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Failure behavior of cement-treated soil under triaxial tension conditions

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Abstract

Drained triaxial tension tests were conducted to investigate the tensile and shear failure behaviors of cement-treated soils under effective confining pressures. In the tests, tensile force was applied on saturated cement-treated soil specimens at effective confining pressures. The experimental result for a cement-treated soil shows that tensile failure occurred at low effective confining pressures, while shear failure occurred at high effective confining pressures. Based on experimental evidence, a failure criterion for cement-treated soil is discussed. In this study, tensile failure is assumed to be dominated by the effective minor principal stress and the Mohr-Coulomb failure criterion is adopted for shear failure. The observed stress states at failure lie on the failure criterion consisting of the tensile and shear failure surfaces, indicating that the proposed failure criterion is suitable for cement-treated soils. The experimental results provide a good understanding of the failure behavior of cement-treated soils that exhibit tensile and shear failure modes.

Keywords: Cement-treated soil; Triaxial tension test; Tensile failure; Shear failure; Failure criterion (IGC: D6)

1. Introduction

Ground improvement by cement mixing has been widely used for structural foundations, remediation methods against liquefaction and excavation supports in practical projects. Recently, column and wall shaped ground improvements have often been employed to reduce construction costs. In the design of column and wall shaped ground improvements, the tensile behavior of cement-treated soils becomes a predominant factor when external forces cause bending moments. Kitazume and Maruyama (2007) carried out centrifuge model tests for cement-treated soil columns subjected to embankment loading to investigate the failure mode of the columns. The results showed that bending tensile failure is induced in the cement-treated columns because of the embankment loading.

Lattice-shaped ground improvement by cement mixing has been developed as a method for mitigation of liquefaction. The performance of this method was demonstrated during the Hyogo-ken Nanbu earthquake in 1995 (Tokimatsu et al., 1996). Namikawa et al. (2007) conducted a finite element analysis of a lattice-shaped ground improvement for mitigation of liquefaction. The numerical results showed that tensile failure occurs at the corners of the lattice-shaped ground improvement during large earthquakes. Khosravi et al. (2016) conducted dynamic centrifuge tests to evaluate the effect of a soil-cement grid reinforcement on the seismic response of deep soft soil profiles. The experimental results showed that strong shaking events are likely to produce cracking in the soil-cement walls. These previous studies indicate that it is important to evaluate the tensile failure behavior of cement-treated

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soils in the design procedure of column and wall shaped ground improvements.

To assess the tensile failure behavior of ground improvement by cement mixing, the failure criterion of cement-treated soils must be determined based on experimental evidence under tensile loading conditions. In current design procedures (CDIT, 2002; BCJ, 1997), the tensile strength is used to assess the internal stability of ground improvement. The tensile strength is defined as the peak tensile stress applied to a specimen under simple tensile loading. A splitting tension test is often used to determine the tensile strength of cement-treated soils. However, the splitting tension test is not considered an element test because the stress condition is not strictly defined at boundaries (Namikawa and Koseki, 2007). A direct tension test is more appropriate for investigation of the tensile behavior of cement-treated soils. However, in the direct tension tests, the tensile behavior is normally measured under an unconfined pressure condition; therefore, the failure criterion under effective confining pressures cannot be provided. The laboratory test in which the stresses are well controlled in three dimensions is required to reveal the failure criterion of cement-treated soils under tensile loading conditions.

In the compression stress region, the failure criteria of geomaterials are normally determined using triaxial compression test results. Triaxial compression tests have been conducted to investigate the shear behavior of cement-treated soils under effective confining pressures (e.g., Kawasaki et al., 1981; Tatsuoka et al., 1997; Ismail et al., 2002). However, the failure criterion at the boundary between the tensile and shear failures cannot be determined from a triaxial compression test in which the mean effective stress is more than one-third of the axial stress. Therefore, the failure criterion of cement-treated soils has never been revealed at the boundary between tensile and shear failures.

Drained triaxial tension tests were conducted to investigate the mechanical behavior of cement-treated soils at the boundary between tensile and shear failures. Namikawa and Mihira (2007) and Namikawa and Hiyama (2014) conducted triaxial tension tests of cement-treated soils and revealed their tension behavior under effective confining pressures. However, those studies only provided experimental results for the tensile failure behavior of cement-treated soils. The present study provides an extension to those studies. The main objective of this study is to investigate the failure behavior of cement-treated soils around the region where the failure mode changes from tension to shear. The drained triaxial tension tests were conducted at effective confining pressures. The failure mode was determined from the stress-strain relationships and the fracture region appearing in the specimens after the failure. The triaxial tension test results for the cement-treated soil with an unconfined compressive strength q_u of 500 kPa show that tensile failure occurs at low effective confining pressures, while shear failure occurs at high effective confining pressures.

Based on the experimental evidence, a failure criterion for cement-treated soils is discussed. In this study, tension failure is assumed to be dominated by the effective minor principal stress and the Mohr-Coulomb failure criterion is adopted for shear failure. The stress states at failure obtained from the tests lie on the failure criterion consisting of tensile and shear failure surfaces, indicating that the proposed failure criterion is suitable for cement-treated soils. The experimental results provide a good understanding of the failure behavior of cement-treated soils that exhibit tensile and shear failure modes.

2. Experimental method

2.1. Specimen preparation

The cement-treated soils used in this study were prepared by mixing Toyoura sand, Portland cement, distilled water and Kaolin clay. The compositions of the cement-treated soils used are listed in Table 1. The specimens consist mainly of Toyoura sand, cement and water; the mechanical properties of the cement-treated sands were examined in this study. A small amount of Kaolinite clay was added to prevent separation of the cement-water paste from the aggregate.

Triaxial tension tests were conducted for two cement contents. The unconfined compressive strength q_u required in practical projects is generally, 300–2000 kPa approximately (Nozu, 2005; Porbaha et al., 2005). The mixing proportions shown in Table 1 was selected to prepare specimens with q_u of approximately 500 kPa for Case 1 and 1000 kPa for Case 2. Triaxial tension tests of the cement-treated sand with higher strength ($q_u = 2000$ kPa) have already been performed by Namikawa and Mihira (2007).

The specimens were prepared by the following procedure. All the materials shown in Table 1 are mixed thoroughly. The mixed materials are placed into a cylindrical mold of 140 (height) × 50 (diameter) mm and compacted with vibration. The specimen is cured under wet condition for 5 days. Thereafter the cylindrical specimen is trimmed to the specimen profile shown in Fig. 1. The specimen diameter is initially 50 mm and is reduced to 45 mm for a distance of 25 mm on either side of the center of the specimen, as seen in Fig. 1. The specimen is cured in de-aired water for 24 h to increase its saturation. In the drained triaxial tension tests, the specimen is consolidated for approximately 1 day; hence, the total curing time is 7 days. The

Table 1
Mixing properties of cement-treated soils.

Case	Water	Cement	Sand	Kaolin
1	18.7	4.5	71.2	5.6
2	18.6	7.0	69.3	5.0

Note: weight (%).