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A Comparison between Simple Shear and Triaxial Tests for Evaluating the Variations of G and D with Matric Suction

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Abstract. Shear modulus (G) and damping ratio (D) are both well known as principal soil dynamic parameters. In the present study, cyclic triaxial and simple shear tests are performed on Firuzkuh silica sand at various shear strain amplitudes using the developed testing devices and peripherals. It is well-understood that degrading curvature of G with shear strain appears in both triaxial and simple shear results. Nevertheless, mean confining stress has dissimilar effects in each of the two tests that does not provide comparable empirical correlations. It is noticed that the variations of G and D with suction stress in triaxial differs from those in simple shear. On the basis of cyclic simple shear results, the increase in suction pressure from zero to the end of transition zone in SWCC leads to increase in G values. In triaxial method, on the other hand, similar increase occurs only up to the inflection point in SWCC, starts reducing afterwards down to a limit value at residual water content. The damping ratio variations with shear strain are generally ascending despite local drops at the strain order of 0.1%, which has appeared in both triaxial and simple shear results.

1 Introduction

Dynamic properties of soil especially shear modulus (G) and damping ratio (D) are frequently considered for evaluating the ground response to dynamic stimulants such as earthquake loads, ocean waves, machine foundations, traffic vibrations and soil-structure interaction. Previous studies have indicated that G and D variations depend on several factors including void ratio, OCR, confining pressure, number of load cycles and saturation degree. Cyclic test methods in various approaches, e.g. triaxial, simple shear and resonant column are most often applied to evaluate the foresaid parameters wherein the specimen initial fabrication and state of stress also affect the results. Considering the specimen condition, two series of cyclic tests were performed in the present research using triaxial and simple shear tests under a wide range of shear strain amplitudes and saturation degrees. The main objective is comparison between simple shear and triaxial testing approach for evaluating dynamic properties of unsaturated sand.

2 Previous Studies

Sand dynamic properties have been studied extensively through experimental testing methods in which their dependency on shear strain and saturation degree is affirmed [1-3]. Cyclic triaxial, cyclic simple shear and resonant column are the most commonly used methods. Moreover, piezoelectric elements are recently applied to oscillate inward the soil specimen to measure the wave propagation velocity and subsequently estimate the dynamic stiffness at very small strains [4]. Shear modulus degradation with increase in cyclic strain amplitude has generally been observed in many studies while the damping ratio behaves on the contrary. For example, Jafarzadeh and Sadeghi (2012) collected and compared a variety of experimental cyclic test results from different studies including their own indicating that normalized shear modulus (G/G_{max}) decreases with increase in cyclic strain (Figure 1) and the damping ratio ascents proportionally [5].

Moreover, capillary effects on dynamic properties comply with trends similar to effective stress. As in Figure 2, the soil-water characteristic curve (SWCC) indicates that reduction in saturation degree leads to rise in matric suction as defined in Equation 1:

$$\psi = u_a - u_w \qquad (1)$$

where u_a and u_w stand for pore air and pore water pressure, respectively. According to the Bishop equation, the product of matric suction and effective stress parameter χ, also known as suction stress, possibly modify effective stress and, subsequently, related parameters such as G and D (see Equation 2) [6, 7].

