論文の内容の要旨

Thesis Summary

論文題目　Evaluation of Liquefaction Potential of Partially Saturated Heap of Iron Ore Fines during Maritime Transportation

（部分飽和条件下における船積み鉄鉱粉の液状化ポテンシャルの評価）

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The problem of liquefaction has raised concerns with the International Maritime Organization (IMO) and their country members due to several accidents and loss of life during the transportation of liquefiable cargoes at sea. In 2009 two vessels capsized and sank following liquefaction of iron ore fines, which were loaded in the Indian ports. In October and November 2010, three vessels sank during the carriage of nickel ore from Indonesia to China with the loss of forty four seafarers, which was very possibly induced by cargo liquefaction. Several vessels had also experienced cargo liquefaction problems after loading bauxite in the Amazon region in northern Brazil.

To avoid the occurrence of liquefaction of iron ore fines during maritime transportation, the IMO has launched investigations since 2009 to study the responses of heaps of iron ore fines. Following four years of cooperation and discussions between related industrial groups, research groups and committee members of the IMO, a draft individual schedule for iron ore fines, which gives instructions to ship operators or masters when transporting iron ore fines, was proposed in 2013. The draft is now under voluntary implementation and is expected to be adopted in the International Maritime Solid Bulk Cargoes (IMSBC) Code in 2015, and would become mandatory from the beginning of 2017.

In order to reveal the liquefaction potential of iron ore fines, this thesis is an independent study from a point view of geotechnical engineering focusing on two types of iron ore fines. The primary objective of this study was to understand the responses of the heap of iron ore fines through characterizing the geotechnical properties of iron ore fines. Delicate laboratory tests were performed focusing on the geotechnical properties of both saturated and unsaturated iron ore fines, such as soil water characteristic curve (SWCC), permeability, undrained shear

strength, liquefaction resistance etc. The overall responses, such as the seepage in the heap, the dynamic responses of the heap were studied by employing numerical tools. The major outcomes from this study are summarized as follows:

1. Soil water characteristic curve (SWCC) of iron ore fines

Iron ore fines are usually loaded into a vessel with relatively uniform nature water content; however, the saturated and unsaturated zones may be soon formed due to the seepage of water in the heap. The properties, such as shear strength, water retention ability, permeability, deformation of the unsaturated soil are largely relied on its SWCC, which indicates the relationship between suction and water content of the unsaturated soil. SWCCs of two types of iron ore fines were measured in this study not only in the low suction range (0.1 kPa -100 kPa) but also in the high suction range (up to 10^6 kPa). A new testing technique, the membrane filter technique, was employed in the SWCC test to study the effect of void ratio on the SWCCs of iron ore fines. In addition, comparisons of SWCCs were made between iron ore fines and common geo-materials mixture. Scanning electron microscope (SEM) observations were also conducted to reveal the characteristics of SWCC of iron ore fines.

2. Permeability of iron ore fines

The property of permeability, which is essential to analyze the seepage, dynamic responses etc. in the heap, was measured for the saturated and unsaturated iron ore fines. To increase the accuracy of measurements, the test was conducted on a triaxial system under constant water head. The system head loss consumed by the surface friction of the water flow paths was estimated in order to obtain more reliable results. Regarding the permeability test of the unsaturated soils, it was found that the filter clogging problem induced by both dust in the flow water and the fines content in the soils affects the test procedures significantly. By following strict rules of evaluation, the system head loss of the measurement system was estimated. As a reference, soil for comparison with iron ore fines, the permeability of saturated and unsaturated Toyoura sand was also evaluated.

3. Liquefaction resistance of iron of fines

Considering the partially saturated condition of the heap of iron ore fines, the liquefaction resistance of the saturated and unsaturated iron ore fines was studied by conducting undrained cyclic loading tests. The test was performed on a specially manufactured triaxial apparatus, on which the measurement systems of pore air pressure, pore water pressure,

volume change of the unsaturated specimens were equipped. Research on the liquefaction resistance of unsaturated soils has been undertaken since the 1970s, of which mostly focused on the clean sands. Previous studies show that the resistance of liquefaction of unsaturated soils is higher than that of saturated soils and the increase was recently well linked to the potential volumetric strain of unsaturated clean sands. However, it was found from this study that the relationship between the potential volumetric strain and the increase in liquefaction resistance induced by degree of saturation (Sr) could not well explain the results of sands with fines content (Fc, particle size ≤0.075 mm), such as iron ore fines (Fc=24%) and Inagi sand (Fc=30%) used in this study. Efforts were taken to explain the combined effect of Sr and Fc on the liquefaction resistance of soils from the fundamental behavior of deformation. A volumetric strain ratio of the potential volumetric strain to the volumetric strain caused by the reduction in effective stress was proposed to be the new parameter to correlate the increase in liquefaction resistance induced by Sr and Fc. Associating with the results of the consolidation tests, the new parameter showed better correlation than previously proposed parameters.

4. Seepage analysis

The saturated zone of the heap of iron ore fines was expected to be the area with the highest liquefaction potential. Thus, the moment, when the highest water table was formed for a given initial Sr, was thought to be the critical condition of the heap to resist the rolling motion. On the other hand, the liquefaction potential of the unsaturated zone of the heap also needs to be considered in order to evaluate the overall responses of the heap under the rolling motion. Seepage analysis was carried out by employing a FEM code to unveil the time-dependent water table and distribution of Sr in the heap. The Van Genuchten model was used in the simulation to establish the relationship between suction, Sr and permeability. The effects of density of iron ore fines, boundary conditions of the heap and parameter setting of the Van Genuchten model were examined through the analysis. An envelope, which indicates the maximum height of water table in the heap for a given initial Sr, and the distribution of Sr in the unsaturated zone were obtained.

5. Dynamic responses analysis

The two dimensional responses of the heap of iron ore fines was evaluated by employing a commercial software, UWLC Ver. 2. A generalized elasto-plastic model was employed to simulate the behavior of liquefiable zone of the heap. Three cases, which focus on the effects of liquefaction potential and low permeability of the unsaturated zone on the overall

response of the heap, were studied. In each case, the response of the heap was examined under different rolling angles from 5° to 30°. The simulation results show that the properties of the unsaturated zone have significant effect on the overall responses of the heap, such as the strain distribution, the liquefaction potential etc., which imply the importance of considerations of the unsaturated zone.

While following the research stream addressed above, discussions on the testing techniques, such as the membrane filter technique used in the SWCC test, the calibration of system head loss and filter clogging problems in the permeability test etc., were also involved in the tests performed in this study. Particularly in the undrained cyclic loading test for the unsaturated soils, the cell pressure control system, which ensures the constant total principle stress during vertical cyclic loading by adjusting the cell pressure, was examined. The test results confirm good performance of the system and validate the necessity of the cell pressure control system in the triaxial system in order to evaluate the liquefaction resistance of the unsaturated soils in a more accurate manner.