Reproduction of shear behavior of fiber-reinforced Toyoura sand by SYS Cam-clay model

Constitutive equation, isotropic consolidation, consolidated drained shear test

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1. Introduction

Several studies have investigated the effect of fibers on the shear-strength behavior of soils. Fiber inclusions significantly improve the strength of soils and can be a viable alternative for soil stabilization in retaining structures, embankments and slopes, as well as subgrade strengthening beneath footings and pavement.

The influence of flexible fibers on the shear-strength and volumetric-change behavior of soils has been investigated through direct shear, conventional triaxial compression and extension, and bender element and ring shear tests. Furthermore, there were attempts to reproduce mechanical behavior of fiber-reinforced soil through the elasto-perfectly plastic constitutive model (Diambra et al., 2010), model based on the superposition of the effects of sand and fibers with using two stiffness matrices independently; energy dissipation model (Michalowski, 2008); equivalent additional stress concept (Wang et al., 2019) and etc. Despite numerous experimental and theoretical studies to analyze the behavior of fiber-reinforced soil, the present understanding is still limited with regard to fiber–soil interaction and discrepancies between different studies.

The objective of this study is to reproduct both isotropic compression and drained shear behavior (Ganiev et al., 2019) of sand with fibers by SYS Cam-clay model, which is an elasto-plastic constitutive model considering ‘soil skeleton structure’.

2. Outline of SYS Cam-clay model

The SYS Cam-clay model is an elasto-plastic constitutive model that expresses ‘soil skeleton structure’ as structure (STR), overconsolidation (OC), and anisotropy, and describes their evolution of the soil skeleton structure associated with development of plastic deformation. As the structure becomes higher, R^* approaches 0, while as OCR becomes larger, R approaches 0. The model can explain the mechanical behavior of typical clays and sands, as well as intermediate soils under a common theory by controlling the evolution of the soil skeleton structure, which is controlling evolution rule parameters (Table 1). The evolution rule parameters are mainly divided into three parts: evolution rule of OC, evolution rule of STR and evolution rule of anisotropy. As for OC, the degradation index of OC m is the positive material constant that controls the rate of OC loss. As for STR, the indices a, b and c are material constants that control the rate of structure decay (in the most cases b=c=1). The other index for structure describing is c_s index that represents the ratio of plastic shear deformation to plastic compression deformation. Information on the detailed explanation of the model is given in Asaoka et al., 1994; Asaoka et al., 1997; Asaoka et al., 2000; Asaoka et al., 2002.

3. Simulation results and discussion

Fig.2 shows isotropic consolidation tests on unreinforced, 0.2% and 0.4% fiber-reinforced sand specimens. The experiments were conducted under very loose density condition, approximately 15-20% relative density, and confining pressure of 600kPa, by initializing back pressure value 100kPa and increasing cell pressure until 700kPa. For all fiber-mixture ratios isotropic consolidation experiments were conducted 3 times in order to validate the reproducibility of test results. The simulation result using SYS Cam-clay model is also shown in this figure. As can be seen from the Fig.2,

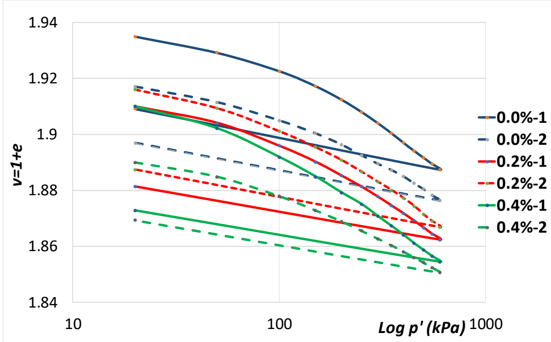


Fig.1. Experimental results of isotropic consolidation performed on the unreinforced and fiber-reinforced specimens

Table 1. Summary of constitutive model parameters of 0.0%, 0.2% and 0.4% fiber inclusions (D_r=80%, p'=100kPa)