$$\sigma' = (\sigma - u_a) + \chi.(u_a - u_w) \qquad (2)$$

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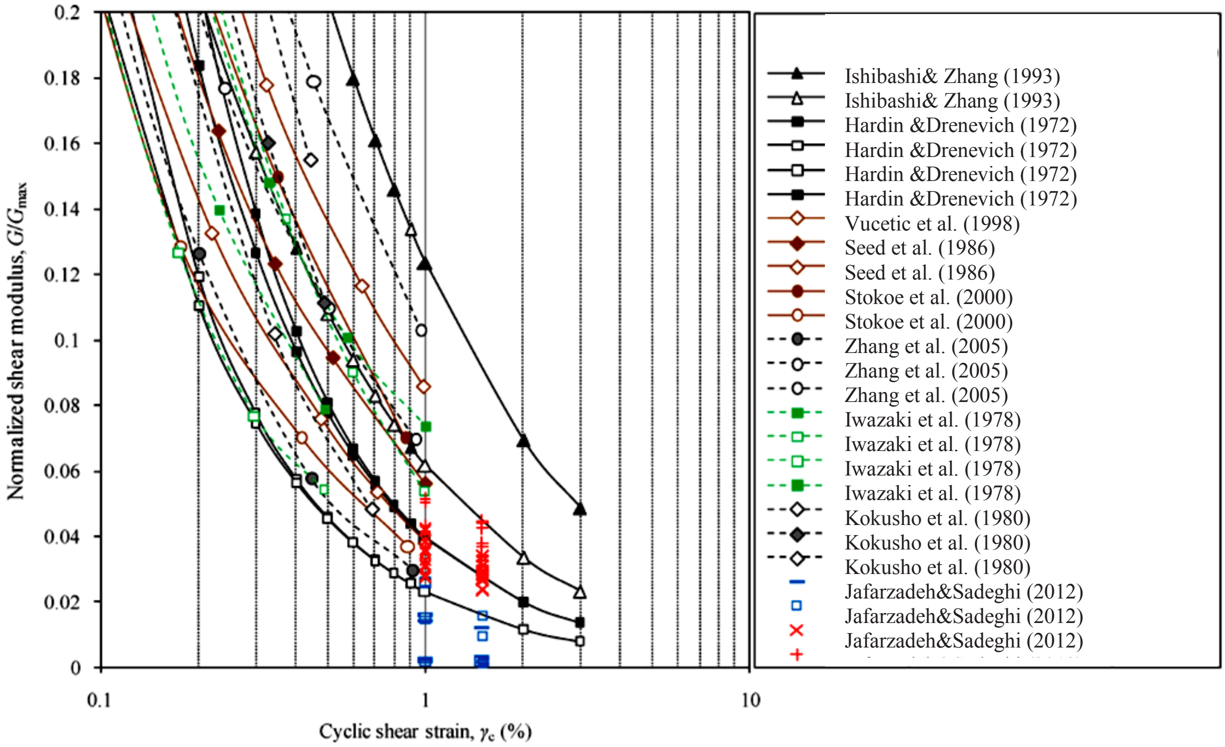

