Study on Prevention of Sliding Failure of Nickel Ore in Bulk

- New Procedure for Evaluating Shear Strength -

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Summary

Nickel ore is natural clay containing large lumps. Every year, around four million tons of this material is transported to Japan from Indonesia, New Caledonia and Philippine by bulk carriers of around twenty thousands to forty thousands tons dead weight tonnage. When nickel ore contains much moisture, slopes of its cargo piles in cargo holds may slide, because its shear strength is low.

To prevent sliding failure of a bulk cargo, it is necessary to evaluate the shear strength of the cargo prior to shipment. Shear strength of nickel ore can be measured by direct shear tests or triaxial compression tests in a laboratory, and the stability of the cargo pile can be evaluated by slope stability calculation which is utilized in the field of soil mechanics based on the measured shear strength. Such method for evaluation, however, cannot be conducted at the time of shipment of nickel ore, because it takes at least a few days. Taking these issues into consideration, we developed a new in-situ test procedure for evaluating shear strength of nickel ore which can be conducted at places of loading for nickel ore in a few hours in view of prevention of sliding failure. To develop the criterion for judgment on sliding failure of nickel ore, we carried out direct shear tests and slope stability calculations for nickel ore from five ports.

The new test procedure mainly consists of three steps, i.e., removal of large particles, insertion of the sample in the mould and cone penetration test. First, particles larger than 19 mm are removed from the wet sample by passing through an appropriate sieve. Next, the sample is inserted in the mould and compacted to make a consistent specimen. Then the cone is pushed down into the specimen and the maximum value of reaction force is measured. When the force is less than 300 N, the nickel ore should not be accepted for loading without taking special safety measures.

1. Transportation of nickel ore and its properties

1.1. Transportation of nickel ore ^{1), 2)}

Nickel ore is natural clay containing large lumps. It is a product of open cast mining and transported to Japan from the ports listed in Table 1, around four million tons per year, by bulk carriers of around twenty thousands to forty thousands tons dead weight tonnage.

When nickel ore contains much moisture, its shear strength is low and the shortage of shear strength may result in sliding failure of a cargo pile. On August 26, 1998, a bulk carrier carrying nickel ore capsized near Okinawa Island. By this accident, ten people were

missing and eleven people were rescued. It was supposed that one of the causes of the accident was sliding failure of the cargo. Furthermore, extraordinary lists of bulk carriers resulted from sliding failure of nickel ore were reported several times.

Table 1. Ports of loading for nickel ore

Countries	Ports		
Indonesia	Gebe	Pomalia	
New Caledonia	Boakaine	Karembé	Kopeto
	Kouaoua	Moneo	Nakety
	Quinne	Poya	Teoudie
	Thio	Tontouta	
Philippine	Hinatuan	Rio Tuba	Tanganito

While loading at the most of all ports listed in Table 1, nickel ore is carried to a bulk carrier anchoring off the pier by barges and is loaded in the cargo holds by ship's grabs. To prevent sliding failure, nickel ore is trimmed as level as practical using ship's grabs. Slopes of a cargo pile, however, still remain after trimming as illustrated in Fig. 1. Usually, cargo handling is suspended in the rain to avoid increase of moisture of the cargo.

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Fig. 1. Shape of trimmed nickel ore

1.2. Properties of nickel ore

The samples of nickel ore from Gebe, Pomalaa, Boakaine, Tontouta and Rio Tuba were used in this research. Table 2 shows solid density, i.e., the density of solid part not including void consisting of moisture and air, of the samples and Fig. 2 shows the grain size distributions of them. The grain size distributions were measured after removing particles larger than 100 mm. In the figure, the abscissa and ordinate denote the grain size in mm and percentage of finer particles in dry weight, respectively. The graphs are the grain size accumulation curves of the samples. The figure shows that nickel ore varies in grain size distribution.

