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Role of Suction on the Seismic Compression of Unsaturated Sand Under Partially Drained Conditions

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Abstract. Unsaturated soils containing occluded air bubbles are commonly encountered in earthquake-prone areas and understanding their seismic compression behavior is of critical importance. This paper presents the results from a series of partially drained cyclic simple shear tests on sands having the same initial relative density but different initial degrees of saturation subjected to a range of cyclic shear strain amplitudes. The results indicate that increasing the shear strain amplitude led to an increase in the volumetric contraction. Further, the test results show that for shear strain amplitudes of 1% and 3%, the volumetric strains after 20 cycles are not strongly affected by the initial suction and degree of saturation. However, for a shear strain amplitude of 5%, the volumetric strain after 20 cycles is greatest for the soils that had a lower initial degree of saturation. In these tests, the degree of saturation was observed to increase while the matric suction decreased. The results indicate that unsaturated conditions may play an important role in seismic compression under partially drained conditions, but only under larger shear strain amplitudes.

Keywords. Unsaturated soil, cyclic simple shear, seismic compression, partial drainage condition.

1. Introduction

Seismic compression is defined as the accrual of contractive volumetric strains in unsaturated soils when subjected to earthquake shaking and has been recognized as a major cause of seismically-induced damage to buildings and geotechnical structures [1]. The state-of-the-practice method used to predict contractive volumetric strain during seismic events consists of a simplified procedure developed by Tokimatsu & Seed [2], which is based on laboratory cyclic simple shear test results for saturated and dry quartz sands reported by Silver & Seed [3]. However, many natural soil layers near the ground surface are above the water table and may be unsaturated, these methodologies may provide overconservative estimates of seismic compression for unsaturated soil layers. Further, common geotechnical applications, i.e. landfills, engineered slopes, drainage system for highway and reinforced soil structures, all involve unsaturated backfills and

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their seismic compression behavior may be a key design factor where small seismic settlement may have a big impact on the applications. Although a semi-empirical methodology has been proposed to predict seismic compression of unsaturated soils by Ghayoomi et al. [4], the mechanism of the seismic compression that unsaturated soils experience during seismic shaking events is not fully understood. Further, the role of drainage conditions has not been fully studied. Therefore, seismic compression on unsaturated soils need further research. In this study, a newly-designed specimen housing with suction control to be used on the NGI-type simple shear device was described, and a series of suction-controlled cyclic simple shear tests were performed on unsaturated sands with four initial suction states in partially drained conditions (no water drainage but free air drainage).

2. Background

Although seismic compression may be an important cause of damage during earthquakes, there are only limited case histories. Konagai et al. [5] reported surface settlement of fill soils along the northeastern shorelines of Tokyo Bay during the 2011 Tohoku earthquake. Surface settlements measured at locations 12-20 m away from the pile were 300-400 mm and gradually increased to approximately 870 mm alongside the base wall. It was verified that the backfill, which primarily experienced seismic compression, was in unsaturated state as the ground water level was found to be at a depth of 25 m.

Recently, experimental advancements have been carried out on the soil dynamic properties and seismic compression behavior of unsaturated soils. Air in the pores of unsaturated soils along with the contribution of matric suction to interparticle forces may affect their dynamic properties at small strains [6]. Air also will have a significant impact on the deformation response of soil layers at larger strains due to its higher compressibility than water. Experimental data presented by Toll [7] and Toll & Ong [8] suggest soil's susceptibility to compression increases with increasing suction (and higher volumetric air content), which may lead to more seismic compression in unsaturated soils during earthquake events. However, the amount of seismic compression that unsaturated soils experienced during cyclic loading was also found to be apparently dependent on the degree of saturation or the effective stress state of the unsaturated soils. Whang et al. [9] found that the degree of saturation was important for the seismic compression of unsaturated soils with moderately plastic fines, with a minimum volumetric strain value at an intermediate degree of saturation of approximately 0.3. Ghayoomi et al. [10] performed centrifuge tests on unsaturated F-75 Ottawa sand layers and found minimum surface settlement happened at a degree of saturation of approximately 0.3, while wetter and drier specimens experienced more surface settlements. Therefore, the mechanism lies in the seismic compression behavior of unsaturated soils has not been understood well and it still deserves further investigation, especially for the site soils in earthquake-prone areas. Since most of the soils experiencing seismic compression are located above the water table and relatively dry near the ground surface with a free air phase, it is especially important to study their seismic compression behavior in partial drainage condition, where air in the pores can escape freely during earthquake shaking but not the water, as this is the more reasonable and practical assumption for the near-surface soils during earthquake events.

