

Research on transport adaption of port-loading solid bulk cargoes which may liquefy based on shear strength

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Abstract. To reveal the relationship between shear strength and transport adaption of port-loading solid bulk cargoes which may liquefy, first of all, the change rule of shear strength under different moistures is obtained based on direct shear test, then the dangerous moisture by direct shear test and transportable moisture limit by traditional method are compared, finally the internal connection of shear strength and transport adaption is obtained. The shear strength theory provides a new thought for transport adaption of solid bulk cargoes which may liquefy.

1. Introduction

With the rapid economic development, China's demand-supply gap in various types of mineral products is increasing, which leads to most mineral products relying on overseas imports by ships. Among them, the import volume of iron ore powder and concentrates in China was 819 million tons in 2013, a 10.2% increase from 2012, accounting for 67.0% of the world's seaborne volume of such goods [1]. However, at the same time, carrying iron ore powder and concentrates, kaolin, nickel ore, etc., due to their own part of fine particles and a certain amount of moisture, may form a free liquid surface or solid-liquid two-phase flow layer in the cabin when the moisture content exceeds transportable moisture limit, which will lead to rollover or even sinking accidents. In 2010 alone, 8 such accidents occurred in our country, causing major casualties and property losses as well as adverse social impacts. This has brought serious negative impact on the development of China's shipping industry, and it has also raised the industry's high attention to the safety of fluidized cargo transportation [2-5].

In order to avoid such accidents, the "International Maritime Solid Bulk Cargo Code" (hereinafter referred to as "IMSBC Code") promulgated by the International Maritime Organization has been enforced globally since January 1, 2011[6]. At the 92nd Session of the IMO Maritime Safety Committee (MSC) held in London, UK, from June 12 to 21, 2013, five types of cargoes such as nickel ore were added to the list of easily liquefied solid bulk cargoes. In domestic, the Ministry of Transport issued the "Safety Management Regulations for Solid Bulk Cargoes for Water Transport" (Ministry of Transport [2011], 638) in November 2011.



Foreign scholars have developed earlier researches on the safe transport of cargoes by sea that may easily liquefy, which can be traced back to the 1960s and 1970s. At that time, they were mainly dedicated to the determination of test methods for flow moisture point and the development of test equipment [7]. In recent years, with the extensive application of ship mechanics and soil mechanics, scholars at home and abroad have conducted further researches on the safe transportation of cargoes which may easily liquefy. In the research of ship stability, Andrei C and other scholars used ship mechanics to study the effect of the fluidization characteristics of solid bulk cargo on the overall stability of the ship [8, 9]; By calculation method of the ship statics, Shen and other scholars discussed the possibility and theoretic basis that the free liquid surface formed by liquefaction of nickel ore result in stability of ship decreasing to negative [10]. The Shanghai Ship and Shipping Research Institute analyzed the liquefaction evolution process of nickel ore and measured the dynamic heeling moment generated by the liquefied ore sand, by a six-degree-of-freedom motion platform test on the cargo tank model loading nickel ore sand [11]. In the determination of transport adaption, Holmes et al. studied the effect of large particles on the results of cargo flow moisture point test [12]; Popek analyzes the effect of organic polymers in concentrate fines on the transportable moisture limit of cargo [13]. Munro et al. tested and compared transportable moisture limits of iron ore concentrates using three different methods recommended by the IMSBC, but the results of three different test methods are not the same, and suggestion was recommended that the research on mechanical properties of easily fluidized cargo should be strengthen [14]. At present, there are relatively few researches on the dynamic characteristics of solid bulk cargoes which may easily liquefy at home and abroad. Prof. Zhou's research group studied the dynamic characteristics and liquefaction characteristics of laterite nickel ores by model tests and dynamic triaxial tests [15, 16]. Wang and others conducted dynamic triaxial tests on bulk fluorspar powders and investigated the effects of moisture content and dynamic stress on the fluidization of fluorspar powders [17].

The above research results have played an excellent theoretical guiding role in the safe transportation of shipping cargoes which may easily liquefy. However, there are few studies on the mechanical properties of solid bulk cargoes which may easily liquefy at this stage. In particular, there is still a lack of in-depth research and effective application of research results on shear strength, despite it's the internal cause of liquefaction of goods.

Based on this, through exploring the change law between internal cohesion with the water content of the easily liquefied solid bulk cargoes and comparing it with the corresponding transportable moisture limit obtained by the traditional testing method, the research on the transport adaption of easily liquefied solid bulk cargoes in port-loading is developed based on the shear strength. The study reveals the internal causes of the phenomenon of liquefaction in solid bulk cargoes, and also provides a brand-new idea for the determination of the transport adaption of it.