Elasto-plastic parameters	sand	0.2%fiber	0.4%fiber
Critical state index M	1.320	1.470	1.620
NCL intercept N	1.850	1.850	1.850
Compression index $\tilde{\lambda}$	0.035	0.035	0.035
Swelling index $\tilde{\kappa}$	0.006	0.006	0.006
Poisson's ratio ν	0.300	0.300	0.300
Soil particle density ρ_s(g/cm3)	2.646	2.646	2.646
Coefficient of permeability k (cm/s)	1.0d-7	1.0d-7	1.0d-7
Evolution parameters			
Degradation index of OC m	0.010	0.010	0.010
Degradation index of STR a (b=c=1)	2.000	2.000	2.000
Ratio of plastic volume strain to plastic deviator strain c_s	1.000	1.000	1.000
Initial parameters			
Specific volume V_0	1.725	1.735	1.745
Degree of structure $1/R_0^*$	2.500	3.000	3.500
Degree of anisotropy ζ_0	0.000	0.000	0.000
Degree of overconsolidation $1/R_0$	123.8	113.5	101.8

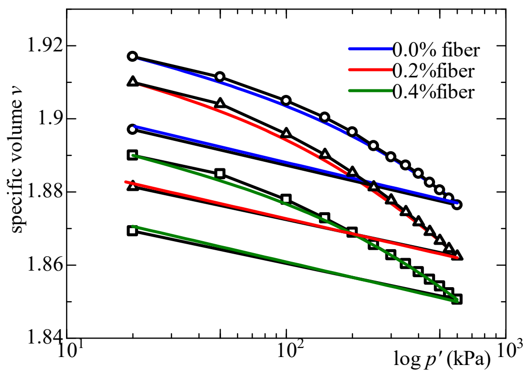


Fig.2. Simulation results of isotropic consolidation performed on the unreinforced and fiber-reinforced specimens

simulation results are in good agreement with the experimental results for three specimens. The parameters, compression index $\tilde{\lambda}$ and swelling index $\tilde{\kappa}$ were obtained from the simulation as follows,

$v_{1e} = N - \tilde{\lambda}\ln p'$ (1)

$v_{ke} = v_k - \tilde{\kappa}\ln p'$ (2),

where v_{1e} and v_{ke} are the specific volumes at the end of isotropic compression and isotropic unloading, v_k specific volume related to the swelling condition.

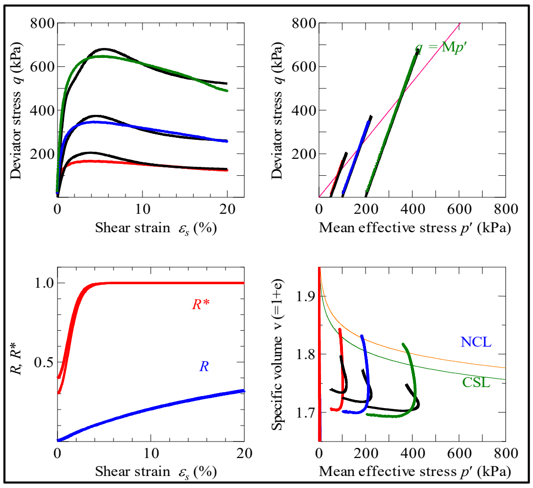
Fig.3 shows the drained triaxial compression tests on unreinforced, 0.2% and 0.4% fiber-reinforced sand specimens. The critical state parameter M was determined depending on content of fiber. After obtaining main elasto-plastic and evolution rule parameters experimental results of drained triaxial compression tests performed under 50kPa, 100kPa and 200kPa with the relative density of 80% were simulated through SYS Cam-clay model.

Fig.3(a) shows comparison between experimental results and simulation for unreinforced specimens with the material constants and initial values given in Tables 1. In q-ε_s curves the simulation result are in good agreement with the experimental result. However, the volumetric change characteristics of simulation result differ from experimental result. The specific volume at the end of test is larger than the one from simulation in $v - p'$ curves. The OC R still remains even at axial strain of 20% in $\varepsilon_s - R$, R^* dependency.