Fig. 2. Grain size distribution of the samples

1.3. Limitation of moisture content³⁾

Sliding failure of nickel ore can be prevented by limiting the moisture content. To limit the moisture content of nickel ore, the upper bound of moisture content should be determined for each type of nickel ore, because it varies so wide depending on properties of nickel ore, in particular on grain size distribution. In laboratory, it is possible to determine the upper bound of moisture content based on shear tests and slope stability calculations. It takes, however, a few days to determine the upper bound of moisture content by such method. There is, therefore, no appropriate method for

determining the upper bound of moisture content in a short time which can be employed in the practice of transportation of nickel ore.

For cargoes which may liquefy, the methods for determining the transportable moisture limit are described in the Code of Safe Practice for Solid Bulk Cargoes⁴⁾. These methods, however, cannot be applied to the determination of the upper bound of moisture content of nickel ore, because sliding failure of nickel ore is the phenomenon caused by the shortage of static shear strength irrelevant to liquefaction which is caused by cyclic loading and increase of pore water pressure.

2. New test procedure

2.1. Outline of the new test procedure

Considering the above issues, we developed the new in-situ test procedure for evaluating shear strength of nickel ore in view of prevention of sliding failure. The proposed test procedure can be conducted at places of loading for nickel ore in a few hours. By applying the test for nickel ore to be shipped, it is possible to avoid the shipment of dangerous nickel ore which contains excessive amount of moisture.

The new test procedure mainly consists of three steps, i.e., removal of large particles from a sample, insertion of the sample in the mould and cone penetration test which is employed for evaluating foundation in the practice of construction of houses and buildings. First, particles larger than 19 mm are removed from the wet sample by passing through an appropriate sieve. Next, the sample is inserted in the mould and compacted to make a consistent specimen. Then the cone is pushed down into the specimen and the maximum value of reaction force, which is called cone penetrating force, is measured. Insertion of the sample and cone penetration test are repeated three times. The results of these tests are represented by the minimum value of three maximum cone penetrating forces which is called representing cone penetrating force hereafter. When the representing cone penetrating force is less than 300 N, it is judged that the nickel ore should not be accepted for loading without taking special safety measures.

It should be noted that the criterion for judgment on prevention of sliding failure in the test procedure is determined under the premise that nickel ore is trimmed as illustrated in Fig. 1 and that increase of moisture content during loading operation is negligible. In other words, nickel ore should be trimmed as far as practical and increase of moisture content due to rain or ingress of sea water into the cargo on a barge should be prohibited for safe transportation, regardless of the judgment based on the new test procedure.

2.2. Removal of large particles¹⁾

When the cone hits a large particle during the cone penetration test, the cone penetrating force increases considerably. On the other hand, macroscopic shear

strength of nickel ore depends on the characteristics of fine particles and effect of large particles on the shear strength of the material is not significant. The large particles should, therefore, be removed from the sample to keep its consistency. Considering the maximum grain size described in JIS A 1210: 1999 (c.f. 2.3) and the diameter of cone (c.f. 2.4), we determined the maximum grain size at 19 mm.

2.3. Insertion of the sample into the mould

Taking the maximum grain size of the sample and clearance between the cone (c.f. 2.4) and the mould into consideration, we specified the diameter and the capacity of the mould at 150 mm and 4,000 cm³, respectively, as illustrated in Fig. 3.

Fig. 3. Specification of the cone and the mould

We specified the compaction procedure based on the standard, JIS A 1210: 1999, i.e., "Test method for soil compaction using a rammer". Table 3 shows five methods for compaction described in the standard. The inner diameter of the mould and maximum grain size of the sample for method "D" in the table are the same those for the new test procedure. Considering the deal of work

Table 3. Conditions for compaction in JIS A 1210

Methods	Weight of rammer [kg]	Dropping height of rammer [cm]	Inner diameter of mould [cm]	Capacity of mould [cm ³]	Number of layers for compaction	Number of droppings for each	Maximum grain size [mm]
A	2.5	30	10	1,000	3	25	19
B	2.5	30	15	2,209	3	55	37.5
C	4.5	45	10	1,000	5	25	19
D	4.5	45	15	2,209	5	55	19
E	4.5	45	15	2,209	3	92	37.5

for compaction and capacity of the mould, we specified the conditions of compaction as shown in Table 4 based on the method "D" described in Table 3. The compactive effort, i.e., the energy of compaction per unit volume, of the new test procedure is approximately 60 % of the one for the method "D" described in Table 3.

