EVALUATION OF LIQUEFACTION RESISTANCE OF UNSATURATED SOILS USING VOLUMETRIC STRAIN RATIO (R_V) INDEX

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1. INTRODUCTION

Liquefaction is a frequently occurring problem taking place when transporting wet granular solid bulk cargoes on board bulk carriers. 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). 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. Soils under the unsaturated condition usually show higher resistance against liquefaction than those under the saturated condition. However, possible governing parameters determining the liquefaction resistance of unsaturated soils are not yet clear. In this study, undrained cyclic loading tests were conducted on soils by employing a stress-controlled triaxial apparatus under the unsaturated case. Liquefaction Resistance Ratio (LRR), which is the ratio between the Liquefaction Resistance (R_L) of soil under unsaturated case compared to its saturated case, was plotted on previously correlated parameters such as potential volumetric strain ($\varepsilon^*_{v,air}$) (Okamura and Soga 2006). A new index proposed by Wang et al. (2016a), called volumetric strain ratio (R_v), will be shown to exhibit better correlation with LRR.

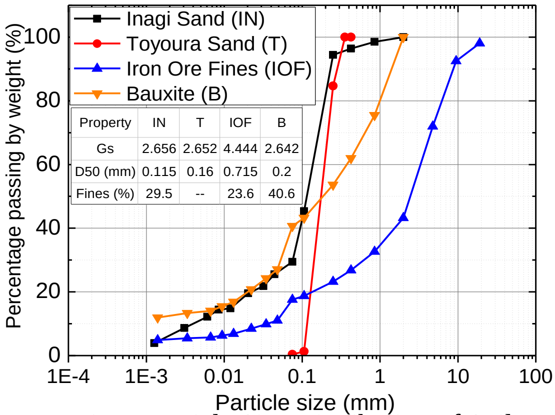

Fig. 1 Particle Size Distribution of Soils

2. EQUIPMENT AND MATERIALS

Undrained cyclic loading tests were conducted on Bauxite (B), which is a sedimentary rock with a relatively high aluminum content, and is the principal source of aluminum. Tests were plotted on existing data of other granular materials namely: Inagi Sand (IN), Toyoura Sand (T), and Iron Ore Fines (IOF). Inagi sand is a silty sand while Toyoura sand is a clean sand. Iron Ore Fines is a mineral where metallic iron can be extracted. The particle size distributions and other material properties are shown in Fig 1.

The liquefaction resistance of soils under unsaturated conditions were investigated using a Triaxial Apparatus with Linkage Double Cell System (Fig. 2). The volume and height changes of the specimen are measured by the inner cell (Fig.2,#8) and Vertical Displacement Transducer (VDT) (Fig.2,#2), respectively. Other details of the apparatus can be further read in Wang et al. 2016b.

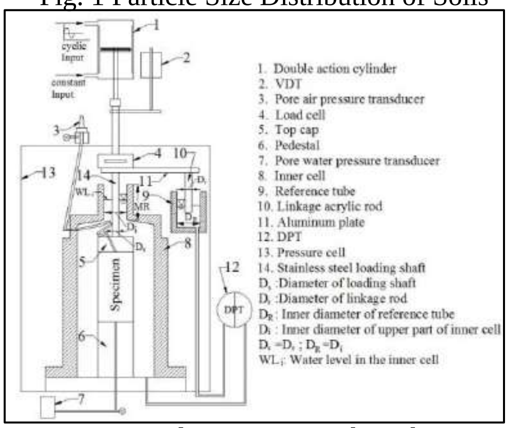

Fig.2 Triaxial Apparatus with Linkage Double Cell System

3. METHODOLOGY

All specimens have height of 10 cm, and diameter of 5 cm. Both saturated and unsaturated specimens were tested. Bauxite was prepared by 1-D compression and saturated by the double vacuuming method. The degree of compaction (D_c) was 80%, with tests under degree of saturation (S_r) values 58%, 84%, and 100%.