2. The basic principle of shear strength

The shear strength of an easy-fluidizing solid bulk cargo refers to the ultimate strength of the cargo against shear failure, which can be measured by shear test. According to Coulomb's law:

$$\tau = \sigma \tan \varphi + c \quad (1)$$

where τ is the shear strength, σ is the normal stress, φ is the internal friction angle, and c is the cohesive force. The internal friction angle φ is one of the shear strength indexes of solid bulk cargoes which reflects its frictional characteristics. It is generally considered to contain two parts: the surface friction of solid bulk cargo particles, and the bite force generated by the embedded and interlocking action. The cohesion force c is a characteristic index of the sticky goods, which includes the original cohesive force formed by the molecular gravitation between the solid bulk cargo particles and the solidification cohesive force formed by the cementation of the solid bulk cargo compound.

The direct shear test is a commonly used method to determine the shear strength of a sample. Normally, horizontal shear force is applied on each four specimens separately under different vertical pressure to obtain the shear stress at the time of failure. Then, according to Coulomb's law, the shear strength parameters of the cargo, namely, the internal friction angle and the cohesion are determined.

A total of 6 cargo species were selected for this study, including 4 nickel mines and 2 clays. A total of 5 direct shear tests were performed for each cargo species under five 5 different moisture contents. The samples were passed through a 5 mm sieve, and the sieved material was dried for use. By adding different amounts of water, the samples were adjusted to 5 sets of dry to wet samples, and the dry density of the 5 sets of samples was controlled to the same value. The direct shear tests were performed with normal pressures of 100 kPa, 200 kPa, 300 kPa, and 400 kPa, respectively, for 5 sets of specimens having different moisture contents and the test results were recorded and processed.

3. Tests results

The change rules between the shear strength index of six types of goods with the moisture content were obtained though the direct shear test on the sample, as shown in Figure 1 to Figure 6.

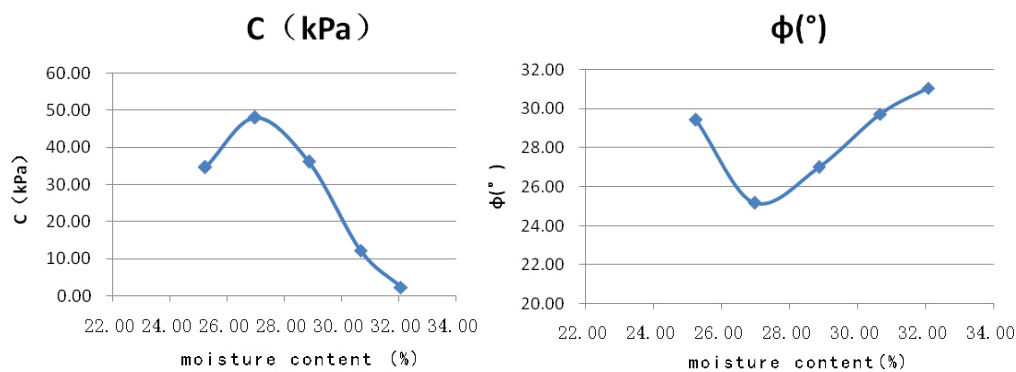


Figure 1. The change law between shear strength index and moisture content of 1# nickel ore

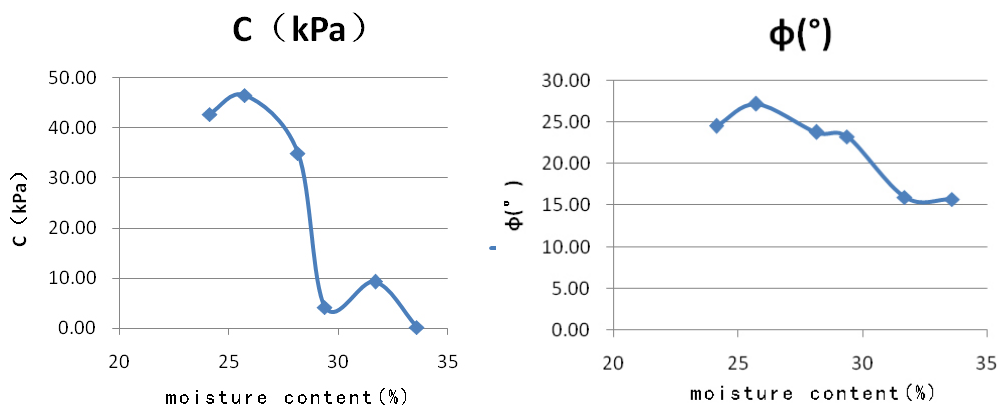


Figure 2. The change law between shear strength index and moisture content of 2# nickel ore