3. Test material

The sand investigated in this study is classified a well-graded sand (SW) according to the Unified Soil Classification System (USCS). The particle size distribution curve is shown in Figure 1. The sand has a coefficient of uniformity $C_u = 6.1$, and a coefficient of curvature $C_z = 1.0$. The specific gravity is 2.61, and the maximum and minimum void ratios are 0.853 and 0.371, respectively.

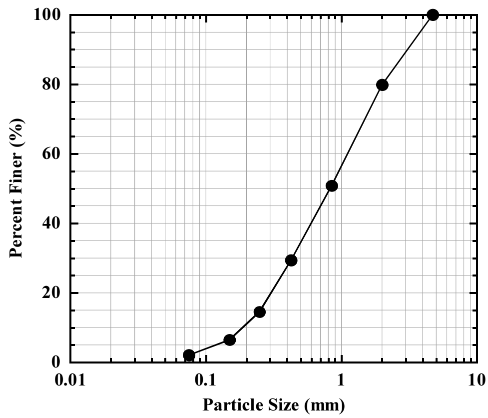
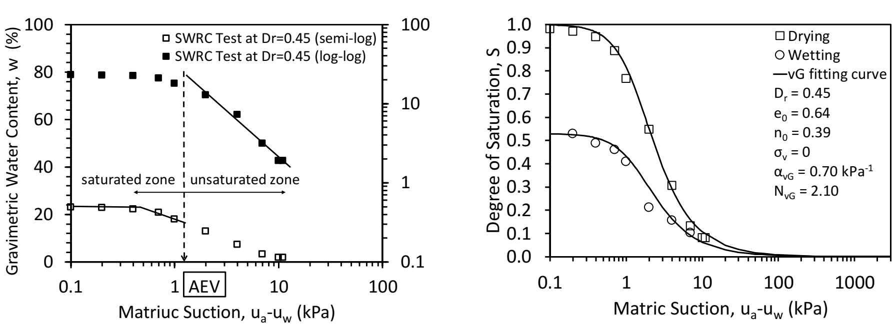


Figure 1. Gradation curve of the well-graded sand (SW).

A hanging column test was used to measure the soil-water retention curve (SWRC) of the SW sand. A saturated soil specimen was first prepared in the funnel with a fritted glass disk (air-entry pressure value of 50 kPa) and then incrementally desaturated by applying negative water pressure (u_w) to the bottom of the specimen while the top of the specimen was left open to the atmosphere ($u_a = 0$). Once the outflow of water from the bottom boundary was almost identical in a time interval of 30 minutes, the sand specimen was considered to reach hydraulic equilibrium. Pasha et al. [11] pointed out that ignoring volume change during SWRC test can lead to peculiar results and major misinterpretation of SWRC. The air-entry pressure value (AEV) of the SW sand at $D_r = 0.45$ was found to be 1.43 kPa using the proposed method, shown in Figure 2(a). The primary drying and wetting path SWRCs at $D_r = 0.45$ are shown in Figure 2(b). A summary of the basic geotechnical properties of the SW sand is presented in Table 1.



(a) AEV determination from Pasha et al. (2015) (b) SWRC for the SW sand at Dr = 45%

Figure 2. SWRC measurements at Dr = 0.45.

Table 1. Summary of the geotechnical properties of the SW sand.

Parameter	Value	Parameter	Value
Specific gravity, G_s	2.61	Maximum void ratio, e_{max}	0.853
Relative density, D_r	0.45	Minimum void ratio, e_{min}	0.371
Effective grain size, D_{10} (mm)	0.20	van Genuchten SWRC parameter, α_{vG} (kPa^{-1})	0.70
Mean grain size, D_{50} (mm)	0.80	van Genuchten SWRC parameter, N_{vG}	2.10
Coefficient of gradation, C_c	1.00	Saturated volumetric water content, θ_s	0.39
Coefficient of uniformity, C_u	6.10	Residual volumetric water content, θ_r	0