Table 4. Condition of compaction in the new test procedure

Weight of rammer [kg]	4.5
Dropping height of rammer [cm]	45
Inner diameter of mould [cm]	15
Capacity of mould [cm ³]	4,000
Number of layers for compaction	5
Number of droppings for each layer	60
Maximum grain size [mm]	19

After the compaction of the sample, the surface of the specimen is formed by leveling off the sample along the brim of the mould.

2.4. Cone penetration test

The cone penetrometer, i.e., the equipment for measuring the cone penetrating force shown in Fig. 4, with the cone of larger type of which the base area is 6.45 cm² is selected for the new test procedure. The speed of penetration is specified at 1 cm/sec, according to standards and the depth of penetration is specified at 15 cm. The maximum value of cone penetrating force is measured during the penetration of cone into specimen until the top the cone reaches to 15 cm from the brim of the mould.

Fig. 4. Cone penetrometer

2.5. Number of repetition of cone penetration tests and the representing value

Cone penetrating force sometimes reaches high resulted from confinement of penetration due to comparatively large particles, even the specimen is formed with particles less than 19 mm. Such phenomenon affects the maximum cone penetrating forces obtained through the cone penetration tests. The results of the tests should be represented by the minimum value of the maximum cone penetrating forces obtained through the tests in order to reduce the effect of such phenomenon on the repeatability of representing value of the results.

Forming specimen for each test using the same sample, we repeated the cone penetration tests 30 times to

investigate the effect of number of repetition of the tests on the repeatability of representing cone penetrating force. The nickel ore from Boakaine, which contains comparatively higher proportion of large particles as shown in Fig. 2, was used for the experiment. Fig. 5 shows the results of the experiment. In the figure, the abscissa and ordinate denote experiment number and maximum cone penetrating force, respectively. The black and white circles denote measured data for samples at 23.0 and 24.5 % in average moisture content, respectively. The moisture content of sample is represented by the wet base one, M_c^{105} , as following:

$$M_c^{105} = \frac{W_T - W_s}{W_T} \quad (1)$$

where, W_T is total weight and W_s is dry weight.

Fig. 5. Maximum cone penetrating forces

The superscript 105 denotes the drying temperature in Celsius. "D < 19 mm" means that the maximum grain size of the sample was reduced to 19 mm. The thinner solid lines denote the minimum value in three data including the former and the latter data in the experiment number. The thicker solid lines, similarly, denote the minimum value in five data. It can be said that the difference between the minimum values in three data and in five data is not significant, in particular in the case that the maximum cone penetrating forces are small. Thus we determined the number of repetition of cone penetration tests for single sample at three.

3. Determination of criterion for judgment

3.1. Outline of determination of the criterion

The criterion of representing cone penetrating force for judgment on prevention of sliding failure is determined by the following steps:

- (1) Determination of primary criteria of moisture content, i.e., upper bound of moisture content of the samples for shear tests, based on the measurement of the relations between moisture content and shear strength and the analyses on the relations between

moisture content and slope stability;

- (2) Conversion of the primary criteria of moisture content to the moisture contents of samples for the new test procedure;
- (3) Measurement of the relations between moisture content and representing cone penetrating force; and
- (4) Determination of the criterion of the representing cone penetrating force based on the representing cone penetrating forces corresponding to the moisture contents from step (2).

3.2. Determination of primary criteria of moisture content

We carried out the direct shear tests ^{3), 5)} for the five samples changing moisture content to obtain the relation between moisture content and shear strength. Table 5 shows the specification of the tests. The maximum grain size of the samples for the tests was 6.7 mm.

