Experimental study on the liquefaction process of iron concentrate on swing table

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Abstract- Liquefaction of the bulk particle cargoes is a serious hidden risk for the ore transportation ship. To further understand the liquefaction mechanism of the particle cargoes, the model experiments have been carried out, by adopting saturated iron concentrate samples and the six degrees of freedom swing table. The effect of external load frequency on pore water pressure and excess pore pressure ratio was investigated. Results show that the external load is the main factor causing liquefaction of the cargo, and the possibility of liquefaction of different parts of the whole cargo is different. The bottom part of the cargo changes the most under different external loads, while the top does not.

1. INTRODUCTION
Liquefiable cargo is a very special kind of solid bulk cargo. When sailing on the sea, the whole cargo will sink and become dense due to the small particle size and poor permeability of the cargo. In addition, the effect of external loads such as ship movement and mechanical vibration can not be ignored. The water between the pores of the cargo particles is not easy to be discharged, leading to the increase of pore water pressure and the decrease of effective stress, namely, liquefaction[1]. At this point, if the external load continues to act, the cargos start to flow, and it is difficult for the moving cargos to return to their original position, causing the ship to lose stability and even capsize. The ship capsizing accident caused by the flow of cargo occurs suddenly, has great harm and is difficult to rescue.

The maritime transport safety of liquefiable cargo has attracted the attention of scholars at home and abroad. Zhao and Ding[2] analyzed the specific risk factors of the ship carrying liquefiable cargos, and determined the possibility of danger, which is convenient for the maritime administrative department to supervise. Zhang[3] analyzed the marine transportation environment of the liquefiable cargos, and predicted the liquefaction of the liquefiable cargos along the coast of China. With the help of soil liquefaction theory, Zhou et al.[4] studied the liquefaction process and mechanism of liquefiable cargo based on the dynamic test of bulk iron concentrate on indoor small shaking table, and concluded that the main reasons for the liquefaction of iron concentrate under external load were the rise of water level and the migration of pore water and fine particles.

At present, the influence of external load factors on the liquefaction of cargos still needs to be further studied. Therefore, in this study, iron concentrate is selected as the research object, and a six-degree-of-freedom swing table is adopted to simulate the movement of the ship, focusing on the variation of pore water pressure and excess pore pressure ratio in iron concentrate under different
excitation frequencies. The conclusions can be provided as a helpful reference for the prevention of maritime transport accidents of liquefiable cargo.

2. Experiment set up

2.1. Experimental equipment and materials

The experimental device is mainly composed of six degrees of freedom swing table, model cabin, pore water pressure sensor and data acquisition instrument. Among them, the motions of single-degree-of-freedom and multi-degree-of-freedom can be simulated by the six-degree-of-freedom swing table, as shown in Fig 1. The model cabin is taken from the typical cargo compartment of a 57000 DWT bulk carrier[5]. The scale ratio of the model cabin is 1:66. It is made of transparent glass and the size is 0.70 m × 0.30 m × 0.50 m (length × width × height). The loading depth is 0.25 m. Considering the condition of no drainage, the model cabin was cleaned before the experiment. The joints around the model cabin were coated with waterproof glue. In addition, to reduce the influence of the reflection waves from the rigid wall of the cargo compartment on the experimental results, thin foam plates were used to pave the side of cargo compartment.

![Figure 1 Six-degree-of-freedom swing experiment table](image)

The experimental samples were made of saturated iron concentrate from the Laotangshan ore wharf of Zhoushan. The physical parameters of the iron concentrate samples are shown in Table 1, and the grain size grading curve is shown in Fig.2. The saturated samples were prepared by dry loading method. The iron concentrate samples were loaded into the model tank and rammed in layers until the samples reached the predetermined loading depth. Then, water was added to the model chamber until it is above the sample surface static settlement. Before starting the experiment, the excess water in the cabin should be discharged to make the water level consistent with the sample height, and the surface of the sample should be smooth.

| Project | Dry density | Porosity | Friction angle | Volume modulus | Shear modulus | Permeability coefficient |
|---------|-------------|----------|---------------|----------------|---------------|-------------------------|
| units   | kg/m³       | --       | °             | Mpa            | Mpa           | cm/s                    |
| value   | 3000        | 0.5      | 35            | 16.5           | 7.61          | 1.2E-7                  |
During the experiment, CYY-2 pore water pressure sensor was used to measure and record the pore water pressure inside the sample in real time. Three sensors are located in the center of the model cabin and the location of the sensors are successively from the bottom to the top of the cargo compartment, as shown in Fig. 3, A (0,0,0.03), B (0,0,0.06) and C (0,0,0.09). After the above steps are completed, the moisture content of the sample is measured by stratified sampling to ensure that the moisture content of each layer of the sample is basically the same.