4. Apparatus and specimen preparation

To study the seismic compression behavior of unsaturated sands, a newly-designed specimen housing was carried out to accommodate a ceramic plate with a high air entry pressure as the bottom boundary, which can control the matric suction through a hanging column setup. Further, the bottom platen accommodates a tensiometer that can be inserted into the specimen to monitor changes in matric suction during cyclic shearing. The top platen of the specimen housing is used to provide drainage for air from the specimen and to transmit shear stresses. The cylindrical specimen has a height of 20 mm and a diameter of 66.7 mm, resulting in a height to diameter ratio of H/D = 0.3, which is less than the maximum value of 0.4 set by ASTM D6528 [12]. A wire-reinforced rubber membrane manufactured by Geonor is used to minimize radial expansion of the specimen during preparation and cyclic shearing but allows free vertical and shear deformation with negligible stiffness from the boundaries. The cross section through the center of the specimen housing along with the attached hanging column setup is shown in Figure 3. Pictures showing the details of the specimen housing are shown in Figure 4.

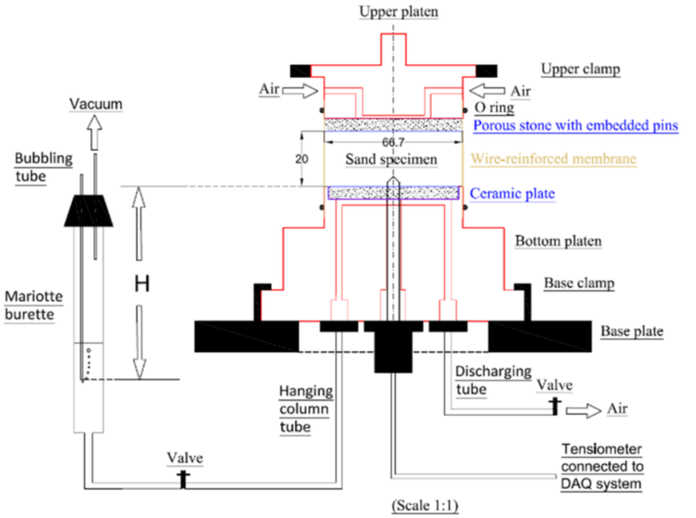
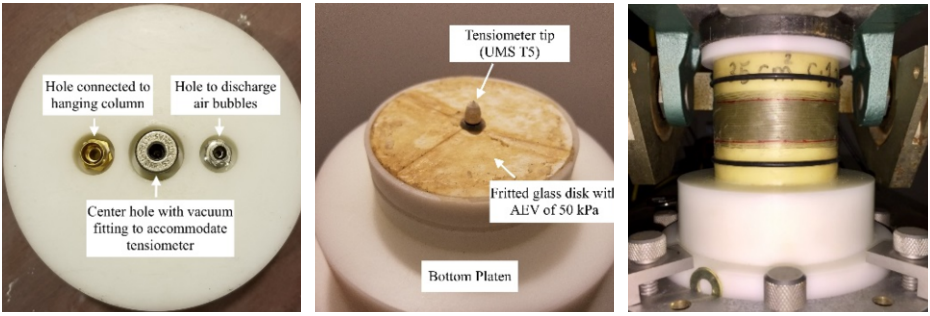


Figure 3. Schematic view of the cyclic simple shear specimen housing for unsaturated soils.

To prepare unsaturated specimens with different initial suctions, the bottom platen was first fastened on the simple shear device using clamps, then dry pluviation method was used to pour pre-weighed sand into the chamber surrounded by the rubber membrane to reach the target relative density of 45%. The dry specimen was slowly saturated by de-aired water through the bottom boundary until water was observed to immerse the top of the specimen. This process was maintained several hours to flush out as much air bubbles as possible within the specimen. With the monitoring of matric suction within the specimen through the inserted tensiometer, saturated specimens were then desaturated to different target matric suctions using the hanging column setup. Since the specimen height is small (20 mm), suction (or degree of saturation) is assumed to be uniform within the specimen. Then, vertical stress was applied to the specimen through the top platen. A picture of the specimen mounted on the cyclic simple shear device is shown in Figure 4(c).



(a) Bottom view (b) Top view (c) Mounted specimen housing

Figure 4. Pictures of the specimen housing for unsaturated soils.

Table 2. Test program.

