Numerical Study on Movement of Iron Concentrate in a Cargo Hold Based on Discrete Element Method

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Abstract—Taking the cargo hold from a 57000 DWT bulk carrier as an example, the movement of iron concentrate particles in the cargo hold was simulated by using the discrete element software EDEM. The effect of water content on the movement of the cargo is replaced by variation of the particle’s friction coefficient. Considering the friction coefficient, particle size grading, particle collision recovery coefficient, rolling amplitude of cargo hold and cargo loading depth, 11 working conditions were designed and simulated. Results show that the decrease of friction coefficient, the increase of rolling amplitude and the loading capacity would aggravate the overall shift of the center of gravity of the cargos. In the case of the same loading depth, the more particles, the stronger the particle collision. And the collision recovery coefficient has little effect on the movement of particles.

1. INTRODUCTION
Caused by the swing and vibration of the bulk cargo carrier encountered by waves during its voyage, fluidization of iron concentrate may occur. Fluidization means that the internal moisture permeates out and the free surface forms. Once the fluidization happens, the ship’s recovery torque can be decreased and also its stability, which would result in some accidents. For this kind of problem, Zhou Jian et al. studied the macroscopic situation of fluidization of bulk iron concentrate based on PFC3D software\cite{1}. Spandonidis and Spyrou studied the relationship among the static angle, material properties and motion characteristics of solid particles in cargo hold by molecular dynamics methods\cite{2}. Song Xiqing et al. studied the particle motion characteristics based on the discrete element method and the finite element method\cite{3}. LI Wenjie and JU Lei obtained the relationship between water content and Coulomb friction through the static tilt experiment, and proposed a numerical evaluation method for ship stability by changing the water content based on the discrete element method\cite{4}. Wei Chen et al. established a new cargo critical stress condition model, which provides a means to evaluate cargo stability\cite{5}. Blasio F V D simulated the viscous force by increasing the force between the particles, and established a set of flow methods for viscous particles based on molecular dynamics\cite{6}.

The objective of this study is to study the movement of liquefiable cargo particles in a cargo hold, and to provide a reference for the safety of maritime transportation of liquefiable cargo. In order to show the movement of particles in the cargo hold and to understand the cargo movement more clearly and intuitively, 11 calculation working conditions based on discrete element methods were designed. Five factors were investigated, including inter-particle friction coefficient, particle size grading, particle collision recovery coefficient, rolling amplitude and loading depth of cargo hold.
2. ESTABLISHMENT OF NUMERICAL MODEL

2.1. Theoretical model
The simple equation of the movement of particle i can be obtained according to Newton's second law, shown in (1)[7].

\[ m_i \ddot{u}_i = \sum F \]

Where, \( m_i \) means mass of particle i, \( I_i \) means rotational inertia of particle i, \( \ddot{u}_i \) means acceleration of particle i, \( \dot{\theta}_i \) means angular acceleration of the particle i, \( \sum F \) means force of particles at the center of mass of particles, \( \sum M \) means external torque of particles at the center of mass of particles.

Hertz-Mindlin (no slip) contact model is adopted for the inter-particle contact model[8], where the inter-particle contact force \( F_n \) can be calculated by (2).

\[ F_n = \frac{2}{3} E^* R^{1/2} \alpha^{3/2} \]

Where, \( E^* \) means equivalent elastic modulus, \( R^* \) means equivalent radius, \( \alpha \) means contact radius.

By using the central difference method to perform numerical integration of (1), the intermediate point of the two iteration times can be obtained to indicate the update speed, shown in (3).

\[
\begin{align*}
(u_i)_{N+\frac{1}{2}} &= (u_i)_N + \frac{1}{2} \left\{ \frac{\sum F}{m_i} \right\} \Delta t \\
(\dot{\theta}_i)_{N+\frac{1}{2}} &= (\dot{\theta}_i)_N + \frac{1}{2} \left\{ \frac{\sum M}{I_i} \right\} \Delta t
\end{align*}
\]

Where, \( \Delta t \) means time step, \( N \) means corresponding time t.

The displacement equation shown in (4) can be obtained by integrating the velocity equation in (3).

\[
\begin{align*}
(u_i)_{N+1} &= (u_i)_N + (u_i)_{N+\frac{1}{2}} \Delta t \\
(u_i)_{N+1} &= (u_i)_N + (u_i)_{N+\frac{1}{2}} \Delta t
\end{align*}
\]

Bring the calculated displacement into the force-displacement relationship to obtain a new variable, and then iterate iteratively to obtain the force and position of particles at each moment.

The calculation procedure of discrete element method is shown in Fig. 1. It first uses the initial contact force \( F_i \) to calculate \( u_i \) on the basis of Newton's second law and then gets new \( F_i \) according to the relationship between force and displacement before iterative calculation.

