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Creep of calcareous sand in Tunisia: effect of particle breakage at low stress level

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Abstract

Aims/hypothesis: One of the critical mechanisms determining creep in granular materials is the breakage of soil particles. This study aims at evaluating the time-dependent creep deformation of calcareous sand at low effective stress conditions.

Methods: K_0 creep tests were performed for both calcareous and silica sands at low stresses of 65 and 120 kPa, and the results of creep tests were compared with the results of constant rate of strain (CRS) tests at high stress levels up to 12 MPa. For a quantitative evaluation of the effect of the particle breakage on the creep deformation of calcareous sand, the relative breakage (B_r) was determined based on the results of sieve analyses.

Results: The results demonstrate that Tunisia calcareous sand experiences significant particle breakage during creep and the consequent creep deformation at low stress level. The determined B_r after creep at low stress level is comparable with that after the CRS test at high stress level.

Conclusions: High potential of particle breakage inherited by characteristic mineralogy of the calcareous Tunisia sand significantly influences the creep deformation at low stress level.

Keywords: Creep, Particle breakage, Calcareous sand, Relative breakage

Introduction

Creep phenomenon, which is the continuous deformation of soils under constant effective stress condition, greatly affects the engineering behaviors of soils, including the long-term ground settlement; therefore, the creep in fine-grained soils has been the research topic of many previous studies [1]. In contrast, studies on the creep in coarse-grained soils have been relatively limited [2–4]. One possible mechanism determining creep in coarse-grained soils (e.g., sand) is the breakage of soil particles under heavily loaded conditions (> 1 MPa) [3, 5, 6]. However, in the case of calcareous sand, the particle breakage can initiate at relatively low effective stress condition because of its characteristic mineralogy. This study aims at investigating time-dependent creep deformation of calcareous sand at low effective stress conditions. To link the creep behavior of calcareous sand with the particle breakage, one-dimensional K_0 compression test was performed first, and the sieve analysis was followed.

Methods

Particle breakage

The breakage of sand particles or particle breakage is affected by a number of factors, including particle size, shape of particles, particle size distribution, void ratio, confining stress level, mineralogy, time, and others [7, 8]. To quantify the degree of particle breakage, the relative breakage (B_r), which was defined by [Hardin [7]] as the ratio between the total breakage measured by the area between particle size distribution curves before and after loading and the breakage potential measured by the area between the particle size distribution curve before loading and the vertical line of 0.075 mm, was employed in this study.

Materials

Tunisia sand, which is the calcareous sand sampled near the lake of Tunis, Republic of Tunisia is used in this study. Tunisia sand is the well-graded angular sand with median diameter of 1.00 mm, specific gravity of 2.75, uniformity coefficient of 12.00, maximum void ratio of 0.77, and minimum void ratio of 0.44. The results of X-ray fluorescence (XRF) analysis revealed that Tunisia sand is mainly composed of 2.6% SiO_2 and 44.8% CaO. The XRF analysis also showed that Tunisia sand has 44.4% LOI (loss-on-ignition), which likely indicates the existence of considerable amount of organic matter. For control experiments, Jumujin sand, which is Korean standard silica sand (89.2% SiO_2), was also comparatively tested. Jumunjin sand is the uniform angular sand with median diameter of 0.43 mm, specific gravity of 2.62, uniformity coefficient of 1.47, maximum void ratio of 0.93, and minimum void ratio of 0.65. Jumunjin sand has only 0.38% LOI obtained from the XRF test. Note that every soil samples were oven-dried to avoid the effect of water-induced chemical reaction on the creep deformation.

Testing methods

K_0 creep tests were performed using the oedometer cell with internal diameter of 100 mm. Sand specimens with initial relative density of 30% was prepared by air pluviation. The vertical load was applied in the oedometer cell in a staged manner until the targeted vertical effective stress (σ_v') for creep test was achieved. The creep tests at the constant σ_v' of 65 and 120 kPa for 23 days or 33,120 min were performed. To investigate the behavior of soils under high stress level, the constant rate of strain (CRS) tests were conducted at a constant displacement rate of 0.02 mm/min until σ_v' reached 1, 2.5, 8, or 12 MPa. Using the results of sieve analysis on the soil samples after each CRS test, the relative breakage (B_r) can be evaluated at σ_v' of 1, 2.5, 8, and 12 MPa. Note that there was no period of creep at the end of the CRS test.

Results and discussion

Time-dependent deformation at low confining stress

Figure 1a compares the particle size distribution (PSD) curves of the soil samples before loading and after creep at 65 and 120 kPa. As can be seen in Fig. 1a, noticeable shift of PSD curves after creep is not observed in Jumunjin sand but pronounced

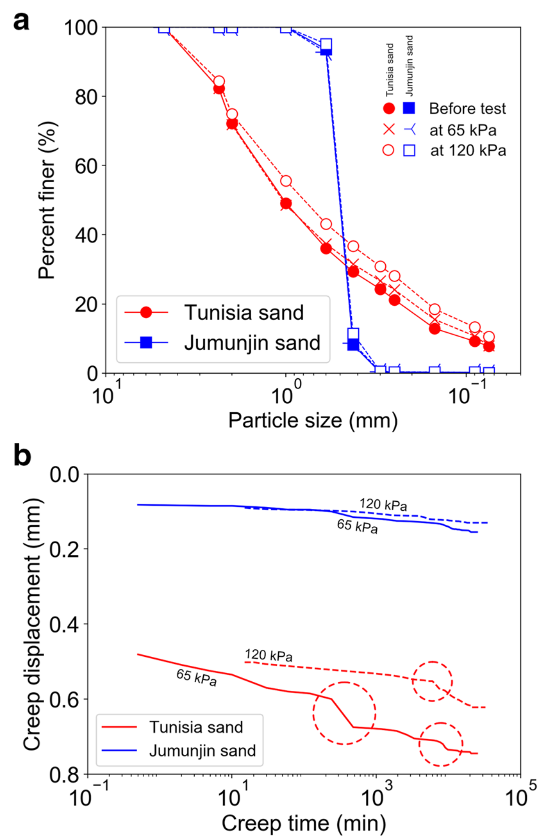

Fig. 1 Creep behaviors of Tunisia and Jumunjin sands at low stresses: **a** Change in particle size distribution curve; **b** Creep displacement during creep

