論文の内容の要旨

Characterization of Liquefaction and Seepage Properties under Different Saturation Conditions of Bauxite During Maritime Transport
（船積みボーキサイトの異なる飽和条件下における液状化特性と透水特性の評価）

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Similar to liquefaction of soils during earthquakes, liquefaction of a solid bulk cargo can occur when excessive cyclic or dynamic loading, induced by rough seas and vessel vibrations, is transmitted to the cargo. If liquefaction of a solid bulk cargo occurs, it may cause the vessel to capsize and it has been found that from 1988 to 2015, there have been 24 suspected liquefaction incidents reported, which resulted in 164 casualties and the loss of 18 vessels (Munro and Mohajerani, 2016). One of the recent incident occurred in Jan 02, 2015 when 46.4 kilotons (handymax type vessel) of bauxite (primary ore of aluminum) being transported by MV Bulk Jupiter capsized on its way from Malaysia to China.

After the loss of MV Bulk Jupiter, the global bauxite industry was requested by the International Maritime Organisation (IMO) to undertake research into the behavior of bauxites during ocean transportation. The global bauxite industry responded by forming the Global Bauxite Working Group (GBWG) to conduct research on the behavior and characteristics of seaborne traded bauxites to inform the IMO in relation to the safe shipping of bauxites (Global Bauxite Working Group, 2017). One of their findings is that Handymax type carriers experience the largest motions for similar sea state conditions (Global Bauxite Working Group (GBWG), 2017), hence the importance of this study.

In order to reveal the liquefaction potential of bauxite, this thesis was conducted as an independent study from a point view of geotechnical engineering focusing on a type of bauxite assumed to be transported by a Handymax type carrier.

Work had been done by Wang (2014) using two types of iron ore material and one of the key findings was that considering the liquefaction potential of unsaturated zone in analysis is important in the overall understanding of the heap subjected to motions experienced by the Capesize (~150 kDWT) type carrier (Wang, 2014). Hence, it is worth to characterize bauxite and investigate how it would respond since it is a different material, when transported by Handymax (~50 kDWT) type vessel. Also in the process of loading the bulk cargoes into the ship and during transportation, the distribution of water contents on the bulk cargoes varies with respect to depth and changes with duration of travel. This causes some change in boundaries on the saturated zone and unsaturated zone of the heap. Thus, water flow properties are equally important to be dealt with in this study and a way to measure them is necessary. Finally, condition that can potentially cause instability on Handymax carrying bauxite heap was needed to be known.

In view of the conditions stated above, this research was performed (1) to characterize bauxite on its geotechnical properties and compare them with other geomaterials, (2) to develop a testing method to measure permeability of bauxite under different saturation conditions, and (3) identify threshold conditions by numerical simulation of dynamic response at different conditions.

For bauxite, three degrees of compactions (D_c) were prepared, labeled as loose (D_c = 65%), medium dense (D_c = 80%), and dense (D_c = 90%). The densities were assigned from published reports and prepared to the equivalent D_c in the laboratory.

The major outcomes from this study are summarized as follows:

1. Liquefaction resistance of bauxite

Considering the unsaturated condition of the heap of bauxite, the liquefaction resistance of the saturated and unsaturated conditions 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.

In terms of liquefaction behavior, it was found out that under saturated condition, bauxite behaves similar to other types of geomaterials in terms of liquefaction resistance curve at lower densities and higher densities. The stress paths and strain curves of bauxite were observed to be similar to iron ore and Inagi sand (silty sand), while Toyoura sand was observed different especially at loose case.

For unsaturated case, previous study had been conducted by Wang et al. (2016a) on iron ore to propose a new index called volumetric strain ratio (R_v). Liquefaction Resistance Ratio (LRR), which is the ratio between the Liquefaction Resistance ($R_{L,Unsat}$) of soil under unsaturated case compared to its saturated case ($R_{L,Sat}$), was plotted against R_v and found out to exhibit better correlation than previously correlated parameters such as LRR vs. potential volumetric strain ($\varepsilon^*_{v,air}$) (Okamura and Soga 2006). Conducting experiments for bauxite at saturation degrees of 84% (Sr=84%) and Sr=58%, bauxite followed the trend of the proposed LRR plotted against $R_{v,}$ exhibiting a better correlation than LRR vs. $\varepsilon^*_{v,air}$.

