Cyclic behavior of fiber reinforced sand with different shape of particles

Liquefaction, cyclic triaxial test, reinforced sand

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1. Introduction

In recent years, several ground improvement methods using fibers as a reinforcing material have been developed. From previous studies it is obvious that the fibers are effective in increasing the compressive strength of soils, while there are some limitations in tensile strength enhancement. Several studies have also investigated the dynamic behavior of fiber-reinforced soils. Some research showed that the addition of fibers improved the damping capacity of soils [1,2], which reduced the potential for soil liquefaction during earthquakes. Additionally, the presence of fibers increased the energy dissipation capacity of soils, which mitigated the effects of seismic waves. However, it is important to note that the dynamic behavior of fiber-reinforced soils can be influenced by several factors, including the type of fiber, fiber content, and distribution of fibers within the soil matrix. Therefore, it is important to conduct comprehensive testing to understand the dynamic behavior of specific fiber-reinforced soil mixes.

For this purpose, a series of cyclic shearing tests were performed here on sandy specimens reinforced with short fibers. Additionally, a geometry of sand particles was also considered in terms of particles' shape as a major fiber-soil interaction mechanism for soil improvement.

2. Materials and methods

Mikawa silica sand #6 with angular (N6) and rounded (R6) particle shapes were used as the host soil in the experiments. Fig. 1 shows the grain size distribution of the two types of sand as well as microscopic images of the sand particles. Table 1 provides information on the physical and geometrical properties of the sand.

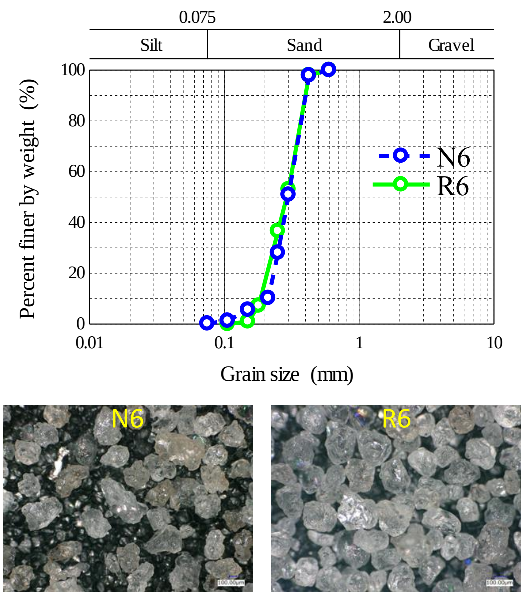

Fig. 1. Grain size distribution and microscopic image of Mikawa sand #6 with different geometry

Polyvinyl alcohol (PVA) fibers were used as the reinforcing material in the experiments, with a length of 12 mm and a diameter of 0.04 mm. The specific gravity of fibers is G_f=1.3, and fibers have a tensile strength of τ=1560 MPa and an elastic modulus of E=41 GPa. The fiber content in the reinforced soil is defined as the mass ratio of the fibers to the sand particles, expressed as $w_f=m_f/m_{sp}$, where m_f is the mass of the fibers and m_{sp} is the mass of sand particles. The fibers were counted as a part of the solid phase, which includes both the sand particles and the fibers. Both unreinforced and fiber-reinforced sand specimens were prepared by mixing sand with fibers in dry condition, and then placing them by side-tapping/vibration in dry condition[3]. To ensure the uniformity of the fiber distribution within the soil matrix, the reproducibility of the experiments was checked. The specimens were compacted in three initial relative densities of D_r=40%, 60% and 80%.

Table 1. Physical properties of Mikawa sand #6 with different geometry

Sand type	N6	R6
Spesific gravity, G_s	2.65	2.65
Maximum void ratio, e_{max}	1.018	0.901
Minimum void ratio, e_{min}	0.643	0.598
Roundness, R_c	1.374	1.244
Aspect ratio, A_r	1.539	1.199

A series of stress-controlled cyclic shearing tests were performed on the prepared sand specimens using a conventional triaxial testing machine under undrained condition. Before the shearing process, all the prepared sand specimens were saturated to a B value of over 0.97 and consolidated at a confining pressure of p_0'=100kPa. Cyclic shearing was performed at a frequency of 0.05Hz with the controlled stress of σ_1'=30kPa with refers to a cyclic stress ratio (CSR) of 0.15.

3. Results and discussion

In Figs. 2 and 3, the cyclic stress-strain responses of both unreinforced and fiber-reinforced Mikawa sand N6 and R6 specimens are presented. The plots show that the addition of fibers led to an increase in the liquefaction resistance and a reduction in the cyclic strain of the sand specimens. The reinforced specimens also exhibited more symmetric deviator stress-strain hysteresis loops than the unreinforced specimens, indicating a more stable behavior. Due to a high number of output data some values of deviator stress missed at a later stage of shearing which led to sharp straight passage of stress-strain curves from compression to extension. The results showed that increasing the fiber content led to a reduction in the axial strain developed during cyclic loading in both compression and extension

繊維で強化された形状の異なる砂の繰返しせん断挙動

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sides. This indicates that the fibers are effective in improving the stiffness of the sand, and thus reducing its deformation under cyclic loading. In addition, fiber-reinforced specimens showed a higher value of critical state line M at the stage of cyclic mobility.

The results show that the Mikawa sand R6 had a higher number of cycles (N_L) required to induce liquefaction compared to the Mikawa sand N6, indicating that the rounded particles in R6 provided better stability and resistance to liquefaction. In particular, for Mikawa sand R6, the addition of fibers led to a significant increase in the number of cycles required to achieve liquefaction. At a fiber content of 0.4%, the number of cycles required for liquefaction increased from around 5 to 33 cycles. For Mikawa sand N6, the effect of fiber reinforcement was less pronounced with the increase of number of cycles required for liquefaction from around 3 to 20 cycles with the fiber content increment, which still resulted in an increase in the liquefaction resistance and a reduction in the cyclic strain.