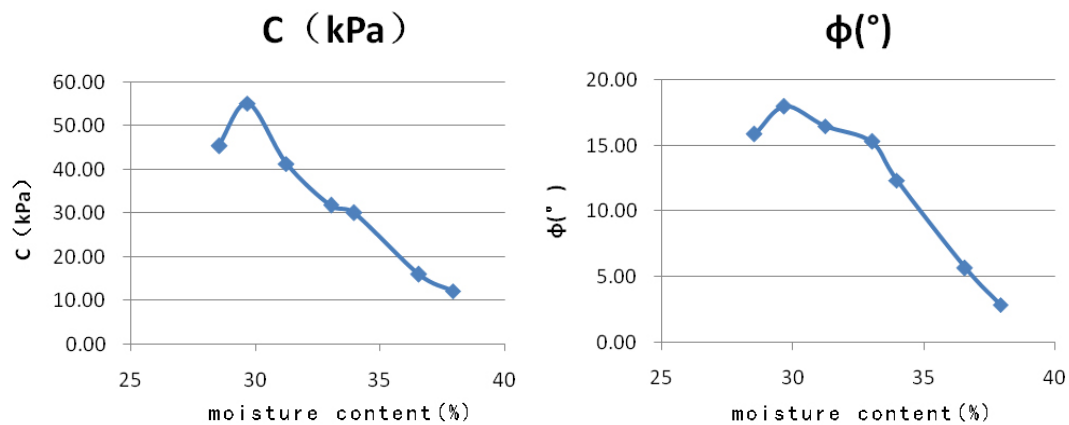


Figure 3. The change law between shear strength index and moisture content of 3# nickel ore

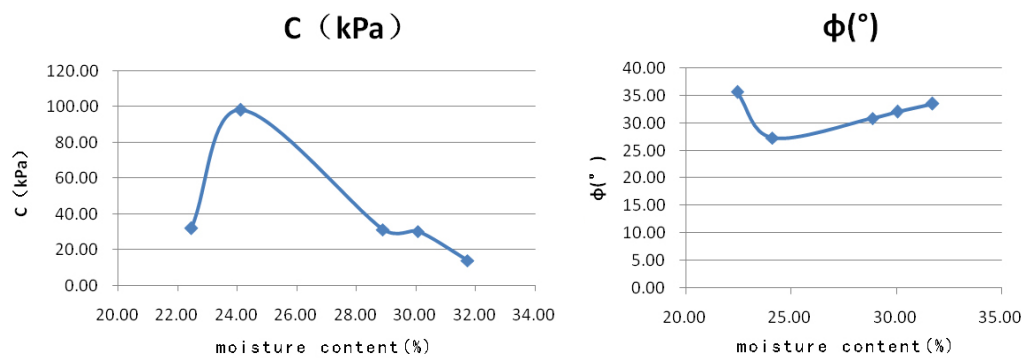


Figure 4. The change law between shear strength index and moisture content of 4# nickel ore

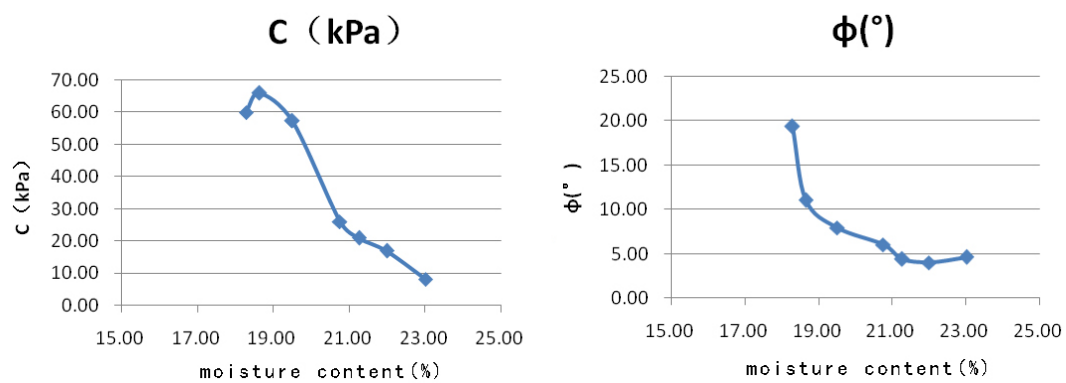


Figure 5. The change law between shear strength index and moisture content of 5# clay