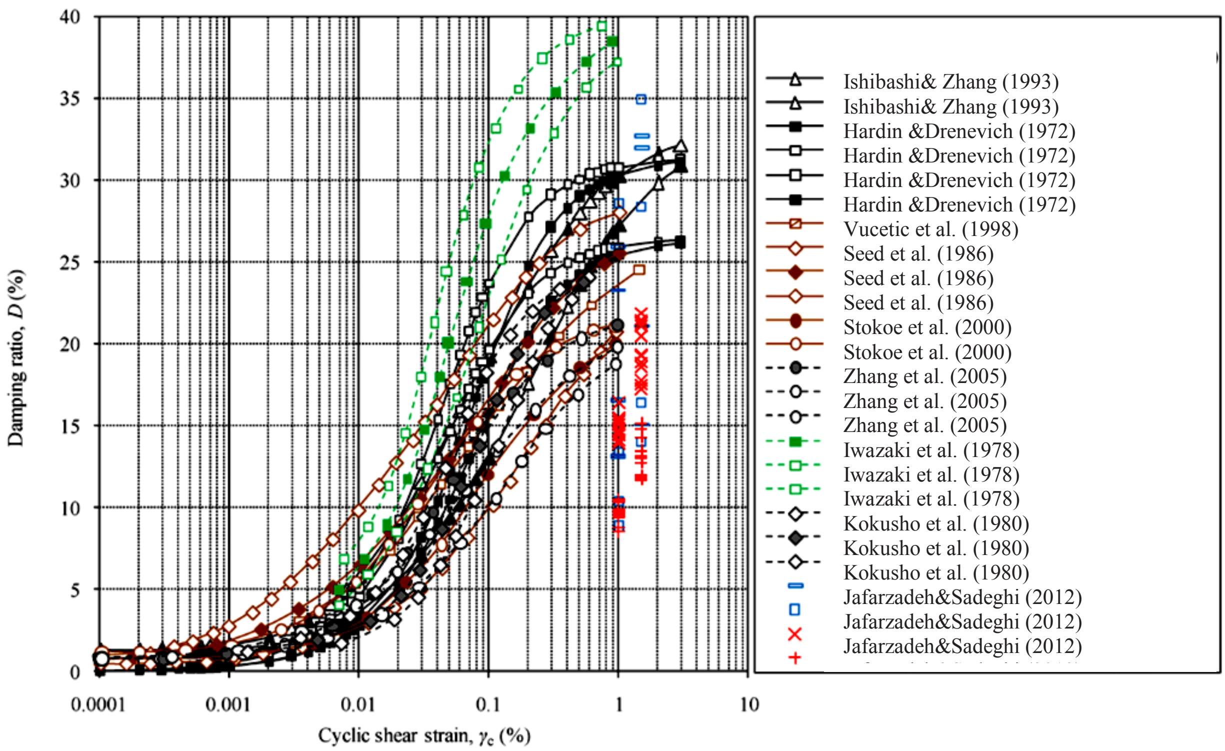

Fig. 1. Typical variation curves of shear modulus and damping ratio with cyclic shear strain, compared by Jafarzadeh and Sadeghi (2012)

As a result of influences on effective stress, matric suction raises the shear modulus and affects the damping ratio in unsaturated soils [8, 9]. Figure 2 shows variations of G_{max} with mean effective stress (σ'_m) from suction-controlled resonant column tests performed by Khosravi et al. where σ_c stands for consolidation stress [10].

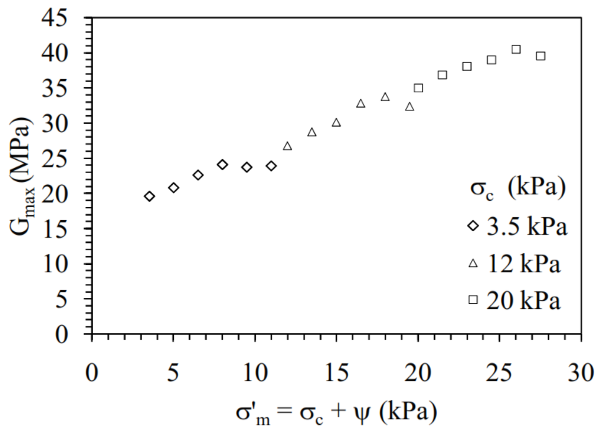

Fig. 2. Variations of maximum shear modulus with mean effective stress considering matric suction ψ (Khosravi et al., 2010)

Matric suction effects on dynamic properties, even for a specimen having the same fabric and density, could vary in accordance with the testing procedure. The present study is an attempt to evaluating the effects of test method on the dynamic properties under unsaturated condition.

3 Device Developments

Providing unsaturated condition, both cyclic triaxial and simple shear devices are developed using high air-entry value ceramics (HAEV) in order to assign the axis translation technique (Hilf, 1956). The pore air and water pressures hence were applied on top and beneath the saturated ceramic to control the matric suction. The employed HAEV ceramic in this study blocks pore air up to a pressure of 300 kPa when saturated. Pore water pressure through the ceramic thus could be practically lower than air pressure to apply matric suction of such range at very low cavitation risk. Depending on the ceramic air entry value, a wide range of matric suction and corresponding degree of saturation are applicable [11].

Mounted in cantilever position on the same feature, one pair of piezoelectric probes, also known as bender elements, are utilized to measure the shear wave velocity for estimating G_{max} at the smallest shear strain could possibly occur through the soil particles (Shirley & Hampton, 1978). Connected to "sending" and "receiving" bender elements, an oscilloscope displays both generated and detected vibrations on the same coordinate through which sent and received peaks are tracked to estimate the time difference and, accordingly, the shear wave velocity (Figure 3).