![Figure 1. Calculation procedure of discrete element method](image)

2.2. Model validation
The numerical model validation of this study was carried out based on the reference [1], and the specific model setting parameters are shown in Tab. I. The three-dimensional square box takes simple harmonic reciprocating motion in x direction, with a frequency of 1 Hz and an amplitude of 60 mm. The comparison of simulation results is shown in Fig. 2, from which the contour shape of the whole particle can be seen. It also can be observed that the numerical calculation results are basically consistent with those in the reference [1] through the comparison between Fig. 2a and Fig. 2b. The
only possible error lies in that the formation of particles is random and the initial state of particles can not be completely consistent.

### TABLE I. Model Validation Parameter Settings

| Parameter                                      | Value                        | Parameter                                      | Value          |
|-----------------------------------------------|------------------------------|-----------------------------------------------|----------------|
| Contact Model                                 | Hertz-Mindlin (no slip)     | Static Friction Coefficient Between Particles and Cargo Hold | 0.32           |
| Particle Density (kg/m³)                      | 2750                         | Dynamic Friction Coefficient Between Particles and Cargo Hold | 0              |
| Particle Diameter (mm)                        | 0.5                          | Coefficient of Collision Recovery Between Particles | 0.01           |
| Shear Modulus of Particles (MPa)              | $4.58 \times 10^6$          | Static Friction Coefficient Between Particles | 0.01           |
| Particle Poisson's Ratio                      | 0.2                          | Dynamic Friction Coefficient Between Particles | 0.005          |
| Density of Cargo Hold Material (kg/m³)        | 7850                         | Target Save Interval (s)                       | 0.01           |
| Shear Modulus of Cargo Hold (MPa)             | $7.92 \times 10^6$          | Mesh Size (mm)                                | 1.35           |
| Coefficient of Collision Recovery Between Particles and Cargo Hold | 0.35                         | Fixed Time Step                              | 20%            |

Figure 2. Results comparison: a: numerical calculation structure of this study b: results of reference [1]

### 3. NUMERICAL SIMULATION

#### 3.1. Physical model

Taking the typical cargo hold from a 57000 DWT bulk carrier as the prototype [9], and considering the limitations of numerical simulation, the geometric scale ratio $\lambda$ was set as 1:660. The cargo hold numerical model is shown in Fig. 3. Typical sections of 57000 DWT bulk carrier and main dimensions of calculation model are shown in Tab. II.
Figure 3. Cargo hold numerical model

| Project               | Symbol | Actual Size of Ship Cargo Hold | Cargo Hold Model (λ = 1:660) |
|-----------------------|--------|--------------------------------|------------------------------|
| Breadth               | B      | 32.3 m                         | 48.8 mm                      |
| Length                | L      | 16.5 m                         | 25.0 mm                      |
| Depth                 | D      | 9.9 m                          | 15.0 mm                      |
| Top Plate Chamfer     | θ₁     | 30°                            | 30°                          |
| Bottom Plate Chamfer  | θ₂     | 45°                            | 45°                          |

3.2. Simulation conditions

Taking into account the factors such as the material properties of liquefiable cargo and the external conditions of ship's transportation on the sea, the rolling amplitude, cargo loading conditions, friction coefficient, particle size grading, and particle collision recovery coefficient have been selected for study. 11 different working conditions have been established in this study, and the detailed parameters are shown in Tab. III.

| Working Conditions | Static and Dynamic Friction Between Particles | Amplitude(°) | Gradation | Coefficient of Collision Recovery | Loading Depth |
|--------------------|-----------------------------------------------|--------------|-----------|-----------------------------------|---------------|
| 1                  | 0.01,0.005                                    | 20           | ①        | 0.01                               | 50%           |
| 2                  | 0.02,0.01                                     | 20           | ①        | 0.01                               | 50%           |
| 3                  | 0.3,0.1                                       | 20           | ①        | 0.01                               | 50%           |
| 4                  | 0.01,0.005                                    | 15           | ①        | 0.01                               | 50%           |
| 5                  | 0.01,0.005                                    | 10           | ①        | 0.01                               | 50%           |
| 6                  | 0.01,0.005                                    | 20           | ②        | 0.01                               | 50%           |
| 7                  | 0.01,0.005                                    | 20           | ③        | 0.01                               | 50%           |
| 8                  | 0.01,0.005                                    | 20           | ①        | 0.02                               | 50%           |
| 9                  | 0.01,0.005                                    | 20           | ①        | 0.03                               | 50%           |
| 10                 | 0.01,0.005                                    | 20           | ①        | 0.01                               | 40%           |
| 11                 | 0.01,0.005                                    | 20           | ①        | 0.01                               | 60%           |
User defined module is used to configure the particle size grading, three different types of gradations was obtained in this study: ①0.45 mm (10%), 0.6 mm (70%), 0.85 mm (20%); ②0.45 mm (20%), 0.6 mm (60%), 0.85 mm (10%); ③0.45 mm (10%), 0.6 mm (60%), 0.85 mm (30%).

Considering the limitation of simulation conditions, the rolling was considered as the main influence of the actual motion of the ship. In addition, due to the fact that the movement of cargo particles in the cabin is relatively slow in the actual shipping process, hence the corresponding parameters were set in this study to further accelerate the movement of particles, i.e., the rolling period is 1s, the rolling center is the centroid of cargo hold, the time step is 20%, the number of meshes is 101250, and the mesh size is three times of the minimum radius of particles.

