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学 位 論 文 要 旨
Dissertation Summary

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論　文　名: (Dissertation Title)　Liquefaction Resistance of Sand Lightly Treated with Enzymatically Induced Calcite Precipitation

炭酸カルシウム析出により改良した砂の液状化強度特性

Soil liquefaction during earthquake can result in severe damage to engineering structures. A wide range of ground improvement techniques have been developed for ameliorating the soil resistance to liquefaction and reducing possible damages. Those techniques include densification, solidification by cement, epoxy or silicates, dewatering, and replacement (Kitazume and Okamura 2010). Currently innovative methods as more environmentally friendly have emerged. One of these technologies is enzymatically induced calcite precipitation (EICP). This method uses urease enzyme instead of bacteria as a promoter for the hydrolysis of urea. Utilizing the urease enzyme itself, which causes Ca^{2+} and CO_3^{2-} to precipitate as $CaCO_3$ crystals in the void spaces and surface of grains, is more straightforward (Yasuhara et al. 2012). The expected reactions are as follows.

$$CO(NH_2)_2+2H_2O \xrightarrow[\text{enzyme}]{\text{Urease}} 2NH_4^{+}+CO_3^{2-} \quad (1)$$

$$CaCl_2 \rightarrow Ca^{2+}+2Cl^{-} \quad (2)$$

$$Ca^{2+}+CO_3^{2-} \rightarrow CaCO_3\downarrow(\text{precipitation}) \quad (3)$$

The applicability of this approach as a liquefaction mitigation had been examined by performing a series of experiment. The experimental results were benefitted to provide better understanding of the undrained cyclic behavior of a lightly treated sand using EICP. A series of undrained cyclic triaxial shear tests were conducted on the EICP-treated sands with testing parameters including particle size of the sand, confining pressure CP, calcite content *CC*, and degree of saturation during curing S_{rc}. The evolution in the liquefaction resistances R_L and the shear modulus G due to calcite precipitation were investigated systematically. Correlation between cyclic stress ratio (CSR) and the number of cycles (N) needed to reach 0.5% and 5% double amplitude (DA) axial strain as well as deformation

characteristic were compared for both untreated and treated sands. Laboratory data correlating R_L and G in the form of CRR-V_{s1} relationship was also compared with existing liquefaction assessment curves.

The results of the undrained cyclic triaxial shear test performing on EICP-treated sands show that there are two underlying mechanisms contributing to the improvement of the liquefaction resistance of the calcite precipitated sand. First, the precipitated calcite binds the sand grains which directly contribute to improving the mechanical properties. This bond is quite effective for reducing the strain and the excess pore pressure generation at the beginning of the cyclic loading up to the *DA* axial strain of approximately 0.5%, as shown in Figure 1. Initially, the *DA* increased very gradually, but after reaching approximately 0.5%DA, it developed a large axial strain in a small number of cycles showing that the beneficial effects of the calcite bond disappeared.