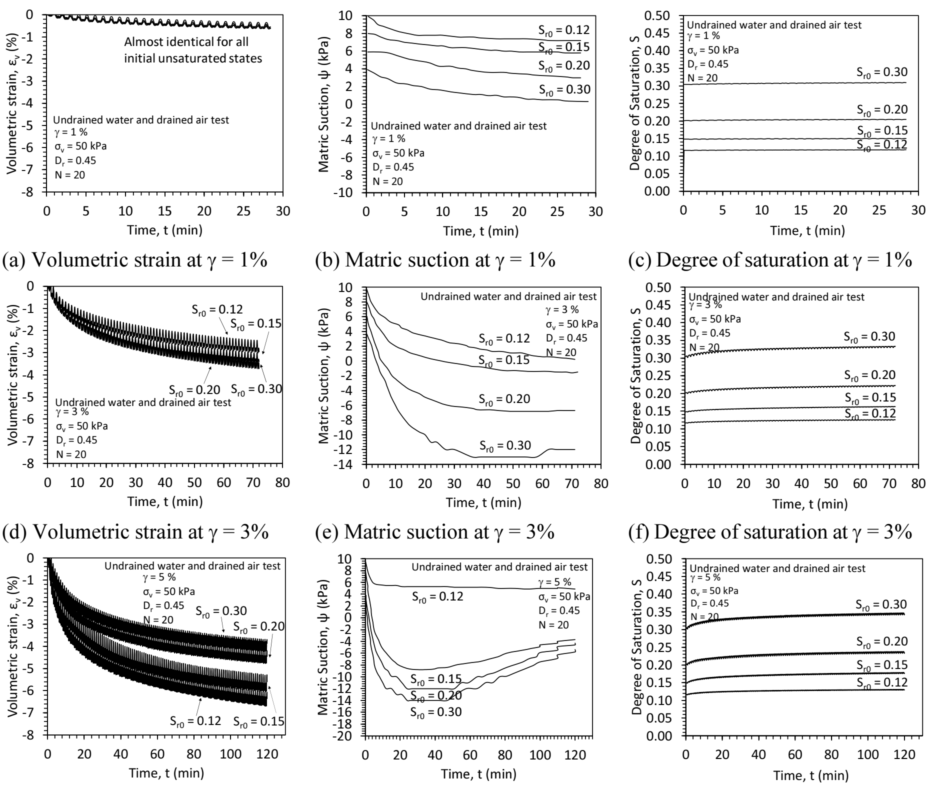
Specimen NO.	$_0$ (kPa)	S_0	w_0	$_{w0}$	γ (%)
A-1	3.87	0.31	0.077	0.123	1
A-2	3.96	0.31	0.075	0.120	3
A-3	4.02	0.30	0.074	0.118	5
B-1	5.93	0.20	0.050	0.079	1
B-2	5.95	0.20	0.050	0.079	3
B-3	5.88	0.21	0.050	0.080	5
C-1	8.01	0.15	0.036	0.058	1
C-2	7.92	0.15	0.037	0.058	3
C-3	7.98	0.15	0.036	0.058	5
D-1	10.15	0.11	0.028	0.045	1
D-2	10.03	0.12	0.028	0.045	3
D-3	9.94	0.12	0.029	0.046	5

5. Test program

Four initial states were chosen to evaluate the seismic compression behavior of the unsaturated sand in partial drainage condition. The initial states of the specimens, like initial matrix suction ψ_0, initial degree of saturation S_0, initial gravimetric water content w_0, initial volumetric water content θ_{w0} and applied cyclic shear strain γ, are presented in Table 2. The vertical stress for all the tests was 50 kPa, which corresponds to the stress condition of the site soil located in a depth of about 2.5 m. And the strain rate was chosen to be 0.833 %/min to ensure drainage of the pore air phase. Since radial expansion of the specimen is minimized by the wire-reinforced rubber membrane, the volumetric strain, ε_v, during cyclic shearing is assumed to be due to changes in height. Seismic compression is a relatively large-strain phenomenon occurred in the field during earthquake events, therefore, shear strains above or equal to 1% were chosen in this study.

6. Test results

The hole allowing air to freely escape on the top cap of the specimen housing was open during the cyclic test and thus water could potentially come out from the hole as the specimen contracts volumetrically and the degree of saturation increases. To compare the results for a partially drained condition (undrained water and drained air), the results from all tests were only shown for the first 20 cycles, during which no water escaped from any of the tests and they could be fairly compared. Due to the partially drained condition, the gravimetric water content of the specimen will remain the same and the change in degree of saturation can be inferred from the volumetric strain using phase relations.



