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UNDRAINED MONOTONIC BEHAVIOR OF SAND IN LARGE STRAIN TORSIONAL SHEAR APPARATUS

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ABSTRACT: This study reports the finding of an influence of relative density on the deformation characteristic of Toyoura sand subjected to undrained monotonic loading. A series of test were performed on hollow cylindrical specimens with relative density from 19% to 72%, by air pluviation method, isotropically consolidated at effective stress of 100kPa and then monotonically sheared under undrained condition. Tests were performed by using a modified torsional shear apparatus that is capable of achieving double amplitude shear strain up to about 100%. The specimen exhibited flow failure for a relative density of less than 20%. Whereas, for the relative density 28 to 72%, specimen showed initially contractive followed by a dilative behavior. Higher relative density lead to an increase in the undrained shear stress at quasi-steady state as well as the true steady state. Denser specimen showed the non-uniform deformation at larger strain, whereas very loose specimen brought to failure by sudden loss of shear strength exhibiting a collapse.

Key Words: monotonic, torsional shear, undrained peak shear stress, saturated sand

INTRODUCTION

Critical state (CS) is defined as the state at which granular material continue to deform at constant stress and constant void ratio. Critical state soil mechanics is an effective way of modeling soil behavior. Granular material when sheared reaches an ultimate state under a unique combination of effective stress and void ratio.

The term “steady state” in connection with experimental studies on the undrained response of sand has often been used to refer to the same concept as the term ‘critical state’. Recent studies showing two states are the same (Verdugo and Ishihara, 1996, Reimer and Seed, 1997).

Soil fabric formed under gravity has anisotropic in nature, such that the material response is stiffer in the vertical compression. A sand sample compressed in the direction perpendicular to the bedding plane, the behavior is more dilative. Samples that exhibit a tendency to dilate, as they are sheared under undrained triaxial condition – tend to generate negative pore pressure. While the pore pressure is becoming increasingly negative the mean effective stress becomes increasingly positive and the strength increases. Consequently, the observed resistance at the steady state becomes increasingly higher than what is expected from field experience.

Vaid et al. (1990) recognized the importance of shear mode in laboratory testing. However, most of the studies conducted using simple shear devices have mechanical limitation to measure strain level upto 20%, as well as measurement of high negative excess pore water pressure during undrained monotonic shearing.

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In a torsional shear test on hollow cylindrical specimens, one can achieve higher strain levels by increasing torsional shear displacements that is applied to the specimen through rotating the top cap (Kiyota et al. 2008). Contrary to triaxial, shear stress in a torsional shear is more representative of specimen response to field during cyclic or monotonic shearing in undrained condition under simple shear condition.

The goal of this paper is to examine the key features of the undrained response of clean sand, focusing on the critical state, phase transformation state, and the flow liquefaction state exceeding shear strain of 50% in single amplitude as well as measurement of large negative excess pore water pressure. For this purpose, we report a series of undrained monotonic test result from a strain controlled hollow cylindrical torsional shear apparatus, isotropically consolidated Toyoura sand.

TEST APPARATUS, MATERIAL AND PROCEDURE

A fully-automated torsional apparatus, shown in Figure 1, was used in this study for laboratory testing. As described by Kiyota et al. (2008), this device was developed in the Institute of Industrial Science, University of Tokyo. It can achieve double amplitude shear strain (γ_{DA}) levels exceeding 100% on the specimen with 300mm in height by using a belt-driven torsional loading system that is connected to an AC servomotor through electromagnetic clutches and a series of reduction gears. Torque and axial load are measured by a two-component load cell, which is installed inside the pressure cell, having axial load and torque capacities of 8 kN and 0.15 kNm, respectively.

The difference in pressure levels between the cell pressure and the pore water pressure is measured by a high-capacity differential pressure transducer (HCDPT) with a capacity of over 600kPa. Volume change during the consolidation processes is measured by a low-capacity differential pressure transducer (LCDPT). An external potentiometer with a wire and a pulley is employed to measure large torsional deformations. Specified shear stress amplitude is controlled by a data acquisition system connected to a computer, which monitors the outputs from the load cell and calculates the shear stress. The measured shear stress is then corrected for the effects of the membrane force.

Toyoura sand (G_s = 2.659, e_{max} = 0.951, e_{min} = 0.608), which is a uniform quartz sand with negligible fines content (F_c <0.1%) was used in this investigation. Seven hollow cylindrical specimens were prepared by air pluviation method, thus producing a sand fabric with horizontal bedding planes, at a various relative density (Table 1).

