Mechanical properties of coral-silt composite soils evaluated on the basis of skeletal structure of coral gravels

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ABSTRACT

Coral gravel soils, which are composite soils consisting of finger-coral fragments and silt matrix, are often found in coastal regions of sub-tropical islands. In this study, for reconstituted soils with various coral gravel fractions up to 44% that was the densest package, a series of triaxial CU-bar and CD tests was conducted to study determination method for soil design parameters in consideration of interaction between soil skeleton consisted of coral fragments and silt matrix. The soil parameters were significantly influenced by volumetric percentage of coral fragments in association with particle interaction and particle crush, when the percentage was larger than 20% for the coral gravel soils examined in this study.

Keywords: coral gravel soil, triaxial test, soil skeleton, particle crush

1. INTRODUCTION

Coral gravel soil is a composite soil consisting of finger-coral fragments and silt matrix. In case of small content of coral fragments, the mechanical behavior is governed by silt matrix, but in case of large content of coral fragments, it is governed by coral fragments. In geotechnical engineering, generally, cohesion parameter \( c \) is used to evaluate undrained shear strength for soils with low permeability and angle of shear resistance \( \phi \) is used for soils to evaluate drained shear strength with high permeability. For the coral gravel soils; however, it has not yet been clarified how to determine the soil parameters \( c \) and \( \phi \) in design practice. The intrinsic mechanical performance for the coral gravel soils has not been studied because the coral fragments make trouble in collecting an undisturbed sample.

Soil samples collected by the conventional rotary type double-tube sampler from the construction site of the shore road are shown in Fig. 1. Because the sampler edge dragged the coral fragments while coring the samples, the collected soil samples were significantly disturbed.

In the present study, for reconstituted soils with various coral gravel fractions, a series of triaxial tests (CU-bar test and CD test) were parametrically conducted to study determination method for soil design parameters such as \( c \) and \( \phi \) in consideration of interaction between soil skeleton consisted of coral gravel fractions and silt matrix.

The coral gravel soils examined in this study were...
collected from the tidal flat on the coast of Urasoe City, Okinawa, Japan. The collected natural coral gravel soils were and sieved by 2 mm mesh to divide into coarse particles and fine particles.

For the silt matrix, the soil particle density was 2.76 g/cm$^3$ and the liquid limit was 22.9%; however, because plastic limit was not performed, the silt was classified into non-plastic. The grain-size distribution curve for the silt is shown in Fig. 2. The fine-grain fraction smaller than 0.075 mm was approximately 50%, and the clay fraction smaller than 0.005 mm was approximately 17% (smaller than 0.002 mm was approximately 13%). These were very typical ones for coral gravel soils found in Ryukyu Islands in Okinawa, Japan. For the coral gravel, most of them were consisting of fragments of finger corals with various shapes, diameters, and lengths (Fig. 3). Note here that there were many prominences on the surface as seen in the photograph.

2 SPECIMEN PREPARATION AND TRIAXIAL TESTS

Volumetric percentages of coral fragments for the specimens examined in this study were set to be 0%, 5%, 10%, 20%, 30%, and 44% as shown in Table 1. The volumetric percentage of coral fragments of 44% means the densest package of the coral fragments, i.e., the coral fragments form a strong skeletal structure. The silt matrix was prepared in a water content of 30% and filled up into the voids of the coral fragments. The sample ID shown in Table 1 was named reflecting the volumetric percentage of coral fragments and silt matrix following “C” and “S”, respectively.

After the triaxial cell was assembled, the cell was filled up by deaired water. The backpressure was set to be 200 kPa to make the specimen sufficiently saturated. Then the specimen was isotropically consolidated by a consolidation pressure of 50 kPa, and then the specimen was axially compressed for shearing under undrained condition for CU-bar test or drained condition for CD test. To meet both representative soil parameters of corresponding to undrained condition for low permeable soils and $\phi$ corresponding to drained condition for high permeable soils, two specimens were prepared for each mix proportion and one was examined by CU-bar test and the other one was examined by CD test. Note here that the consolidation pressure of 50 kPa was equivalent to the overburden effective stress at a depth of 5 – 6 m, because the bulk density of the coral gravel soils were in a range of 1.81 – 2.01 g/cm$^3$.

3 RESULTS OF THE TRIAXIAL TESTS

Test results of the triaxial CU-bar tests are shown in Fig. 4: (a) relationship between principal stress difference $q$ ($= \sigma_1 - \sigma_3$) and axial strain $\varepsilon_a$, and (b) excess pore pressure $\Delta u$ and axial strain $\varepsilon_a$. For the samples with smaller volumetric percentage of coral fragments such as C0S100, C5S95, and C10S90, principal stress difference significantly increased at the beginning, then it gradually increased or remained at almost constant at strains larger than 1%. Excess pore pressure increased at the beginning, and then it gradually decreased but remained in positive value. These behaviors are generally observed for normally consolidated clayey soils. On the other hand, for the samples with larger volumetric percentage of coral fragments such as C30S70 and C44S56, principal stress difference significantly increased at the beginning, then it gradually increased or remained at almost constant at