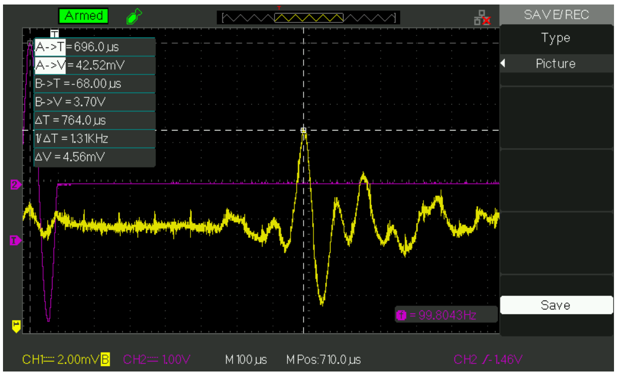

Fig. 3. Generated and detected vibrations on the same amplitude-time coordinate

Figure 4 shows the cap and pedestal which are compatible with an HEAV and a pair of piezoelectric ceramics. Shear wave generation by piezoelectric probes is considered as a non-destructive procedure since causes neither excess pore pressure nor fabric change. Although not precisely gauged, the generated shear strain is so low that no degradation could be observed in shear modulus, hence this could be the reason that the strain amplitude corresponds to G_{max}, often reported amid 10^{-6} to 10^{-7} m/m.

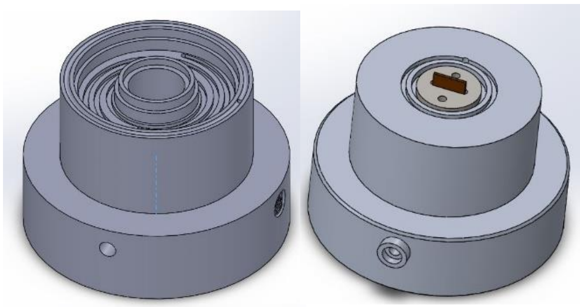

Fig. 4. Schematics of cap and pedestal compatible with bender element and HAEV ceramic

Both triaxial and simple shear devices are equipped with electromechanical actuator inducing motions as low as 10 microns to provide small shear strain amplitudes as low as 10^{-4} m/m for a specimen having 70 mm diameter and height of 160 mm. The closed-loop control on the electro mechanic strain actuator beside the shear wave piezo-probes supply a wide range of shear strain amplitudes ranging from 10^{-6} through 10^{-2} m/m.

4 Material and Sample Preparation

Firuzkuh silica sand (code 161) was selected as testing material for which physical properties were determined and sieve analysis was performed based on ASTM D422-63, indicating a uniform gradation (Figure 5). According to the USCS, Firuzkuh sand belongs to SP category. Firuzkuh silica sand has become a standard sand and used at different universities in Iran for research purposes including AUT[1].

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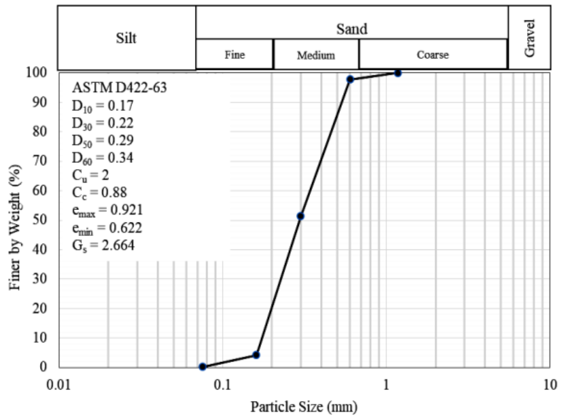

Fig.5. Firuzkuh Sand (code 161) Gradation Curve

The specimens were remolded using moist tamping method (Ladd 1991) with a relative density (Dr) of approximately 5% at the end of consolidation. CO_2 and de-aired water were percolated the next steps to substitute the existing pore air with de-aired water as much as possible without back pressure application. Afterwards, the saturation degree was eventually increased to 100% by means of Skempton's pore pressure parameter, B-Value. In isotropic triaxial approach, back pressure application procedure continues until a value of almost 0.95 to 1 is obtained for pore pressure parameter. Due to K_0 condition of specimen in simple shear approach, however, one may hardly reach values above 0.9 for B assuming 100 percent degree of saturation (Head 1998). Consolidation stage began right after the acceptable B-value reached and the volume change was logged in the form of dissipative pore water. Saturated tests were performed with zero matric suction at this step. For unsaturated testing program, on the other hand, the drying path in SWCC was traversed to the target water content (Figure 6).