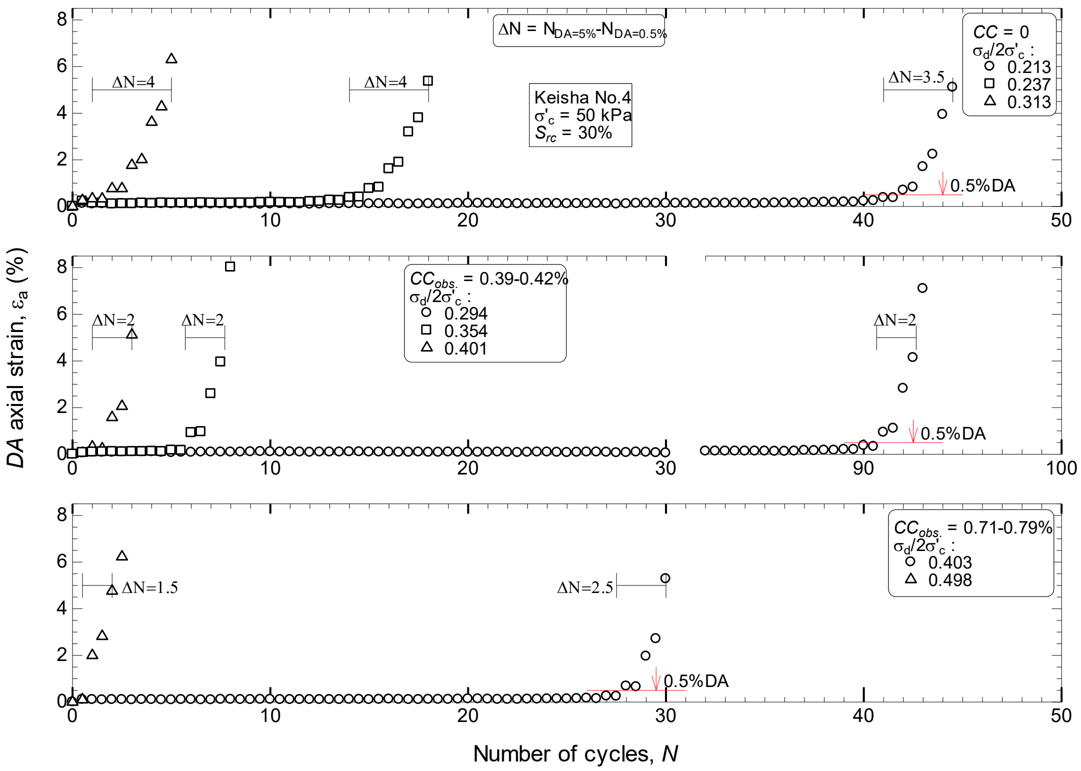

Figure 1 Development of *DA* axial strain with number of cycles (*N*)

Second, relative angularity provided by the precipitated calcite (calcite crystals) or the ratio of the crystal size to the grain size of the sand enhances the dilative nature of the calcite treated sands. The number of cycles needed to reach the failure criterion of 5%DA after attaining 0.5%DA depends significantly on the relative angularity. The higher the relative angularity, the higher the number of cycles needed to liquefy.

A significant difference in the angularity of the calcite precipitated sands of Keisha No.4 and Toyoura sand was observed using scanning electron microscopy (SEM) images. The size of the calcite crystal precipitated in the two sands is more or less the same, and the grain size of the Toyoura sand is approximately 5 times smaller than that of the Keisha No.4. Hence, the relative angularity provided by the calcite crystals is much higher for the treated Toyoura sand. This fact confirms that the liquefaction resistance of the calcite-precipitated sand depends on the grain size of the sand. For a certain amount of *CC*, the precipitation in the finer sand seems to be more effective than in the courser sand.

It is interesting to note that the amounts of the urea and $CaCl_2$ needed to obtain a given R_L can be significantly reduced by decreasing the S_{rc}. At low degree of saturation during curing, the precipitated calcite tends to congregate more at the inter particle contact points directly relating to the mechanical properties improvement. Microscopic observation using SEM images clearly revealed this advantage. It was confirmed that 1% of calcite precipitation at a low degree of saturation during curing could double the liquefaction resistance. However, excessive volumetric strain in the order of 1% degrades the bond between sand particles. With regards to the confining pressures, liquefaction resistance is more tangible in a low confining pressure, indicating significant improvement from the bond of the calcite, but it decreases with increasing in the confining pressures showing a clear stress level dependency.