![Figure 3 Pore water pressure sensor (a) and layout (b)](image)

2.2. Loading scheme

In order to study the influence of the external excitation frequency on the liquefaction process of the liquefiable cargos, it is assumed that the energy received by the cargos is the same, that is, the acceleration value of the external excitation is constant, so the influence of the excitation frequency variation is studied. According to the formula of acceleration, frequency and amplitude, the frequency and amplitude of the final external load are determined as shown in Equation 1. Assuming the acceleration is 0.2 g, the amplitude of different frequencies is shown in Table 2. The excitation mode is harmonic sinusoidal wave, and the cargo hold moves vertically.

\[ \alpha = 4\pi^2 f^2 A \]

(1)

Where, \( \alpha \) is acceleration (m/s²), \( f \) is frequency (Hz), \( A \) is amplitude (mm).

| Frequency (Hz) | Amplitude (mm) |
|---------------|----------------|
| 2/3/4/5/6/7/8/9/10 | 12/5.5/3.1/2.0/1.5/1.0/0.8/0.6/0.5 |

![Figure 2 Grain size grading curve of iron concentrate sample](image)
3. Results analysis
In the liquefication experiment of iron concentrate, the excess pore water pressure values at the monitoring points A, B and C were selected to reflect the changes of pore water pressure inside the sample. If the pore water pressure inside the sample can counteract the effective stress from the upper part, it indicates that the sample has been fluidized. At this point, the ratio of pore water pressure to total stress, namely the excess pore pressure ratio, is 1.0.

![Figure 4 Curves of excess pore water pressure (ratio) at cargo hold monitoring point at 5 Hz](image)

Figure 4 Curves of excess pore water pressure (ratio) at cargo hold monitoring point at 5 Hz

The changes of excess pore water pressure and excess pore pressure ratio at monitoring points A, B and C at 5 Hz in the Fig.4 show that all the curves of the three monitoring points in the cabin conform to the above liquefaction overview, that is, the excess pore water pressure is stable and the excess pore pressure ratio is 1.0. Hence, cargo liquefaction occurs at all the three monitoring points in the cabin at 5 Hz. The numerical value of the excess pore water pressure at point A is the largest, followed by point B and the smallest at point C, which is related to the position of the monitoring point. A is at the bottom of the cabin and C is at the top of the cabin.

![Figure 5 Curves of excess pore water pressure (ratio) at monitoring point A under four loads](image)

Figure 5 Curves of excess pore water pressure (ratio) at monitoring point A under four loads

It is shown in Fig.5 that excess pore water pressure (ratio) values at monitoring point A are rising over time at four kinds of loads. The excess pore water pressure at 3 Hz first peak and excess pore pressure ratio is 0.8 at this time. Due to 3 Hz is low frequency which does not make excess pore water pressure further increase, so the dissipation significantly after peak, excess pore water pressure began to reduce, but with the increase of vibration time, the effective stress at A point is declining and fell faster than excess pore water pressure, so excess pore pressure ratio at 3 Hz can continue to rise. The other three kinds of loads have high frequency values, so the excess pore water pressure (ratio) value
The excess pore water pressure (ratio) curves at Point C under the four loads is shown in the Fig 7. It is also similar to that at Point A in Fig 5. All of the values increase with time, but since point C is on the top of the cargo hold, the excess pore water pressure is small. The excess pore water pressure at
Point C at 7 Hz was significantly lower than that of the other three loads, and its excess pore pressure ratio was far lower than 1.0 in the whole process, so the cargos at point C at 7 Hz were not liquefied. The excess pore water pressure under the other three kinds of loads has a sharp rise and fall, which is due to the fact that point C is located at the top of the cabin and the cargo has poor stability and is prone to small displacement. In addition, the excess pore pressure ratio under the three loads has a period equal to 1.0, so the cargos at point C under the three loads are partially liquefied or completely liquefied. Therefore, the top cargo of the cargo hold is also easy to liquefy under high and low loads, but the top cargo liquefy trigger time is similar to that of the bottom cargo hold.

4. Conclusion
The influence of external incentive factors on the liquefaction of cargos is analyzed in this study from experimental method. The excess pore water pressure values of simple were recorded with time. The study gives the following major findings:

1. The load can cause the excess pore water pressure (ratio) to rise, but in different areas under different loads, the excess pore water pressure (ratio) change curves are different, so the cargo liquefaction situation is also different. Top cargos and bottom cargos have the most liquefaction cases, which is the most prone region.

2. The influence of the external load at the different parts of the whole cargos is different. Due to the top of the cargos is not only easy to liquefaction, effective stress value is also low, the smallest load can make the cargo at the top of the liquid, the liquefaction triggering time of the top of the cargos at 3-7 Hz is basically the same at 3-7Hz, which is less affected by the load change. In addition, due to the maximum effective stress value of bottom cargo, the rising speed of excess pore water pressure value under high and low loads is influential, under different loads, the liquefaction trigger time of bottom cargo is different, and the bottom is greatly affected by the change of load.

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