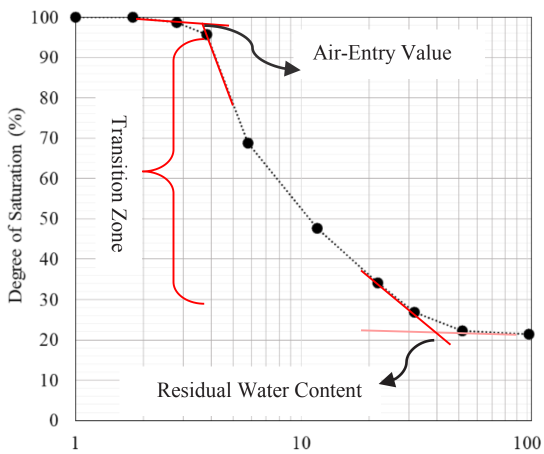

Fig. 6. Firuzkuh sand SWCC including unsaturated zones in

It takes almost two to fifteen days to reach the hydraulic equilibrium at a particular matric suction, depending on the aimed saturation degree and soil hydraulic properties. Representing different zones of SWCC in Figure 6, five values for matric suction were selected to provide triaxial and simple shear unsaturated specimens with consolidated relative density of 5 % under 100 kPa confining pressure (Table 1).

Table 1. Specimens condition after consolidation for both triaxial and simple shear tests.

Relative Density (%)	Confining Pressure (kPa)	Matric Suction (kPa)	Sat. Degree (%)
5	100	0	100
		2.8	97
		6	68
		50	22
		100	21

Pore air and pore water pressure were both controlled through the tubes during cyclic loading. At larger strains, however, small volume changes occur after a number of cycles, which may influence on net stress ($\sigma - u_a$), suction stress or void ratio.

5 Tests Results

5.1 Dynamic Shear Modulus (G)

Cyclic triaxial and simple shear tests are performed on Firuzkuh silica sand under similar conditions as shown in Table 1 to determine shear modulus and damping ratio at various saturation degrees. The G and D parameters are measured for the 5th hysteresis loop except for bender element results which is not influenced by number of cycles. Shear modulus has degraded with rise in shear strain in both approaches (Figure 7). The stiffness values obtained from simple shear tests are almost 55% lower at the beginning of the curve compared to triaxial results, with respect to different state of stress and loading procedure. Nevertheless, the curves get closer to each other at larger strains. Comparison between TXT and SS results shows that substantially higher G modulus has been obtained through TXT tests. TXT results indicate that shear modulus has risen with increase in matric suction (ψ) up until the middle of transition zone at SWCC as a peak, thereafter falling moderately (Figure 8). The corresponding saturation degree at peak value of G is about 68% for TXT results in which the peak is more pronounced at smaller strains, verifying the strain dependency of suction effects. Obviously, the lowest values of G are obtained in saturated specimens with zero matric suction.

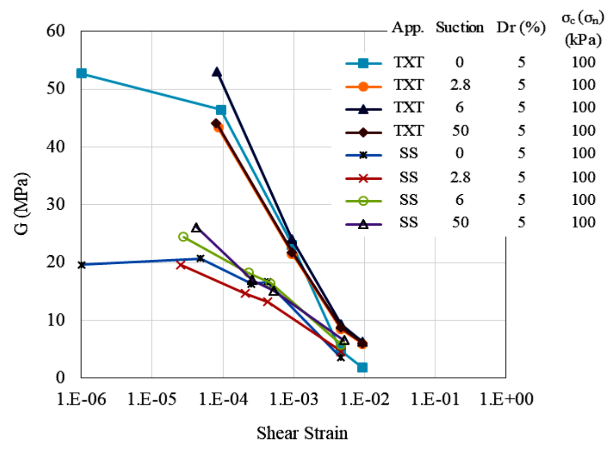

Fig. 7. Shear modulus degradation curves from triaxial (TXT) and simple shear (SS) methods