| Sample | Percentage of coral fragments in volume | Percentage of silt matrix in bulk volume | Bulk density | Water content |
|--------|----------------------------------------|------------------------------------------|--------------|--------------|
| C0S100 | 0%                                     | 100%                                     | 1.81 g/cm$^3$| 29.8%        |
| C5S95  | 5%                                     | 95%                                      | 1.82 g/cm$^3$| 26.6%        |
| C10S90 | 10%                                    | 90%                                      | 1.86 g/cm$^3$| 24.5%        |
| C20S80 | 20%                                    | 80%                                      | 1.89 g/cm$^3$| 22.2%        |
| C30S70 | 30%                                    | 70%                                      | 1.95 g/cm$^3$| 19.1%        |
| C44S56 | 44%                                    | 56%                                      | 2.01 g/cm$^3$| 16.3%        |
strains larger than 5%.

For the samples with volumetric percentage of coral fragments larger than 30%, although the excess pore pressure increased at the beginning, it changed to decrease with strain larger than 1% and became negative value at strain larger than 2%. In particular for C44S56, very significant negative excess pore pressure was observed, e.g. −120 kPa at strain of 15%. C44S56 showed significantly large shear strength corresponding to the closed drainage valve from the specimen although the skeletal structure of coral fragments significantly tended to dilate with shearing. Because the perfect undrained condition like the CU-bar tests is not realistic for the in situ coral gravel soils, the significant negative excess pore pressures observed in the CU-bar tests are thought to be overestimated. Therefore, for the samples with dense package of coral fragments such as C44S56, the undrained shear strengths obtained from the CU-bar tests were overestimated, resulting in an unfavorable design.

Very significant jagged variation was observed during the shear test for C44S56. This jaggy was probably caused by particle crush of coral fragments, which resulted in a momentary decrease in the principal stress difference. This is consistent with the jagged behavior caused by particle crush as reported in the DEM simulation for crushable soils in Lobo-Guerrero and Vallejo (2006). Similar behavior was also observed for C30S70, as well as C20S80, indicating that some coral fragments contacted each other and crushed during the shear test. Therefore, whether coral fragments contact each other or not can be judged with the threshold value in the volumetric percentage of coral fragments of 20%.

The test results of the triaxial CD tests are shown in Fig. 5: (a) relationship between principal stress difference $q (= \sigma_1 - \sigma_3)$ and axial strain $\varepsilon_a$, and (b) excess pore pressure $\Delta u$ and axial strain $\varepsilon_a$. Similar to the results of CU-bar tests, the maximum principal stress difference tends to increase with increase of volumetric percentage of coral fragments, particularly for C44S56 with densest package forming a strong skeletal structure.

For the samples with volumetric percentage of coral fragments less than 10%, volume compression was observed in the entire process of shear test up to the strain of 15%. For the samples with volumetric percentage of coral fragments of 20% and 30%, volume compression was observed at the beginning, but it changed to volume expansion at larger strains, however, the observed value was very small. For the sample C44S56, very significant volume expansion was observed after a slight volume compression at the beginning. This remarkable volume expansion, i.e., dilation, resulted in a significant strain softening.

In the relationship between principal stress difference and axial strain, for the samples with volumetric percentage of coral fragments less than 10%, very smooth curves were observed; however, for the samples with volumetric percentage of coral fragments larger than 20%, some jagged variation was observed, particularly for C44S56.

Relationships between the maximum principal stress difference and volumetric percentage of coral fragments obtained from both the CU-bar and CD tests are plotted in Fig. 6. In the previous figures (Figs. 4 and 5), a typical data set for each sample was selected and plotted to simplify the graphs; however, because two or three specimens for each sample were examined, all the test results were plotted in Fig. 6. In both the CU-bar and CD tests, shear strength slightly increased with increase of volumetric percentage of coral fragments up to 20%, but it significantly increased with that larger than 20%.

For the samples with volumetric percentage of coral fragments less than 20%, the maximum principal stress difference $q_{\text{max}}$ obtained from the CD tests was slightly larger than that obtained from the CU-bar tests. The tendency is consistent with both the positive excess pore pressure in the CU-bar tests and the volumetric percentage of coral fragments larger than 30%, although the excess pore pressure difference and axial strain, for the samples with volumetric percentage of coral fragments larger than 30%, although the excess pore pressure difference and axial strain, for the samples with volumetric percentage of coral fragments larger than 30%, although the excess pore pressure difference and axial strain, for the samples with volumetric percentage of coral fragments larger than 30%, although the excess pore pressure difference and axial strain, for the samples with volumetric percentage of coral fragments larger than 30%, although the excess pore pressure difference and axial strain, for the samples with volumetric percentage of coral fragments larger than 30%.
compression in the CD tests corresponding to the loose package of the silt matrix. The slight densification during the CD tests is the reason for the larger shear strength; however, the difference between those two test series was very small. This small difference was consistent with the small difference in stress paths between CU-bar and CD tests. Note here that, if the silt matrix is in loose package like the samples examined in this study, the undrained shear strength obtained from the CU-bar tests should be primarily used for design.