2. Water flow characteristics of bauxite

The property of permeability, which is essential to analyze the seepage, dynamic responses etc. in the heap, was measured for the saturated and unsaturated bauxite. Permeability tests were performed on Triaxial apparatus using a flexible wall.

Previous researches utilize ceramic disks (Goh 2015) placed on top of the specimen and bottom while in this research, membrane filter (Nishimura et al., 2012) was introduced to the top cap and bottom pedestal instead of the traditional ceramic disk for unsaturated specimens. In order to measure the head difference of the fluid flowing through the

specimen, a Local Pin-Type Sensor wrapped by membrane filter (same material as that of top and bottom pedestal) was used to measure the head difference directly. The inflow rate was measured by using a Mariotte's bottle which supplies the constant head, placed on a weighing scale in which the mass is received by the computer at a specified interval. The outflow rate, on the other hand was measured by using a differential pressure transducer (DPT). It was found out that the *k* of soils could be measured using the newly developed Local Pin-Type Sensor at various Sr, where values are obtained by simple average when inflow rate equals outflow rate (steady state condition) and measured head is reasonably stable.

Current tests were done on bauxite (range: $1x10^{-5}$ to $1x10^{-3}$ cm/sec), iron ore (range: $1x10^{-5}$ to $1x10^{-4}$ cm/sec), and Inagi sand (range: $1x10^{-5}$ to $1x10^{-4}$ cm/sec). The local pin-type sensor was found out to be ineffective for Toyoura sand.

Bauxite was found to behave closer to Inagi sand in its permeability properties under saturated and unsaturated conditions.

By utilizing the information obtained from SWRC, indirect method using Van-Genuchten Model (VG Model) was used to evaluate *k* values under unsaturated condition. The experimental data results were compared with VG model and in general, the VG model estimate is an underestimate of the results that can be obtained from the experimental data. This implies that direct measurement of *k* values is necessary.

3. Seepage analysis

From the *k* and SWRC tests data, seepage analysis was carried out using GuSLOPE 2.0 using the experimentally obtained values. The final distribution of water on the heap was simulated to identify the 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.

Initial degree of saturation of 90% (Sr_{init}=90%) was considered for seepage analysis for modeling. Results show that the water distribution is a function of the density of the heap with looser materials having higher wet base in general. The shape of the wet base accumulated is generally ellipsoidal, with the peak at the centerline of the cross section, tapering to the side boundary.

4. Dynamic responses analysis

Upon knowing the material properties and distribution of water on the heap, the two dimensional response of the heap of bauxite was evaluated by employing a commercial software, UWLC Ver. 2. A generalized elasto-plastic model (PZ-model) was employed to simulate the behavior of liquefiable zone of the heap. Two cases, which focus on the effects of liquefaction potential and 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°, under different densities, and then compared with

iron ore. From the simulation results, it was found out that bauxite at loose condition ≤5° rolling angle; medium dense: ≤10° rolling angle; and dense: ≤15° rolling angle could withstand a 360 cycle rolling motion. This number was adopted from the narrative of events from the Bahamas Maritime Authority (BMA) report on the case of MV Bulk Jupiter. For iron ore fines, a dense (D_c = 92%) could withstand ≤10° rolling angle.

Like the previous study by Wang (2014), it was also found out that assuming the unsaturated region to be liquefiable decreased the overall resistance of heap of bauxite. Hence, consideration of liquefaction potential of the unsaturated zone in the heap of bauxite for Handymax type carrier is necessary to evaluate the overall liquefaction potential of the heap.

As recommended application, this study provides a qualitative understanding of the behavior of heap of bauxite during maritime transport. While simple assumptions were adopted to describe the kind of motions a ship may experience in a typical voyage, the results suggest thresholds and extents for different heap densities and wet base, which can affect the safety of the carrier.

Although bauxites have large differences in particle size distribution depending on the deposit and subsequent processing, the results in this study can be helpful for other gradations by following similar methodology and approach.