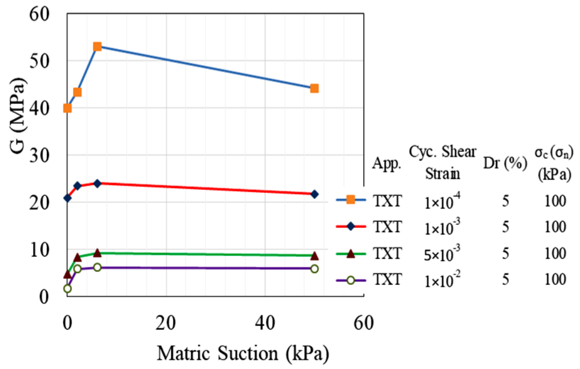

Fig. 8. Strain dependency of suction (ψ) effects on shear modulus from TXT

Similar tests were performed using the simple shear apparatus in which the peak values of G have occurred at higher matric suction (ψ) in comparison with triaxial tests. Therefore, the corresponding degree of saturation has reached to the zone of residual water content in SWCC (Figure 9).

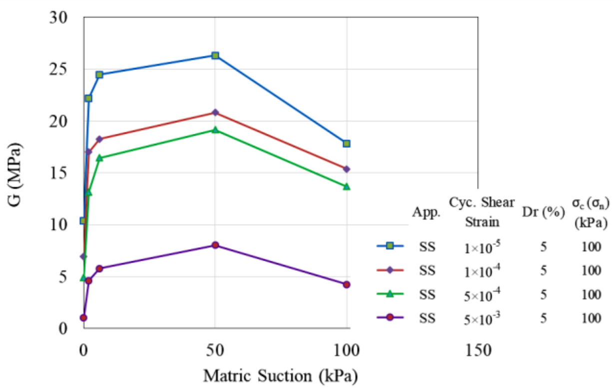

Fig. 9. Strain dependency of suction (ψ) effects on shear modulus from SS tests

Concerning the horizontal stress reaction from inside of rigid annular rings (Figure 10), the confining mean stress in simple shear specimen is known to be lower than isotropic triaxial. Furthermore, the shear load and deformation is directly applied on the specimen in simple shear device while, on the other hand, it is deduced indirectly from deviatoric vertical stress in triaxial test. It can be concluded therefore, that the state of stress at K_0 condition in simple shear tests is responsible for shifting the extreme point of G-γ curvatures to the right comparing to triaxial tests through comparing the results of Figures 8 and 9.

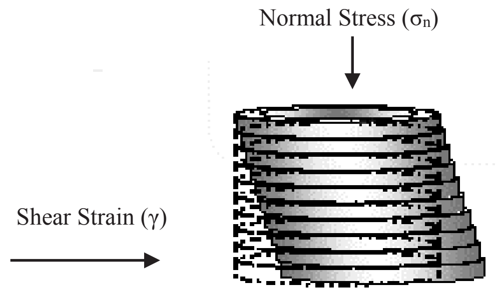

Fig. 10. Schematic of shear deformation of annular rings in simple shear device

The descending part of G-γ curves in both triaxial and simple shear results (Figures 8 and 9, respectively) follows a steeper trend in values concerned with smaller cyclic shear strain amplitudes than the larger strains, confirming that the suction stress appears to be more effective at small strain behavior.

5.2 Damping Ratio (D)

For both triaxial and simple shear cyclic tests, the damping ratios were determined for the 5th hysteresis loop considering the loop area as an index of energy loss (Figure 11). Since it would have been difficult to detect on manual oscilloscope, the shear wave damping was neglected at piezoelectric range of strain.