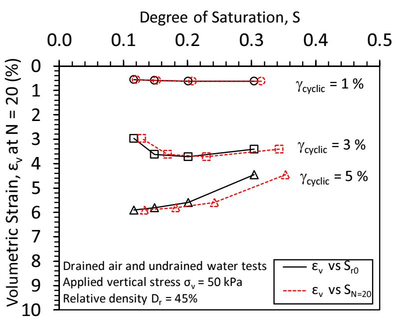
(a) Volumetric strain at γ = 1% (b) Matric suction at γ = 1% (c) Degree of saturation at γ = 1%

(d) Volumetric strain at γ = 3% (e) Matric suction at γ = 3% (f) Degree of saturation at γ = 3%

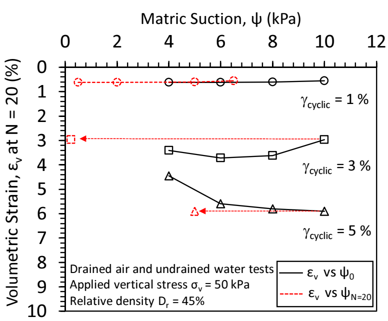
(g) Volumetric strain at γ = 5% (h) Matric suction at γ = 5% (i) Degree of saturation at γ = 5%

Figure 5. Time series of the key variables during cyclic simple shear testing of unsaturated SW sands.

Volumetric responses, matric suctions measured from the tensiometer (assumed $u_a = 0$) and degrees of saturation inferred from volumetric strains were shown in Figure 5, most of the volumetric strain accumulation occurs within the first few cycles. Volumetric responses were almost identical for all the unsaturated specimens with different initial degree of saturation under cyclic strain of 1% and no big change in degree of saturation was observed. Specimens with higher initial suctions showed stiffer responses at strain level of 3%, the smallest volumetric strain occurred at $S_{r0} = 0.12$ and was 2.6% while the largest volumetric strain was 3.6% when $S_{r0} = 0.20$, which may due to the effective stress state of the unsaturated specimens. The results in Figure 5(g) indicate that the drier specimens experienced more seismic compression when subjected to shear strain of 5%, which was due to the compression or the collapse of the air voids. Matric suction decreased gradually (measured pore water pressure increased) when sands settled down at shear strain of 1%. However, at larger shear strains of 3% and 5%, matric suctions decreased even to negative values (positive pore water pressure) due to local pressurization. Since the tensiometer tip only measured a specific point within the specimen, it was possible to develop positive water pressures in the pores especially when subjected to high strain levels. The developed positive water pressures (negative matric suctions) would gradually decrease to stable negative values (positive matric suctions) along with the redistribution of pore water within the unsaturated specimens. Water pressures in the pores were still positive at the end since only the first 20 cycles were shown here, which can be observed in Figures 5(e) and 5(h) for wetter unsaturated specimens.



(a) Volumetric strain vs degree of saturation



(b) Volumetric strain vs matric suction

Figure 6. Synthesized cyclic simple shear results on unsaturated soils under different shear strain amplitudes.

Additionally, larger changes in degree of saturation were observed for wetter sands at the same cyclic shear strain level. And for the specimens with the same initial conditions, larger cyclic shear strain would lead to a larger change in degree of saturation. Synthesized results were shown in Figure 6, suction influences the volumetric response when subjected to cyclic strains of 1% and 3%, but specimens with higher suctions will lead to more seismic compression under strain level of 5%, as higher suction results in more air voids and it is the dominant factor influencing the volumetric response in larger cyclic strain loadings. Only positive matric suctions at N = 20 are shown in Figure 6(b), as wetter unsaturated specimens may need more cycles to stabilize matric suction (or redistribute the water in the pores).

7. Conclusion

Results from cyclic simple shear tests on unsaturated SW sand under partially drained conditions indicate that while increasing the shear strain amplitude always leads to an increase in the volumetric contraction, unsaturated conditions do not always have a major effect. For shear strain amplitudes of 1% and 3%, the volumetric strains after 20 cycles are not strongly affected by unsaturated conditions. However, for a shear strain amplitude of 5%, the volumetric strain after 20 cycles is greatest for the soils that had a lower initial degree of saturation. In all tests, the degree of saturation was observed to decrease while the matric suction decreased.

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