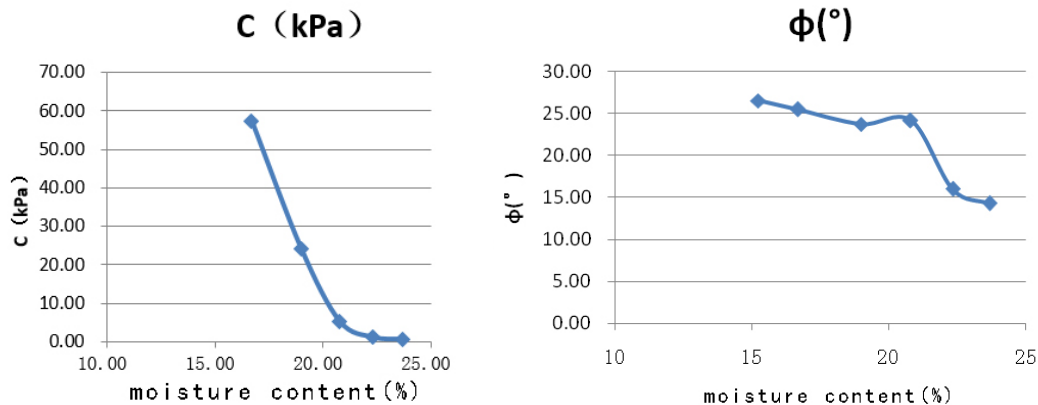


Figure 6. The change law between shear strength index and moisture content of 6# clay

4. Analysis and discussion

Based on the above test data, analyses and discussions are as follows:

(1) The change laws between cohesive force c and the moisture content are the same in the 6 direct shear test of different samples, and the basic law is that c increases first and then decreases with the increase of moisture content. When the moisture content increases to a certain value, the cohesive force gradually approaches 0, then the cargoes are liquefied.

(2) The change law between internal friction angle ϕ and moisture content of the six samples varies. Among them, the internal friction angle ϕ of 2# nickel ore, 3# nickel ore, 5# clay, and 6# clay decrease with the moisture content increasing, and finally reach a steady state at a relatively low value. However, the internal friction angle ϕ of 1# nickel ore and 4# nickel ore shows a trend of decreasing first and then increasing with the increasing of water content.

(3) It can be seen from the above two analyses that the change rules between cohesion force c , which is the index of shear strength, with the moisture content are more consistent, and the relationship between the change of c and the transport adaption of cargoes should be selectively analyzed.

(4) Table 1 shows the results of the direct shear method and the traditional method (Penetration test method). The traditional insertion method was used to obtain the flow moisture point, and then to obtain the corresponding transportable moisture limit which is 90% of the flow moisture point; through the fitting curve of Figure 1~ Figure 6, the moisture content of 6 different samples which is referred as “dangerous water content” below is obtained separately when the correspond cohesive is 10kPa. From the table, it can be seen that the transportable moisture limits of the six samples measured by the method of Penetration test are 30.3%, 29.6%, 36.4%, 32.1%, 23.0%, and 21.1%, respectively. Meanwhile, the dangerous moisture contents of the six samples obtained by the direct method are 30.7%, 29.0%, 38.2%, 32.0%, 22.8%, and 20.9%, respectively. The relative deviations of the two methods are -1%, 2%, -5%, 1%, 1%, all of which are within 5%. It can be seen that the dangerous moisture content based on the shear strength theory agrees well with the transportable moisture limit measured by the traditional method. The above phenomenon not only proves that the internal shear strength of the cargo has a strong intrinsic correlation with the transport adaption, but also provides a brand-new idea for the determination of the transport adaption of the cargo that is easy to liquefy.

Table 1. Statistics of test results of the direct shear method and the traditional method

Sample name	Penetration test method		Direct shear method	relative deviations D
	flow moisture point (FMP)	Transportable moisture limit	Corresponding moisture content at	$D = (TML - MC) / TML$

		(TML)	c=10kPa (MC)	
1# nickel ore	33.7%	30.3%	30.7%	-1%
2# nickel ore	32.9%	29.6%	29.0%	2%
3# nickel ore	40.4%	36.4%	38.2%*	-5%
4# nickel ore	35.7%	32.1%	32.0%*	0%
5# clay	25.5%	23.0%	22.8%	1%
6# clay	23.5%	21.1%	20.9%	1%

Note: The value with * is based on a small range of changes in the trend.

5. Conclusions

This study innovatively applied the shear strength theory in geotechnical tests to the determination of the transport adaption of easily liquefied solid bulk cargoes. The main findings are as follows:

(1) Cohesion increases at first then decreases with the moisture content of the cargoes increasing. When the moisture content increases to a certain value, the cohesion gradually approaches 0, and the cargoes are liquefied. The above phenomenon shows that the reduction of the internal shear strength of cargoes is the essential reason for the fluidization of easily liquefied solid bulk cargoes.

(2) The “dangerous moisture content” based on the shear strength theory agrees well with the transportable moisture limit measured by the traditional method, and the respective relative deviation of the six samples is within 5%. This not only proves that the internal shear strength of the cargo is highly intrinsically related to its transport adaption, but also provides a brand-new idea for the determination of the transport adaption of easily liquefied solid bulk cargoes.

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