Table 5. Specification of direct shear test

Apparatus	Maruto S-08A
Normal force	Vertical load by means of weight from top of specimen
Method for shearing	Driving lower shearing box horizontally
Shear force	Load for confining the upper shearing box in motion
Test condition	Constant vertical load
Maximum grain size of sample	6.7 mm
Diameter of specimen	60 mm
Thickness of specimen	Approximately 30 mm
Horizontal displacement speed	1 mm/min
Maximum horizontal displacement	9 mm

Fig. 6 is an example of the shear strength of the samples. In the figure, the abscissa and ordinate denote normal stress and resisting tangential stress, respectively.

Fig. 6. Shear strength of a sample

The normal stress is calculated based on the vertical load and the resisting tangential stress is analyzed based on

the peak value of shear force or the shear force at 8 mm in horizontal displacement. e is the void ratio defined by the following formula:

$$e = \frac{V_v}{V_s} = \frac{V_T - V_s}{V_s} = \frac{V_T \cdot \rho_s \cdot g}{W_s} - 1 \quad (2)$$

where,

V_v and V_s are volumes of void space and solid in the total volume V_T , respectively;

ρ_s is solid density;

g is gravity acceleration; and

W_s is dry weight corresponding to V_s .

The resisting tangential coefficient $\tan\phi$, i.e., the internal friction coefficient obtained through direct shear tests, is the inclination of the graph. The cohesion c is the resisting tangential stress where normal stress equals to zero. It should be noted that the shear strength of wet nickel ore obtained through direct shear tests and one obtained through triaxial compression tests showed good agreement^{3), 5)}.

Fig. 7 shows the relation between moisture content and shear strength of the sample of nickel ore from Gebe. In the figure, the abscissa denotes moisture content. The ordinates denote resisting tangential coefficient and cohesion. $\bar{e}$ is the average of the void ratios at the relevant tests. We also measured the shear strength of samples of nickel ore from other four ports and analyzed the relations between moisture content and shear strength of these samples which are used to determine the primary criteria of moisture content.

Fig. 7. Relation between moisture content and shear strength

We carried out two-dimensional numerical calculation of sliding failure in the same way as that for the slope stability calculations utilized in soil mechanics based on the relation between moisture content and shear strength and on the average density of the samples for direct shear tests.^{3), 6)} As illustrated in Fig. 8, the safety factor corresponding to sliding line, which is assumed to be an arc, is calculated by "Fellenius method", and the danger of sliding failure is indicated by "critical safety factor", i.e.,

the minimum value of safety factors obtained through calculations changing sliding lines.

Fig. 8. Slope stability calculation

In order to maintain the slope stability for important structure under construction, the critical safety factor derived by this calculation method should generally be kept at least 1.2. To prevent sliding failure of solid bulk cargoes, it can analogically be said that the critical safety factor should be kept not less than 1.2 during transportation.

Table 6 shows the conditions of calculation determined based on the investigation of the shapes of cargo piles. Fig. 9 shows the relation between moisture content and critical safety factor of the sample from Gebe.

Table 6. Conditions of slope stability cal.

Slope width [m]	7
Slope height [m]	5
Width of flat part [m]	13
Acceleration Condition	Static Heel 30 [deg]

Fig. 9. Relation between moisture content and slope stability

In the figure, the abscissa and ordinate denote moisture content and critical safety factor, respectively. The moisture content corresponding to the critical safety factor 1.2, i.e., the primary criterion of moisture content for preventing sliding failure, is 35.7 %. Similarly, the primary criteria of moisture content of the other samples were analyzed and the results are shown in Table 7.

Table 7. Primary criteria of moisture content

Ports of loading for nickel ore	Gebe	Pomalaa	Boakaine	Tontouta	Rio Tuba
Primary criteria of moisture content [%] (D < 6.7 mm)	35.7	33.4	26.8	29.6	42.7

3.3. Conversion of moisture content ^{1), 2)}

The primary criteria of moisture content, i.e., the moisture content of the samples of which the maximum grain size is 6.7 mm, should be converted to the moisture contents of the samples for the new test procedure to determine the criterion of representing cone penetrating force.