4. RESULTS ANALYSIS

4.1. Effect of friction coefficient on iron concentrate particle movement

The particle movement under different friction coefficients is shown in Fig. 4. It can be seen that the particle inclination is the largest under working condition 1, followed by working condition 2, and the particle inclination under working condition 3 is the smallest, with almost no flow. It also can be seen that the larger the Coulomb friction coefficient is, the less likely the particles are to flow.

The normal contact force of particles is the normal impact force of particles. The larger of the normal impact force, the greater the number of particle collisions. The higher of the frequency, and the more intense the particle movement. The kinetic energy of particles is an important indicator to measure the speed of the particles. It should be emphasized that when the particles are stationary, i.e. when the time is 0, the normal contact force between particles is 0.00088 N under the action of gravity. The comparison of normal contact force, kinetic energy and center of gravity offset of particles under working conditions 1, 2 and 3 is shown in Fig. 5. It can be seen that the smaller the friction coefficient is, the larger the normal contact force of particles, and the more intense the collision of particles is, i.e. the normal contact force of particles will decrease with the increase of friction coefficient. It also can be seen that when the friction coefficient changes, the kinetic energy of particles and the center of gravity offset of particles will decrease with the increase of friction coefficient over time. In addition, under a single working condition, with the increase of time, it is difficult for particles to return to their original position under the action of inertia, and the displacement of particles will become larger and larger, resulting in a lower center of gravity offset and a greater degree of particle inclination with time.
4.2. Effect of rolling amplitude on iron concentrate particle movement
The detailed comparison of simulation results of working conditions 1, 4 and 5 is shown in Fig. 6. It can be seen from Fig. 6 that the larger the rolling amplitude is, the more obvious the change of normal contact force is, and the greater the peak value will be. It also can be seen from Fig. 6 that under three different working conditions, the particle kinetic energy and the center of gravity offset decreases with the rolling amplitude decreases, and the decrease of the center of gravity offset is more obvious.

4.3. Effect of particle size grading on iron concentrate particle movement
In the case of half load depth, 4450 particles were loaded in working condition 1, 7810 particles were loaded in working condition 6, 6450 particles were loaded in working condition 7, and the detailed data comparison of working conditions 1, 6 and 7 is shown in Fig. 7. It can be seen that the peak kinetic energy of working condition 6 is not much different from that of working condition 7, the peak kinetic energy of particles in working condition 6 is slightly larger, and the peak kinetic energy of particles in working condition 1 is much higher than that in other two working conditions. In addition, Fig. 7 also reflects the inverse proportion relationship between the number of particles and the collision degree of particles. Hence it can be concluded that under the same loading depth, the more particles are loaded, the higher the center of gravity is, but the difference of the center of gravity offset is not obvious.

4.4. Effect of collision recovery coefficient on iron concentrate particle movement
The detailed data comparison of working conditions 1, 8, 9 is shown in Fig. 8. It can be seen that there is almost no difference in the normal contact force of particles under the three working conditions, the change rate of particle kinetic energy is exactly the same, and the center of gravity offset is basically the same. Hence it can be concluded that different collision recovery coefficients have little effect on the normal contact force and kinetic energy of particles, and the degree of particle collision is almost the same.
4.5. Effect of cargo loading conditions on iron concentrate particle movement

The detailed data comparison of working conditions 1, 10 and 11 is shown in Fig. 9. It can be concluded that the cargo load is directly proportional to the collision degree of particles. It also can be seen that the peak value of normal contact force in working condition 1 and working condition 11 is almost the same, but the change range of normal contact force in working condition 1 is larger, which shows that the particle collision in working condition 1 is more intense under high loading rate. In addition, the particle kinetic energy of working condition 1 is almost the same as that of working condition 10, and the particle kinetic energy of working condition 11 is maintained at a low level. The change range of the particle's center of gravity offset under working condition 11 is larger, as well as that of condition 10 is the smallest.

5. CONCLUSION

The correctness of the numerical model in this study is verified by comparing with the published data. 11 working conditions in this study were established to simulate the movement of iron concentrate in bulk carrier cargo hold under different working conditions. By changing the friction coefficient to replace the effect of water content, the following conclusions can be drawn.

1. The movement amplitude of particles will significantly decrease with the increase of the friction coefficient of particles, and the effect of water content can be replaced by variation of the particle’s friction coefficient. Under a single working condition, the movement amplitude of particles will increase with time due to the effect of inertia.

2. The collision of particles will be more intense with the increase of rolling amplitude, and the change of the center of gravity offset of particles will also be larger. The change of collision recovery coefficient has little effect on the movement of particles. Under a certain loading volume, the smaller the particle size grading, the larger the movement amplitude of particles. In addition, the normal
contact force and kinetic energy of particles will be maintained at a higher level with the increase of particle loading.

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