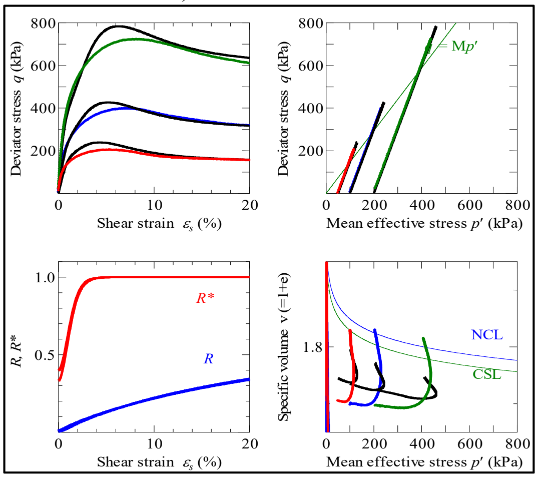
Fig.3(b) represents simulated results for 0.2% fiber-reinforced specimens. It can be seen that all material constant parameters and evolution rule parameters are the same as for the unreinforced specimens, except only CSL parameter M in Table 1. The degree of STR R^* and OC R in initial conditions were different from that of unreinforced sand. Like the unreinforced sand, in q-ε_s curves the simulation result fitted faithfully with the experimental results. However, the volumetric change characteristics in simulation results differ from experimental results. One of the reasons is that the soil is not at the critical state even at the shear strain of 20% in this model. The OC is still remains at the end of shearing. With the same material constants as for 0% and 0.2% fiber reinforcement the simulation results for 0.4% fiber mixture ratio was obtained. According to the experimental and simulation results, the CSL parameter was fixed at M=1.62 (Table 1). In q-ε_s curves it is obvious that all stress paths are reproduced with good agreement with experimental results as shown in Fig.3(c).

4. Conclusion

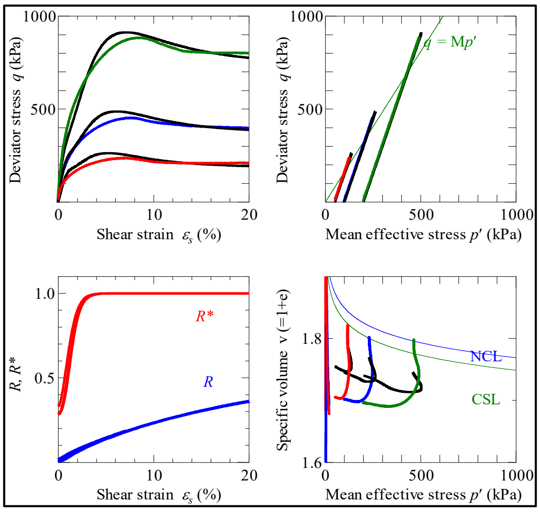
The simulation results are in a good correspondence with the experimental results, which shows that the soil parameters and initial values are simulated faithfully. Although there is a difference in dilatancy behavior between the simulated results by SYS Cam-clay model and triaxial compression tests, it is still reliable that the determined soil parameters and initial values can reproduce the mechanical behavior of both unreinforced and fiber-reinforced soil. Based on the simulation results it can be concluded that as content of fibers increases, the CSL parameter M increases, initial degree of structure $1/R_0^*$ increases and initial degree of OC $1/R_0$ decreases with the same elasto-plastic and evolution rule parameters, which is implied that other characteristics of pure sand still remain as principal.



a) Unreinforced sand



b) 0.2% fiber-reinforced sand



c) 0.4% fiber-reinforced sand

Fig.3. Simulation results of drained triaxial compression tests

Reference 1) Diambra et al. (2010): Fiber reinforced sands: Experiments and modelling. Geotextile and Geomembranes 28, 238-250. 2) Michalowski (2008): Limit analysis with anisotropic fibre-reinforced soil. Geotechnique 58 (6), 489-501. 3) Wang et al. (2019): Numerical Analysis of Fiber-Reinforced Soils Based on the Equivalent Additional Stress Concept. Int. J. Geomech. 19 (11): 04019122. 4) Ganiev et al. (2019): Study on the mechanical properties and stiffening effect of short fiber-reinforced geomaterials. Proceedings of 54th annual conf. JGS. 5) Asaoka et al. (1994): Soil-water coupled behavior of saturated clay near/at critical state. Soils and foundations 34 (1), 91-105. 6) Asaoka et al. (1997): Soil-water coupled behavior of heavily overconsolidated clay near/at critical state. Soils and foundations 37 (1), 13-28. 7) Asaoka et al. (2000): Superloading yield surface concept for highly structured soil behavior. Soils and foundations 40 (2), 99-110. 8) Asaoka et al. (2002): An elasto-plastic description of two distinct volume change mechanisms of soils. Soils and foundations 42 (5), 47-57.