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Liquefaction resistance of sand remediated with carbonate precipitation at different degrees of saturation during curing

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Abstract

In recent years, innovative soil improvement methods have provided more environmentally friendly and sustainable solutions for liquefaction countermeasure techniques. One such technology is enzymatically induced calcite precipitation (EICP), in which urease enzyme is used, 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 $CaCO_3$ crystals in the void spaces and surface of grains, is more straightforward than using bacteria. In this study, the effects of the degree of saturation during the precipitation of calcite on the behavior of sand that has been lightly cemented using EICP were investigated through a series of undrained cyclic triaxial tests. Liquefaction strength curves correlating the cyclic stress ratio with the number of cycles needed to cause 5% double amplitude (DA) axial strain were compared for treated and untreated sand. It was found that the lower the degree of saturation during calcite precipitation and the higher the calcite content in the samples, the higher the liquefaction resistance of the EICP-treated sand. This can be clearly explained by the spatial distribution of the calcite in the sand. Microscopic observations by scanning electron microscopy (SEM) revealed that, in sand cured at a lower saturation degree, the precipitated calcite tended to be more concentrated at particle contacts than was the case in fully saturated sand. It was confirmed that only 1% of calcite precipitation at a lower degree of saturation (30%) can double the liquefaction resistance. However, excessive strain in the order of 1% degrades the bonding between sand particles.

Keywords: Soil improvement; Calcite precipitation; Degree of saturation; Triaxial test; Liquefaction resistance; Geotechnical engineering

1. Introduction

Soil liquefaction during earthquakes can result in severe damage to engineering structures. In order to ameliorate the soil resistance to liquefaction and thus reduce the potential for damage, a variety of ground improvement methods have been developed, including densification, solidification by cement, epoxy or silicates, dewatering, and replacement (Kitazume and Okamura, 2010). However, alternative techniques have emerged in recent years that may provide more environmentally friendly and sustainable solutions. One such innovative approach is the use of calcium carbonate (calcite) precipitation processes to bind soil particles. The enzymatic hydrolysis of urea, known as urease activity, is necessary for this process, and Bacillus pasteurii, a common soil bacterium with a highly active urease enzyme (Ferris et al., 1996), is used in the microbially induced calcite precipitation technique (MICP) (DeJong et al., 2006). However, it may be difficult to constrain the extinction and/or generation of living bacteria in natural environments, and the changes in the mechanical properties induced by this technique using

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microbial metabolism may not be sufficiently straightforward to be controlled (Yasuhara et al., 2012). Hayashi et al. (2010b) and Yasuhara et al. (2012) attempted to use the urease enzyme itself, instead of bacteria, to promote the hydrolysis of urea, and successfully produced calcite in sand. They confirmed enzymatically induced calcite precipitation (EICP) to be an effective means of improving the mechanical properties of sand in the same manner as MICP.

Irrespective of how the calcite is precipitated, microbially or enzymatically, the precipitated calcite improves the mechanical properties of sand. Laboratory tests on the mechanical behavior of calcite-precipitated sand have been carried out extensively, including unconfined compression tests, triaxial compression tests, and oedometer tests. With regard to drained triaxial tests at an effective confining pressure, of 100 kPa for instance, for a small amount of calcite precipitation of calcite content of $CC = 1\%$ and 3%, the shear strength of loose sands increased by 10–30% and 50%, respectively, where CC, calcite content, denotes the dry weight ratio of precipitated calcite to sand (Feng and Montoya, 2015; Hayashi et al., 2010b; Lin et al., 2016). As the precipitated calcite content increases further, clean sands become rock-like materials with an unconfined compressive strength, typically higher than several MPa (Chu et al., 2012; van Paassen et al., 2010; Yasuhara et al., 2012).

On the other hand, there has been little research conducted on undrained cyclic shear behavior, including liquefaction resistance and deformation characteristics. Hayashi et al. (2010a) studied the effects of calcite precipitation on the liquefaction resistance of sand in a triaxial apparatus at an initial effective confining pressure of 100 kPa. They observed a vast improvement in liquefaction resistance; the precipitation of $CC = 1.3\%$ and 3% doubled and tripled the liquefaction resistance, respectively. Montoya et al. (2013) also conducted cyclic direct simple shear tests and reported that, for $CC = 2.6\%$, the liquefaction resistance of a calcite-precipitated sand was approximately four times higher than that of untreated sand. These results strongly suggest that a small amount of precipitated calcite is capable of ameliorating the resistance to liquefaction of sand. Considering the fact that the execution cost of existing liquefaction countermeasure techniques is usually excessively expensive, the quantity of reagent solution used in the calcite precipitation is an important issue to be considered.

The spatial distribution of calcite in the treated soil has been microscopically observed using scanning electron microscopy (SEM). It was reported that the calcite crystals were widely distributed spatially, not only at the inter-particle contact points, but also over the entire particle surfaces (Al Qabany et al., 2012; DeJong et al., 2006; Feng and Montoya, 2015; Lin et al., 2016; Yasuhara et al., 2012). Cheng and Cord-Ruwisch (2012) and Cheng et al. (2013), noticed the importance of saturation degree on the distribution of calcite, and stated that, "For a low degree of saturation condition, air occupies most of the pore spaces, and the surface of grains is covered with absorbed MICP solution, which is predominantly concentrated at the inter-particle connection points, forming menisci shapes. Therefore, calcite precipitation occurred mainly at the contact points, which directly contributes to the strength improvement." They investigated the strength of sand treated with MICP at different degrees of saturation and confirmed that, for a similar CC, sand treated at low saturation conditions had a higher strength than that treated at fully saturated conditions. The necessary calcite content to exhibit an improved unconfined compressive strength for sand at a degree of saturation of 20% was only approximately one-third that necessary for sand treated at a fully saturated condition.

Although the effectiveness of calcite precipitation at a lower saturation degree condition may be apparent, it is necessary to lower the saturation degree of the sand because liquefiable soil is always in a condition of full saturation. Ground dewatering is a simple method to lower the degree of saturation temporarily. A further method, proposed by Okamura et al. (2011), is air injection, 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 a reagent solution of EICP has been examined through numerical simulations (Umesh and Okamura, 2014).

In the present study, the undrained cyclic shear behavior of sand that is lightly cemented with EICP is investigated, to understand the effects of degree of saturation during the precipitation process. Sand specimens were prepared at different degrees of saturation with EICP, and undrained cyclic triaxial shear tests were conducted. The range of calcite content studied in this study is lower than 1%, because only a limited number of tests on cemented sand in this range are reported in the literature, even though significant improvements in the liquefaction resistance may be anticipated. The morphology and spatial distribution of calcite at the microscale were analyzed with microscopic observation.

2. Precipitation test in test tube

Urease (Kishida Chemical Co., Ltd.: 020-83242) found in bacteria and in plants, such as sword beans, was used throughout this study. Urease enzyme hydrolyzes urea to produce carbonate ions, and the chemical precipitation of $CaCO_3$ takes place in the presence of calcium ions. The expected reactions to obtain the $CaCO_3$ precipitation are as follows.

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

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

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

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