It is important to note that the liquefaction resistance of unreinforced sand increased with increasing relative density. In the case of D_r=80%, the sand was too dense to liquefy even under cyclic loading. However, at D_r=60%, liquefaction was still possible and the fiber reinforcement could be effective in improving the liquefaction resistance (results were not presented due to the space limit).

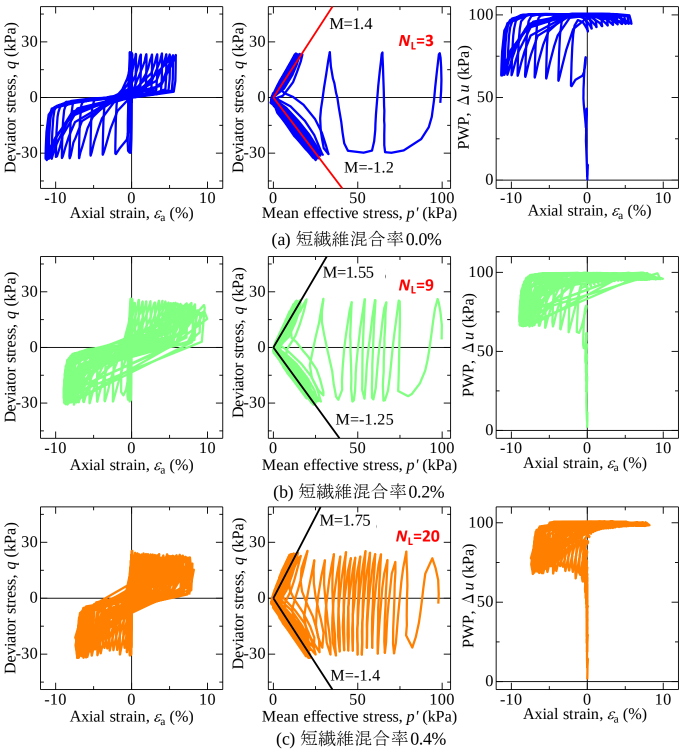

Fig. 2. Comparison of cyclic behavior of Mikawa sand N6 with different fiber contents (D_r=40%, p_0' =100kPa, CSR=0.15)

4. Conclusions

The followings are main conclusions:

- The addition of fibers to sandy soil increased the liquefaction resistance, even in loose conditions, where the required number of cycles to induce liquefaction increased significantly in fiber-reinforced soil compared to unreinforced soil.
- Fiber-reinforced samples showed more symmetric development of deviator stress-strain hysteresis curve, and developed less axial strain in extension than unreinforced sand.
- In terms of the geometry of sand, the study found that the Mikawa sand R6, which has more rounded particles, had a higher resistance to liquefaction compared to the Mikawa sand N6 with more angular particles. The results of the study provide insight into the potential application of fiber-reinforced sand in improving the dynamic behavior of soils, particularly in seismically active areas.

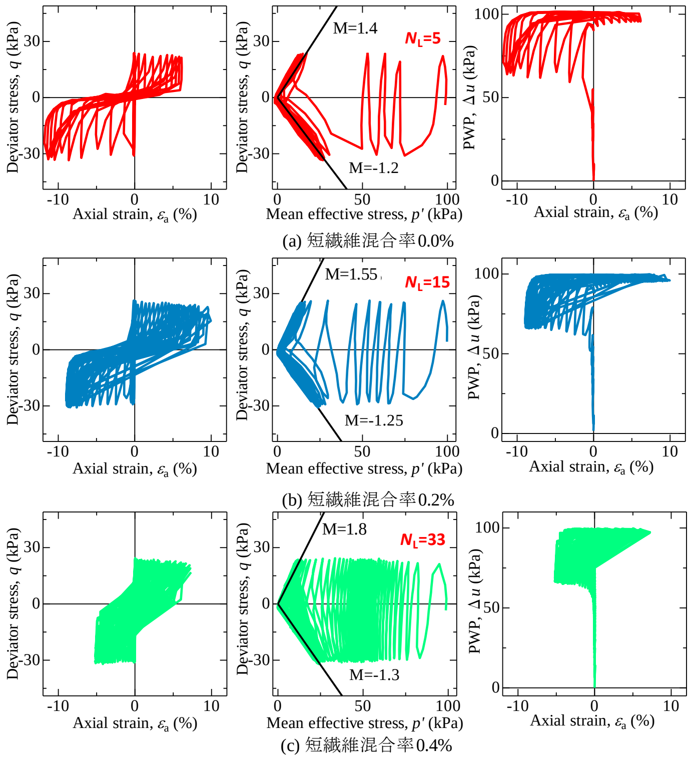

Fig. 3. Comparison of cyclic behavior of Mikawa sand R6 with different fiber contents (D_r=40%, p_0' =100kPa, CSR=0.15)

Reference: 1) Li, H., Senetakis, K., 2017. Dynamic properties of polypropylene fibre-reinforced silica quarry sand. Soil Dyn. Earthq. Eng., 100, 224-232. 2) Li, H., Senetakis, K., Coop, M.R., 2019. Medium-strain dynamic behavior of fiber-reinforced sand subjected to stress anisotropy. Soil Dyn. Earthq. Eng., 126, 105764. 3) Ganiev, J., Yamada, S., Nakano, M., Sakai, T., 2022. Effect of fiber-reinforcement on the mechanical behavior of sand approaching the critical state. J. Rock Mech. Geotech. Eng., 14 (4), 1241-1252.