For samples with volumetric percentage of coral fragments larger than 20%, the shear strengths obtained from the CU-bar tests were significantly underestimated because of the unrealistically large negative excess pore pressure, i.e. unrealistically large effective stress in the field, resulting in the unrealistically large shear strength. The shear strengths obtained from the CD tests also show the similar tendency corresponding to volume expansion; however, these are much smaller than those obtained from the CU-bar tests. From the point of view of determination of soil design parameters, for sample C44S56, the undrained shear strength obtained from the CU-bar test was too large to be used in design, because the too large strength was caused by the unrealistically large negative pore pressure. In consideration of this fact, the drained shear strength should be used in design for the sample with abundant coral fragments (volumetric percentage of coral fragments larger than 20% in this study).

Relationship between the maximum and the residual values of stress ratio, $(q/p')_{\text{max}}$ and $(q/p')_{\text{res}}$, respectively, and volumetric percentage of coral fragments, and the relationship between their ratio, $(q/p')_{\text{res}}/(q/p')_{\text{max}}$, and the volumetric percentage for the CD tests are shown in Fig. 7. For the samples with dense package of coral fragments, which form a skeletal structure, the stress ratio $q/p'$ became larger than 2 (shear resistance angle larger than 50°). This value is significantly larger than that for normal soils. This larger shear resistance angle is probably caused by the high angularity of coral fragments with abundant prominences on the particle surface as shown in Fig. 3.

The plots of $(q/p')_{\text{max}}$ can be approximated as a moderate concave curve, the plots for $(q/p')_{\text{res}}$ can be approximated as a moderate convex curve, and the plots for $(q/p')_{\text{res}}/(q/p')_{\text{max}}$ can be approximated as a convex curve with a peak value. Similar to the tendency for the maximum principal stress difference $q_{\text{max}}$, the stress ratios $(q/p')_{\text{max}}$ and $(q/p')_{\text{res}}$ increase with volumetric percentage of coral fragments. In addition, when the volumetric percentage of coral fragments increased over 20%, the difference between $(q/p')_{\text{max}}$ and $(q/p')_{\text{res}}$ became significant, in particular, the residual value was approximately 15% smaller than the maximum value for the volumetric percentage of coral fragments of 44%.

### 4 OBSERVATION OF INTERNAL FABRIC BY CT SCANNER

For the samples with volumetric percentage of coral fragments of 5% (CSS95), 20% (C20S80), and 44% (C44S56), internal fabric and structure of the samples before and after the shear tests were observed by CT scanner, and the CT images are shown in Fig. 8. In the CT images with 256 grayscale, light and dark colors indicate high and low densities, respectively. Because the coral fragments used in this study were from a sort of finger corals as shown in Fig. 3, cross sections of coral fragments can be identified as circular or ellipsoidal shapes and longitudinal sections of coral fragments can be identified as long grains. Some of finger coral fragments had branched shapes.

In CSS95 with small amount of coral fragments, it can be confirmed that the coral fragments were not crushed even after the large deformation, because each coral fragment was isolated from the others. In C44S56 with abundant coral fragments in the densest package, almost all of the coral fragments contacted to others, and it can be confirmed that most of them were crushed.
by the large deformation. The particle crush can be identified in the CT images as cracks, which is seen as thin black lines in the coral fragments. From these observations focusing on the particle crush in the CT-images, it is evidenced that the jaggy variation in the stress–strain relationship observed in Figs. 4a and 5a was associated with the crushing of coral fragments.

In C20S80 with volumetric percentage of coral fragments of 20%, most of the coral fragments almost contacted to some others and it can be confirmed that some coral fragments were crushed by the large deformation. Therefore, it can be said that, in determination of shear strength for coral gravel soils, not only the interparticle contacts but also the particle crush of coral fragments has to be considered.

5 SUMMARY

The present paper examined the mechanical characteristics of coral gravel soils consisting of coral fragments and silt matrix. In both the CU-bar and CD tests, shear strength significantly increased with increase of volumetric percentage of coral fragments larger than 20%. For samples with volumetric percentage of coral fragments larger than 20%, particularly 44% that is the percentage for the densest package, the shear strengths obtained from CU-bar tests were significantly overestimated as design parameter, because these large strengths were derived from unrealistically large negative excess pore pressure caused by significant dilatancy. The shear strengths obtained from the CD tests were much smaller than those obtained from the CU-bar tests. In consideration of this fact, the drained shear strength should be used in design for the samples with dense package of coral fragments. Significant jagged variation observed during shear test for the samples with volumetric percentage of coral fragments larger than 20% was caused by particle crush, which was visually evidenced through CT-images observed before and after the triaxial tests. In evaluation of the shear strength for coral gravel soils, the interparticle contact as well as the particle crush is one of the key factors governing the shear strength.

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