
| Particle normal stiffness $k_n$ (Pa) | 1e8   | Particle density $\rho$ (g/cm$^3$) | 2700 |
| Particle shear stiffness $k_s$ (Pa) | 1e8   | Particle friction $\mu$ | 0.5  |
| Stiffness ratio $k = k_n/k_s$ | 1     | Acceleration of gravity $g$ (m/s$^2$) | 9.81 |

3.2. Direct shear test simulation

To effectively calibrate the internal friction angle, direct shear tests under confining pressures of 100 kPa, 200 kPa, 300 kPa and 400 kPa are completed. When the shear displacement reaches 4 mm or the shear stress reaches the peak, the shear strength of the sample can be obtained. The simulation of direct shear test is shown in Fig. 1.

![Fig. 1. Simulation of direct shear test.](image)

Table 2. Shear strength under different confining pressures.

| Normal stress (kPa) | Shear strength (kPa) | Normal stress (kPa) | Shear strength (kPa) |
|---------------------|----------------------|---------------------|----------------------|
| 100                 | 86                   | 300                 | 237                  |
| 200                 | 159                  | 400                 | 291                  |

![Fig. 2. Relationship between shear strength and normal stress.](image)

According to the shear strength theory of soil, the shear strength of soil is expressed as a function of the normal stress on the sliding surface:

$$\tau_f = \sigma \tan \varphi$$

where $\tau_f$ is the shear strength of soil, $\sigma$ is the normal stress, $\varphi$ is the internal friction angle.

From Eq. (8), there exists a linear relationship between shear strength and normal stress. Therefore, the inclination of the straight line based on the linear fitting equation is the internal friction angle of the soil. The variation of shear strength of samples under different confining pressures are shown in
Fig. 2 and Table 2. According to the numerical simulation results, the internal friction angle between particles is 36°, which is about 4.17% error compared with the iron concentrate in the reference [2]. The main reason for this error is that the particle number generated in modelling are different from the actual iron concentrate particles.

4. Cargo hold sloshing test simulation

4.1. Model building
The size of the numerical model of the rectangular cargo hold established in this study is 0.06 m * 0.04 m. This is a 1:250 scale cargo hold model according to the actual cargo hold size of 57,000 DWT bulk carrier [3]. The loading height of cargo is set as 0.0195 m. To further study the movement of cargo in the cargo hold, the sway motion of the cargo hold is mainly discussed. The amplitude of sway motion is 0.003 m and the frequency is 1 Hz. Based on the particle size of cargo in the direct shear test above, the initial state of the numerical model is shown in Fig. 3, and the real-time loading curve of sway motion is shown in Fig. 4.

4.2. Cargo sloshing test simulation
The closer the installation position of cargo hold transverse baffles is to the surface of cargo, the more stable the cargo movement is [7,9]. Combined with engineering practice, discontinuous transverse baffle is selected, and then three groups of baffles with different lengths are simulated. Three groups of baffles with different lengths are: case 1: L1=0.02 m, case 2: L2=0.015 m, and case 3: L3=0.01 m. Meanwhile, the numerical simulation without baffles is used as the control case 0.

4.3. Result analysis
To better discuss the effect of transverse baffles of different lengths on the cargo stability, the variations of the center of gravity offset of cargo and the contact force are considered. Fig. 6 shows the variation of the center of gravity of cargo without baffle, while Fig. 7 shows the variation of the dynamic contact force on the bulkhead induced by the cargo movement.
Fig. 6. Center of gravity offset of cargo: (a) x-direction; (b) y-direction.

From Fig. 6, in the condition of no baffles, the offset of the center of gravity in the x-direction mainly fluctuates between 0.0022 m and 0.0038 m, while the offset in the y-direction increases with time. In this case, the stability of cargo in the cargo hold is very poor, and it is easy to slosh. From Fig. 7, there is a little difference in forces on the left and the right bulkhead. However, the force on the left bulkhead is slightly greater than that on the right. The reason for this phenomenon is that the initial movement direction of the cargo hold is to the left.

Fig. 7. Dynamic contact force on the bulkhead induced by the cargo movement: (a) left side; (b) right side.

Fig. 8. Center of gravity offset of cargo: (a) x-direction; (b) y-direction.
Fig. 9. Dynamic contact force on the bulkhead induced by the cargo movement: (a) left side; (b) the right side.

As can be seen from Fig. 8, when the length of baffle is 0.015 m, the center of gravity offset of cargo in the x-direction and y-direction is smaller than that in the cases of 0.02 m and 0.01 m. It can be seen from Fig. 9 that the forces on the left bulkhead and the right bulkhead are basically uniform in each case. However, when the length of baffle is 0.02 m, the bulkhead is subjected to greater force. Combined Figs. 6 and 7, the installation of transverse baffles in the cargo hold has a great influence on the center of gravity offset of cargo, but a small influence on the force on the bulkhead.

From the analysis and discussion above, it can be deduced that under the current working conditions, when the length of the transverse baffle is 0.015 m, the overall center of gravity offset of cargo is the smallest. This also shows that when the length of transverse baffle is about 1/4 of the length of the cargo hold, the good stability of cargo in the cargo hold could be ensured.

5. Conclusions

To effectively guarantee the stability of iron concentrate safe transportation, the movement characteristics of iron concentrate in the cargo hold is mainly studied in this study. And the influence of adding transverse baffles on the center of gravity offset of cargo and the dynamic contact force of bulkheads are considered. Then the influence of different lengths of transverse baffles on the stability of iron concentrate in the cargo hold is analysed in detail. The main conclusions are summarized as follows:

- The stability of iron concentrate can be effectively promoted by the installation of transverse baffles. The center of gravity offset of cargo in the y-direction is most affected by the arrangement of baffles.
- When the length of transverse baffle is 1/4 of the length of cargo hold, the stability of iron concentrate in the cargo hold is the best.

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