Characteristic behavior in long-term consolidation for subtropical soils

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ABSTRACT

When a long-term consolidation test is conducted for a soft soil sample collected from a coastal area in Ryukyu Islands, Okinawa and Kagoshima Prefectures, Japan, a noticeable delayed settlement may occur during secondary consolidation, which sequentially occurs after primary consolidation. Such behavior is apparently similar to the “delayed consolidation” generally observed in long-term consolidation under a consolidation pressure between the overburden effective stress and the consolidation yield stress for slightly overconsolidated clayey soils. The “delayed consolidation” for clayey soils can be explained by the isotache concept that is derived from strain rate dependency of compression curves. However, because the soils collected from the coastal area in Ryukyu Islands are cohesionless and consisting of fine coral soils without viscosity, the isotache concept which is strongly related to viscosity should not be applicable. Therefore, the delayed settlement during the secondary consolidation is thought to be caused by factors other than viscosity. In this study, a series of long-term consolidation tests was conducted for reconstituted soil specimens with different grain-size distribution curves collected from Nakagusuku Bay Port in Okinawa. As a result, it was shown that delayed settlement during secondary consolidation for soft soils in the coastal areas can be explained by the effect of particle crushing.

Keywords: long-term consolidation, delayed settlement, particle crushing

1 INTRODUCTION

When a long-term consolidation test is conducted for a soft soil sample collected from a coastal area in Ryukyu Islands, Okinawa and Kagoshima Prefectures, Japan, a noticeable delayed settlement may occur during secondary consolidation, which sequentially occurs after primary consolidation. Such behavior is similar to the “delayed consolidation” generally observed in long-term consolidation under a consolidation pressure between the overburden effective stress and the consolidation yield stress for slightly overconsolidated clayey soils. The “delayed consolidation” for clayey soils can be explained by the isotache concept (Šuklje, 1957) that is derived from strain rate dependency of compression curves (Watabe et al. 2012). However, because the soils collected from the coastal area in Ryukyu Islands are consisting of fine coral soils without viscosity, main mineral of the soil particles are consisting of aragonite (Watabe et al. 2015). Therefore, the isotache concept which is strongly related to viscosity should not be applicable to the delayed settlement for the soils in Ryukyu Islands.

Because coral reefs are widely developed in the subtropical coastal area, biological remains such as coral fragments and foraminifera are accumulatively deposited around Ryukyu Islands. In other words, the soft soils in Ryukyu Islands are composed of coral fragments with silt/sand matrix (Watabe et al. 2015; 2017). The minerals of those calcareous particles originated from coral fragments and foraminifera are mainly aragonite and calcite, respectively. Because calcareous sand/silt is a friable material, it may tend to show a progressive additional settlement as a result of particle crushing with increase of compressive stress. This behavior is essentially different from the original meaning of consolidation, but should be related to delayed settlement during secondary consolidation.

From the background mentioned above, in this study, the authors experimentally confirmed whether such delayed settlement during secondary consolidation occurs or not due to particle crushing. More specifically, reconstituted soil specimen was prepared by adjusting grain-size distribution by mixing of fine and coarse particles collected from segregated fine and coarse soil portions at a reclamation site, where dredged clayey soils were dumped into the construction site of Awase Artificial Island in Nakagusuku Port, Okinawa, Japan. Then, long-term consolidation test was conducted for the soil mixtures in the laboratory of the Port and Airport Research Institute, Yokosuka, Japan. Based on the test results, the delayed settlement was examined focusing on the effect of particle crushing.
2 TEST PROCEDURE

Clay sample and sand sample were collected at different point nearby of the land reclamation site of Awase Artificial Island of Nakagusuku Port, Okinawa city, and respectively sieved passing through 2-mm mesh. The clay sample mainly contains fine particles smaller than 0.075 mm and the sandy sample only contains coarse particles as remains on a 0.075-mm sieve. Soil particle densities of clay and sand samples were 2.75 Mg/m$^3$ and 2.81 Mg/m$^3$, respectively.

To examine variety of soils with different grain-size distribution curves from clay to sand, five different soil samples were prepared adjusting mix proportion in dry mass ratio of clay to sand (Clay : Sand of 100:0, 75:25, 50:50, 25:75 and 0:100). Water content of each soil sample was set as follows: equivalent to the liquid limit (58.44%) for 100:0, and proportional to clay mix ratio (0.75 and 0.5 times of 58.44% for the samples of 75:25 and 50:50, respectively). Water content for the samples of 25:75 and 0:100 were not adjusted because original value was higher than the calculated value in the above method. Soil samples and test conditions are summarized in Table 1. A clayey soil sample (100:0, 75:25 and 50:50) in slurry state was molded into an oedometer ring with a collar; incrementally loaded up to 40 kPa; tentatively unloaded and trimmed into the height of the oedometer ring (20 mm) after removal of the collar. A sandy soil sample (75:25 and 0:100) was molded into an oedometer ring (20-mm height) without collar. The prepared soil specimen was set into the oedometer; incrementally loaded up to 160 kPa as preliminary consolidation stage; then the target consolidation pressure (640 or 1280 kPa) was loaded as long-term consolidation stage.

A grain-size distribution test consisting of sedimentation test and sieving test was conducted before and after the long-term consolidation test to investigate the effect of particle crushing on delayed settlement during the long-term consolidation behavior.

3 TEST RESULTS

3.1 Long-term consolidation test

Consolidation curve ($\varepsilon - \log t$ curve) for clayey samples (sand fraction less than or equal to 50%) and sandy samples (sand fraction larger than or equal to 75%) is shown in Figs. 1 and 2, respectively.