Ground improvement using EICP approach at a low degree of saturation during curing is a novel and innovative technique in the area of civil engineering. In this method, liquefiable ground may be de-saturated by injecting air first and chemical agents in the form of solution are then injected. After allowing ample time for precipitation, air injection may be halted and degree of saturation becomes high again. Ground de-saturation using air injection for lowering the degree of saturation temporarily is originated by Okamura et al. (2011) which has primarily been developed as a liquefaction countermeasure. They indicated that the application of appropriate air pressures to the soil effectively expels pore water in the soil around the air injector, and the degree of saturation can be lowered to about 30% during air injection. Furthermore, the effectiveness of air injection together with chemical solution of EICP has been examined through numerical simulations (Umesh and Okamura, 2014).

In the other side, the small-strain shear modulus G_{max} increases with CC and CP, and decreases with S_{rc} irrespective of sand types. This increasing is approximately proportional to a power function "n" of confining pressure of around $n \approx 0.5$ for the untreated sands and less than that for the treated sands showing the improvement in their stiffness. The improvement by reducing the degree of saturation during curing was also observed revealing the effectiveness of calcite formation in the low S_{rc} as occurred in the liquefaction resistance of calcite treated sands. It was found that G_{max} increased more than 50% in the range of CC from 0 to 0.4% and the increasing rate slowed down for the larger range of CC, indicating that even smaller amount of calcite precipitation contributes to ameliorating G_{max}. For both sands tested of Keisha no.4 and Toyoura sand, G_{max} increased with CC in the same rate even though they have significantly different in particle size. The shear modulus G of the calcite-precipitated sand seems to be insensitive to the grain size in the small-strain level. In a high strain level of around 0.2%, however, G of the treated sands decreases sharply and comes close to that of the untreated sand.

Laboratory data of the calcite treated sands in the form of CRR-V_{s1} relationship was compared with existing liquefaction assessment curves as depicted in Figure 2. It shows that both the R_L and the G_{max} directly relating to the V_{s1} increase with increasing calcite content. The untreated sands data reside at around the curve separating liquefaction occurrence and no liquefaction zone prepared by Andrus and Stokoe (2000). While calcite treated sands data are positioned in the right side considerably apart from any empirical curves. It means that small amount of the precipitated calcite ameliorates significantly shear-wave velocity V_s bring up the specimen to the right side of the existing empirical relations. This is due to the nature of calcite precipitated sand that effects of calcite are much more significant on V_s than R_L particularly in the smaller range of CC. Laboratory data correlating liquefaction resistance and small strain shear modulus in the form of CRR-Vs1 relationship of calcite treated sands tend to show different trend with that of untreated sands and existing empirical prediction curves prepared by researchers. This fact reveals that the existing liquefaction assessment curves are not applicable for assessing *CRR* of the calcite treated ground.

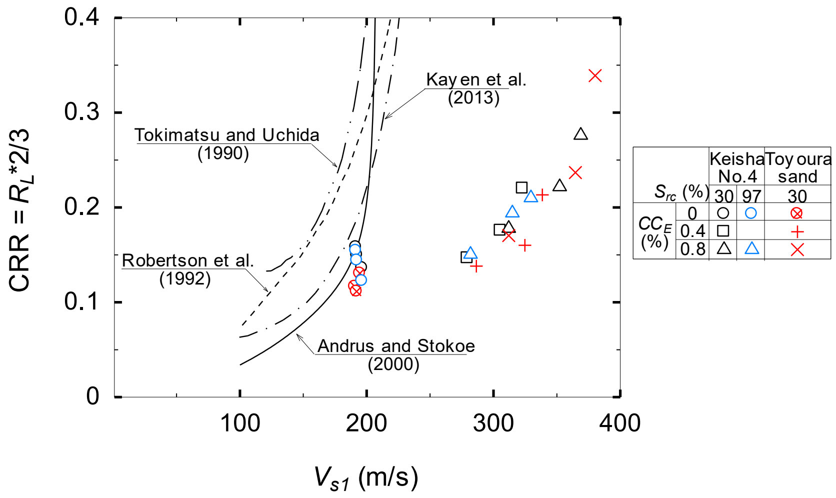

Figure 2 Relationship between *CRR* and V_{s1}