4. RESULTS AND DISCUSSIONS

4.1 Liquefaction Resistance Ratio (LRR)

Tests are performed to determine a soil's Liquefaction Resistance (R_L) by observing the number of cycles of loading at a particular shear stress amplitude before it 'fails'. It is defined in this study as the cyclic stress ratio at N=20 cycles of the liquefaction resistance curves with a double amplitude shear strain criteria of 5% (DA=5%). Figure 3 shows the liquefaction resistance curves for Bauxite, while superimposing it on representative IOF plot under S_r=71% and 100%.

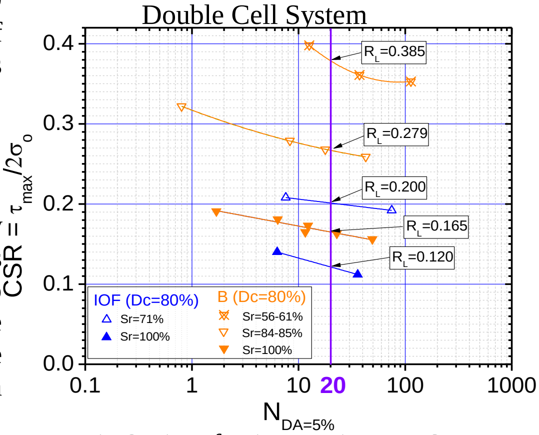

Fig.3 Liquefaction Resistance Curves

LRR values are used to correlate with various parameters to observe a trend.

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LRR is the ratio between the R_L of soil under unsaturated case compared to its saturated case. It is expressed mathematically as:

$$LRR = R_{L,unsaturated} / R_{L,saturated} \qquad (1)$$

4.2 Potential Volumetric Strain ($\varepsilon^*_{v,air}$)

Okamura and Soga (2006) considered the effect of compressibility of pore air in the unsaturated soils on $LRR_{DA=5\%}$ and proposed a parameter, potential volumetric strain ($\varepsilon^*_{v,air}$) to correlate $LRR_{DA=5\%}$. $\varepsilon^*_{v,air}$ is regarded as the volumetric stain of the specimens caused by pore air compression when the excess pore air pressure equals the initial confining pressure and is obtained by applying Boyle's law:

$$\varepsilon^*_{v,air} = \frac{\sigma_0'}{p_b+\sigma_0'}(1-S_r)\frac{e}{1+e} \qquad (2)$$

where, p_b is the absolute value of back pressure (kPa) and e is the void ratio. Fig.4 shows for clean sands (indicated by hollow shape plots), Okamura and Soga (2006) were able to obtain a unique trend governing the relationship between LRR and $\varepsilon^*_{v,air}$. From the tests conducted, the Toyoura data coincided with the existing plot, thereby supporting the trend. However, other soils with fines did not coincide with the trend. Thus, use of the single parameter $\varepsilon^*_{v,air}$ as an index may be insufficient to represent the response characteristics of different soils or the same soil under different test conditions (Wang et al 2016).