![Fig. 1. Consolidation curves for clayey samples with sand content smaller than or equal to 50%.](image1)

![Fig. 2. Consolidation curves for sandy samples with sand content larger than or equal to 75%.](image2)

Table 1. Test conditions for long-term consolidation tests.

| Dry mass ratio of clay to sand (Clay : Sand) | Preliminary consolidation pressure (kPa) | Long-term consolidation pressure (kPa) |
|--------------------------------------------|----------------------------------------|--------------------------------------|
| 100:0                                      | 640                                    |
| 100:0                                      | 1280                                   |
| 75:25                                      | 640                                    |
| 75:25                                      | 1280                                   |
| 50:50                                      | 640                                    |
| 50:50                                      | 1280                                   |
| 25:75                                      | 640                                    |
| 25:75                                      | 1280                                   |
| 0:100                                      | 640                                    |
| 0:100                                      | 1280                                   |

Consolidation curves for clayey samples with higher clay content (larger than or equal to 75%) show S-shaped primary consolidation curve which transitioning from convex to concave shape. The curve for sample of dry mass ratio of clay to sand of 75:25 under a consolidation pressure of 640 kPa shows the largest settlement, but this large settlement is something strange and probably due to stuck of the loading piston in the preliminary consolidation stage. Consolidation curves for sandy samples with smaller clay content (smaller than or equal to 25%) show instantaneous settlement just after the loading, even for the sample with dry mass ratio of clay to sand of 50:50. In addition, settlement in strain during the long-term consolidation...
was almost smallest both in clay sample (100:0) and sand sample (0:100). Normally, if fine particles are consisting of clay minerals such as kaolinite, illite or smectite with flaky or platy particles, the larger content of clay particles results in the larger settlement because clay mineral particles form a bulky structure. However, in this study, because fine particles are consisting of round shape particles derived from coral fragment fracturing, clay sample and sand sample have almost the same void ratio.

For the sandy samples with sand content larger than or equal to 75%, the relationships show convex curves after the end of primary consolidation (EOP) at approximately 100 seconds and after, while for the clayey samples with sand content smaller than or equal to 50%, the relationships show almost straight lines after the end of primary consolidation at approximately 1000 seconds and after.

![Consolidation curves offset at the end of primary consolidation for samples with sand content smaller than or equal to 50%.](image1)

![Consolidation curves offset at the end of primary consolidation for samples with sand content larger than or equal to 75%.](image2)

Because time and settlement at the end of primary consolidation are different for each test condition, the end of primary consolidation was defined at the intersection of the extrapolated lines of linear portion during primary consolidation stage and the linear portion in the beginning of the secondary consolidation stage in the consolidation curve. In order to directly compare the test results, the consolidation curves shown in Figs. 1 and 2 are offset in elapsed time and strain at the end of primary consolidation, and the consolidation curves are redrawn in Figs. 3 and 4, respectively.

The curves show unusual shape in the initial portion of these curves due to the effect of the offset. When the elapsed time exceeds 500 seconds, however, the sandy samples with sand fraction larger than or equal to 75% show linear relationship for a while but change to significant delayed settlement with convex shape after the elapsed time over 1×10^6 seconds (about 12 days). While the clayey samples with sand fraction smaller than or equal to 50% show almost linear or slightly convex shape.

For the sandy samples, the delayed settlement seen against the logarithm of the elapsed time tends to show concave curve when the elapsed time exceeds 1×10^7 seconds (about 116 days), and then gradually converges to a final settlement.

### 3.2 Grain size distribution test

Sedimentation test and sieving test were sequentially conducted to obtain grain size distribution curve for the samples both before and after the long-term consolidation test. Grain size distribution curves were obtained for samples with dry mass ratio of clay to sand of 0:100, 25:75 and 75:25 are shown in Figs. 5, 6 and 7, respectively.

In all the samples, the proportion of small particle sizes increased after the test even for the clayey sample with dry mass ratio of clay to sand of 75:25. This indicates that particles crushed during the long-term consolidation test.

In the sand sample (0:100) in Fig. 5, increase of fine particles smaller than 0.075 mm, which were not originally contained before the long-term consolidation, is remarkable. This fact indicates that particle crushing was mainly occurred in coarse particles. Similar tendency was observed in the sandy sample (25:75) in Fig. 6. On the other hand, in the clay sample (100:0) in Fig. 7, fine particles increased even though coarse particles were almost not contained before the long-term consolidation test. These results indicate that coarse soil particles tend to be crushed by high contact pressure due to a limited number of particle contacts; however, if coarse soil particles are surrounded by fine particles, smaller particles tend to be crushed rather than coarse particles, resulting in smaller settlement in strain as a time-consuming behavior caused by fine particle crushing.
In the present study, a series of long-term consolidation tests was conducted for reconstituted soil samples as mixtures with different dry mass ratio of clay to sand (clay:sand of 100:0, 75:25, 50:50, 25:75 and 0:100). The main conclusions derived from this study are written hereunder.

1) Sandy samples with a sand content of larger than or equal to 75% in this study showed significant delayed settlement with concave shaped consolidation curve from around $1 \times 10^6$ seconds (about 12 days), and then, when the elapsed time exceeded $1 \times 10^7$ seconds (about 116 days), the consolidation curve transitioned to convex shaped curve with showing a tendency of convergence into a certain value.

2) The proportion of small particle sizes increased after the long-term consolidation test, particularly in the sandy samples. This is due to particle crushing during the long-term consolidation test.

3) Consequently, it was found that the cause of delayed settlement during consolidation in the soft ground deposited at coastal area in Ryuku Island is due to particle crushing of coral-derived soil particles.

**ACKNOWLEDGEMENTS**

This study was carried out as collaborative research among Hokkaido University and Okinawa General Bureau, Cabinet Office, Government of Japan. Long-term consolidation tests were conducted in the laboratory at Port and Airport Research Institute.

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