When nickel ore looks wet, it is supposed that water is contained not only in particles but in the void space. In such condition, it is deemed that the particles contain moisture as much as possible. We, therefore, measured the moisture content of particles in the range of 6.7 mm to 19 mm just after wiping the water on each particle soaked into water for long time. The moisture content measured can be regarded as the maximum moisture content in particles.

The moisture content can be converted by the following formula with the maximum moisture content in particles in the range of 6.7 mm to 19 mm and the proportion of particles finer than 6.7 mm in particles up to 19 mm in dry weight:

$$M_C^T = \frac{p \cdot M_C^S + (1-p) \cdot M_C^L - M_C^L \cdot M_C^S}{1 - p \cdot M_C^L - (1-p) \cdot M_C^S} \quad (3)$$

where,

M_C^T : moisture content (D < 19 mm);

M_C^L : moisture content (6.7 < D < 19 mm);

M_C^S : moisture content (D < 6.7 mm); and

p : proportion of particles up to 6.7 mm in particles up to 19 mm in dry weight.

Table 8 shows the results of the conversion of moisture content. The upper bounds of moisture content in view of prevention of sliding failure of samples for the new test

procedure are shown in the bottom of the table.

Table 8. Conversion of moisture content

Ports of loading for nickel ore	Gebe	Pomalaa	Boakaine	Tontouta	Rio Tuba
Percentage of particles less than 6.7 mm in particles less than 19 mm in dry weight [%]	90.8	88.7	81.7	87.6	84.3
Maximum moisture content of particles in the range of 6.7 mm to 19 mm [%]	18.7	15.2	14.7	16.6	24.7
Moisture content [%] (D < 6.7 mm)	35.7	33.4	26.8	29.6	42.7
Converted moisture content [%] (D < 19 mm)	34.4	31.7	24.8	28.2	40.5

3.4. Relation between moisture content and representing cone penetrating force

To investigate the relation between moisture content and representing cone penetrating force, we carried out the new test procedure for five samples changing moisture content. Fig. 10 shows the relations between moisture content and representing cone penetrating force of the samples of nickel ore. In the figure, the abscissa and ordinate denote moisture content and representing cone penetrating force, respectively. The black circles indicate the measured data. The white circles indicate the upper bounds of moisture content and the representing cone penetrating forces corresponding to them.

3.5. Criterion for judgment on sliding failure

Based on the results of the tests on the relation between moisture content and representing cone penetrating force, the representing cone penetrating force of each sample corresponding to the criterion of moisture content was analyzed as shown in Fig. 10. The results are shown in Table 9. Based on the values listed in the table, we determined the criterion of representing cone penetrating force at 300 N as a round number of the maximum value of them as illustrated in Fig. 10.

Fig. 10. Relation between moisture content and representing cone penetrating force

Table 9. Representing cone penetrating forces at the criteria of moisture content

Ports of loading for nickel ore	Gebe	Pomalia	Boakane	Tontouta	Rio Tuba
Criteria of moisture content [%] (D < 19 mm)	34.4	31.7	24.8	28.2	40.5
Representing cone penetrating forces corresponding to the criteria of moisture content [N]	195	290	250	190	285

It is recommended to avoid the shipment of the nickel ore of which the representing cone penetrating force is less than the criterion without taking special safety measures. For the transportation of such cargo, the cargo should be trimmed level to the boundaries of the cargo holds by employing a box type bulk carrier or the cargo is fully loaded in cargo holds by means of block loading taking the strength of ship structure into account.

4. Conclusion

To prevent sliding failure of nickel ore in bulk, we developed a new test procedure which can be conducted in a few hours at places of loading for evaluating shear strength of nickel ore in view of prevention of sliding failure. The new test procedure can contribute to planning of a fleet of bulk carriers by making it possible to acquire the data of nickel ore unsuitable for shipment without taking special safety measures.

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