in Tunisia sand indicating the significant amount of the particle breakage even at the relatively low stresses [3, 9]. It is also noted that Vesic and Clough [10] found that the particle crushing of silica sand at low confining stress level in the order of 100 kPa is minimal. Figure 1b shows the change in the vertical displacement during K_0 creep at the constant σ_v' of 65 and 120 kPa. Unlike to Jumunjin sand, Tunisia sand exhibits a high number of kinks in the curves of the creep displacement. To understand this irregularity from a mechanical viewpoint, it is worth noticing Ter-Stepanian [11] who described a stochastic nature for the creep deformation of which the rate is not necessarily uniform owing to the particulate nature of soils governed by forces at randomly oriented interparticle contacts. During creep, any small perturbation in applied load at the contacts or time-dependent loss in material strength can lead to sliding, breakage or yield at asperities. It is evident that the particle breakage, which is also initiated at the randomly oriented interparticle contacts, significantly renders jump-like and non-uniform change in the creep deformation in Tunisia sand. Note that the magnitude of the creep displacement in Fig. 1b is higher at 65 kPa than at 120 kPa under K_0 condition, which could be explained by higher potential of particle rearrangement induced by interparticle frictional sliding at lower contact normal force in a very loose sand subjected to a lower confining pressure.

Carbonate sands are considerably softer than quartz, and consequently the grains of carbonate sands can crush relatively easily [12, 13]. In fact, particle breakage for calcareous sands can continue for a long time under constant stress levels because of the usually well graded PSD curves and so the wide dispersion of magnitudes of the real inter-particle contact forces, on itself varying all the time due to local crushing and particle displacement.

It is of great interest that the soil particles of the Tunisia calcareous sand can be crushed at such a low stress level whereas the particle breakage usually occurs at very high stresses. Figure 2 shows the variation of B_r as a function of $\sigma_v^{'}$ for K_0 creep test and CRS test in Tunisia and Jumunjin sands. The value of B_r in Tunisia sand reaches 0.17 at the high vertical stress of 12 MPa in the CRS test. Previous study of [Choo et al. [14]] shows that the yield stress of Tunisia sand is approximately 1 MPa, and thus high values of B_r obtained from the CRS tests logically reflect the process of particle breakage caused by continuous supply of external fracture energy [9, 15]. Surprisingly, B_r values of 0.07 and 0.14 even at the constant low stress of 65 kPa and 120 kPa in the K_0 creep tests are comparable with those of CRS test at very high stresses of the order of 10 MPa. Static fatigue at the interparticle contacts [9] is likely to explain the particle breakage during creep at low stresses in Tunisia sand which is composed of weak angular calcareous sand particles and soft organic matter. Therefore, it can be concluded that characteristic creep response of Tunisia sand is significantly governed by particle breakage during creep at low stress level.

Conclusions

This study aims at investigating the creep of calcareous sand at low stress conditions. To link the creep behavior of calcareous sand with the particle breakage, one-dimensional K_0 creep test was performed. For comparison, the CRS tests were conducted until the compressive stress reached very high values. The values of relative breakage

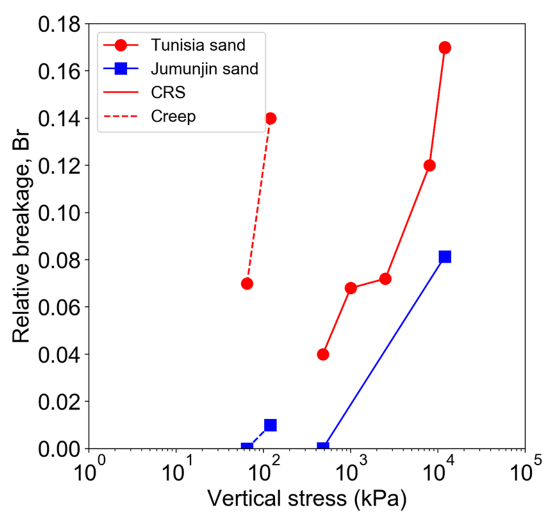

Fig. 2 Variation of relative breakage as a function of vertical stress for creep and CRS tests

were evaluated using the results of sieve analysis on the samples after each K_0 creep test and CRS test. The key observations of this study are as follows:

1. Tunisia calcareous sand experiences significant creep deformation at very low stress level of the order of 100 kPa mainly due to considerable amount of particle breakage. In contrast, Jumunjin silica sand with negligible particle breakage at very low stress level exhibits insignificant creep deformation.
2. The value of relative breakage of the Tunisia sand after the creep test at low stress level of the order of 100 kPa was comparable with that after the CRS test at high stress level of the order of 10 MPa, which reflects that the creep phenomenon at low stress level can be significant for tested calcareous sand with weak and soft particles.

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Authors' contributions
MK and LTB performed experiment presented in this manuscript. HC deduced the values from experimental results and wrote an initial manuscript. The corresponding author YHJ supervised the experiment and completed this manuscript. All authors contributed to the final version of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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