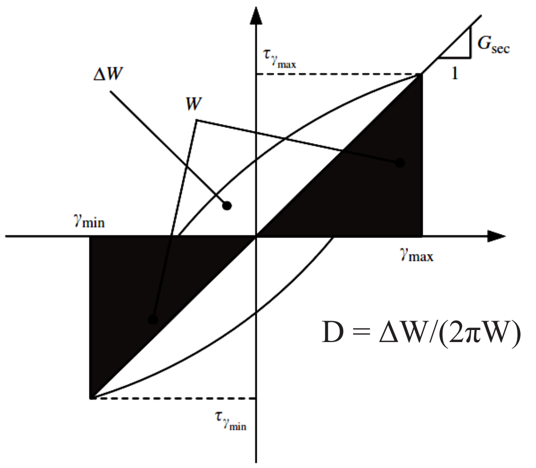

Fig. 11. Schematic damping ratio for cyclic load

Dissimilar to shear modulus, the damping ratio has risen with shear strain amplitude and also not seriously influenced by the magnitude of matric suction. As indicated in TXT results, limited sectional reduction occurs in D-γ graphs wherein the matric suction represents the beginning of transition zone in SWCC.

Afterwards, no drastic variations are observed (Figure 12). Based on shear strain amplitude, however, variations of damping ratio with suction using SS tests have gone through different trends of fluctuation albeit commonly decline at air-entry value (Figure 13).

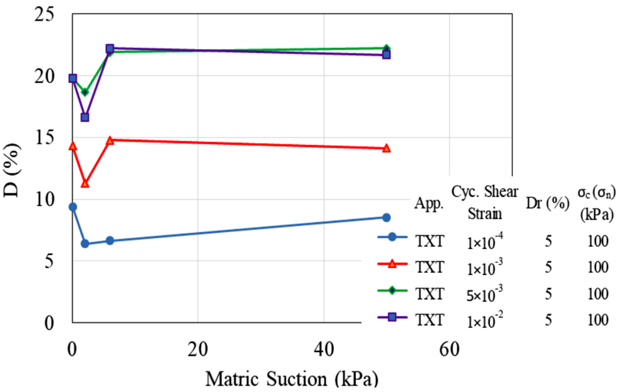

Fig. 12. Damping ratio variations with matric suction (D-ψ) under various shear strain amplitudes in triaxial tests

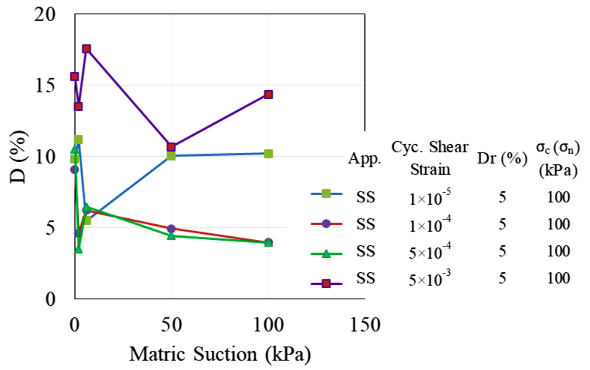

Fig. 13. Damping ratio variations with matric suction (D-ψ) under various shear strain amplitudes in SS tests

6 Conclusions

Automated triaxial and simple shear devices were developed through featuring HAEV ceramic and piezoelectric probes, also known as bender elements. Cyclic tests were carried out under a wide range of saturation degrees and small strain amplitudes.

The cyclic tests were carried out using Firuzkuh silica sand under various saturation degrees. Strain dependency was observed for both shear modulus (G) and damping ratio (D) as in previous studies. The most important findings of the study are summarized below:

1. The increase in matric suction lead to higher values of G in both approaches, while a positional peak occurred at transition zone and residual water content in triaxial and simple shear results respectively.
2. Due to similar specimen and testing factors, the foresaid disagreement refers to different stress state conditions and loading procedures in either of the test methods.
3. No particular trends or drastic variations with matric suction were observed for damping ratio except for local decline at the beginning of suction transition zone in SWCC.

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