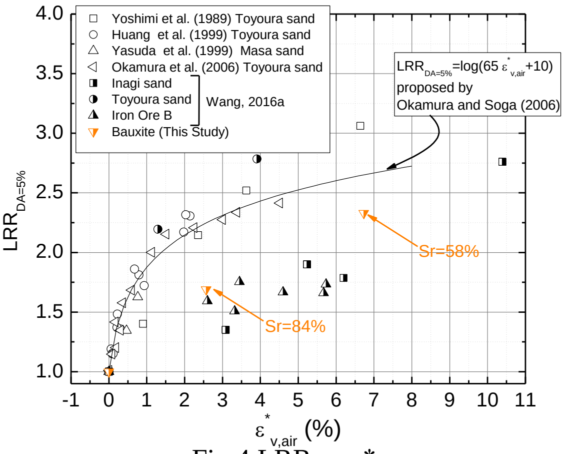

Fig.4 LRR vs $\varepsilon^*_{v,air}$

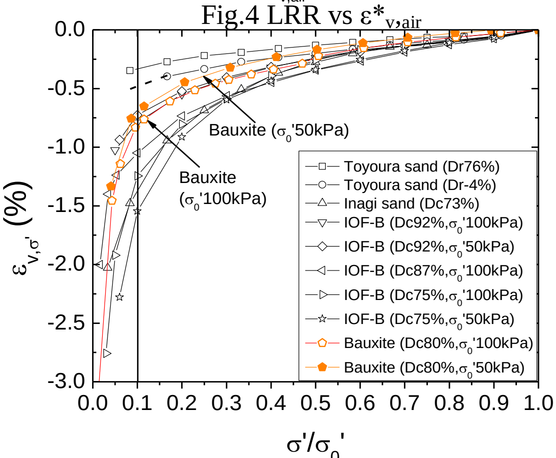

Fig.5 Isotropic consolidation tests (Unloading)

4.3 Volumetric Strains of Saturated and Unsaturated Soils

Volumetric strains of saturated and unsaturated soils under undrained conditions are influenced by the strain due to cyclic shear loading ($\varepsilon_{v,\tau}$), reduction of confining pressure ($\varepsilon_{v,\sigma}'$), and compressibilty of pore air can ($\varepsilon_{v,air}$), in which the mathematical relationship can be written as:

$$\varepsilon_{v,\tau} + \varepsilon_{v,\sigma}' = \varepsilon_{v,air} \qquad (3)$$

In Eq 3, it can be said that $\varepsilon_{v,\tau}$ is the motion inducing loss of effective stress, and $\varepsilon_{v,\sigma}'$ and $\varepsilon_{v,air}$ are the motions to recover the effective stress. Hence, the single parameter $\varepsilon^*_{v,air}$, which is the maximum value of $\varepsilon_{v,air}$ as an index may be insufficient to represent the response characteristics of different soils on different test conditions. To estimate the reduction of volumetric strain caused by $\varepsilon_{v,\sigma}'$, isotropic consolidation tests were conducted on the saturated specimens. After consolidation up to a specified initial effective confining pressures the effective confining pressure was decreased step by step to simulate the reduction process of effective confining pressure σ' during undrained cyclic loading. The relationship between the ratio σ'/σ_0' and $\varepsilon_{v,\sigma}'$ during the unloading process is shown in Fig. 5. Clearly, such relationship is different for different materials. The results also show that the volume of the specimens may expand significantly when σ' reduces to a relatively low value, e.g. less than $0.1\sigma_0'$.

4.4 Volumetric Strain Ratio (R_v)

In this study, $\varepsilon_{v,0.9\sigma}'$ (i.e. $\varepsilon_{v,\sigma}'$ induced by 90% reduction of σ_0') is used to represent $\varepsilon_{v,\sigma}'$ in the calculation of R_v. Figure 6 shows the relationship between R_v:

$$R_V = \frac{\varepsilon^*_{v,air}}{\varepsilon_{v,0.9\sigma'}} \qquad (4)$$

in which $\varepsilon_{v,air}$ is represented by $\varepsilon^*_{v,air}$, at $LRR_{DA=5\%}$. Compared with $\varepsilon^*_{v,air}$ (Fig. 4, from Eq. 2), R_v shows better correlation with $LRR_{DA=5\%}$ (i.e. effect of soil types is minimized). This suggests that LRR is related not only on the strains caused by the compressibility of the pore air but also the stiffness of the soil skeleton.

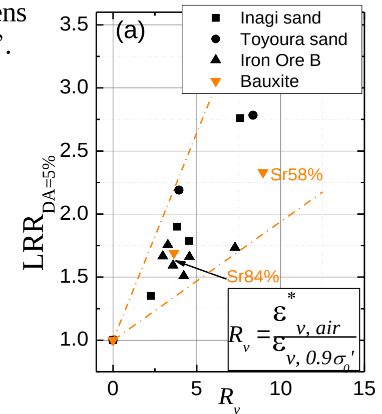

Fig.6 LRR vs R_v for various soils

5. CONCLUSIONS

LRR plotted against $\varepsilon^*_{v,air}$ results to a unique trend for clean sands while the data for soils with fines do not coincide

LRR plotted against a proposed index R_v minimizes the effect of soil types and exhibits a better correlation.

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