Air pluviation technique was employed to make it possible to minimize the degree of inherent anisotropy in the radial direction (i.e. moving radially the nozzle of the pluviator and at the same time circumferentially in alternative directions, i.e. first in clockwise and then anti-clockwise directions as recommended by De Silva et al., (2006) of the hollow cylindrical sand specimens.

Table 1: List of test performed

Test No.	Relative Density, Dr (%)	Void ratio, e	Mean effective stress (p_o'), (kPa)
1-1*	19.0	0.884	100
1-2*	28.5	0.857	100
1-3*	36.8	0.823	100
1-4**	47.9	0.766	100
1-5**	51.6	0.766	200
1-6**	60.3	0.739	100
1-7**	72.0	0.693	100

*Specimen dimension: 300x150x90mm, **Specimen dimension:200x100x60mm [Height, Outer dia, Inner dia]

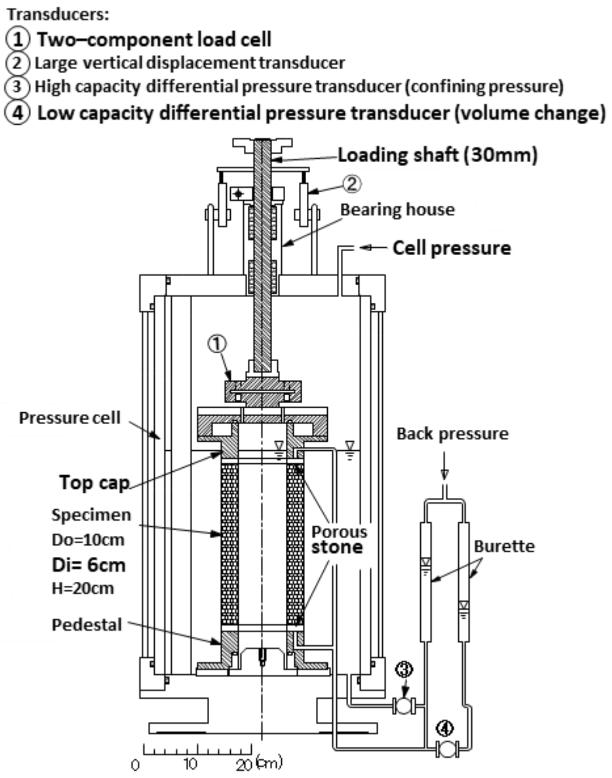


Figure 1. Torsional shear apparatus employed in this study

High degree of saturation (i.e. Skempton's B-value > 0.95) was achieved by the double vacuum method (Ampadu, 1991), while circulating de-aired water into the specimens. The specimens were isotropically consolidated by increasing the effective stress state up to a p_0' = 100 kPa, with a back pressure of 200 kPa. Each sample was subjected to undrained monotonic torsional shear stress(corrected for membrane force, Chiaro et al. 2017) at a shear strain rate of 0.5%/min exceeding single amplitude shear strain of 50%.

LARGE STRAIN UNDRAINED MONOTONIC TEST RESULTS

Definition of undrained strength

Under low confining pressure and low relative density, the steady state may appear at two stages during undrained monotonic loading. The first is the shear strength at quasi-steady state (QSS), after the peak shear stress (the onset of flow liquefaction, (Ishihara et. al. 1993)). It is associated with the temporary local minimum shear stress. QSS has significant importance for engineers because it corresponds to the peak and minimum undrained shear strength of the sand at small strain level (< 1%). The second is a true steady state (TSS) at the final stage of deformation. In the following section, undrained shear strength at QSS and TSS is investigated with the deceases in the void ratio.

Effective stress path during undrained monotonic loading

Figure 2 corresponds to the effective stress path during undrained monotonic loading of loose to dense Toyoura sand isotropically consolidated at effective stress of 100kPa. From Figure 2a to 2d, we can observe as expected, the sand becomes less contractive (more dilative) with the decreasing void ratio from 0.884 to 0.693. When the void ratio of the sand is less than 0.788, (Figure 2b, 2c, and 2d)), the point of minimum mean effective stress appears where the dilatancy behavior changes from contractive to dilative. This point is named as phase transformation (PTL) by Ishihara et al. (1975). Whereas for the sample with void ratio 0.884 (Figure 2a), PTL did not reach and sample behaved contractive, reaching a state of *p'=0*. It is noteworthy that the inclination of PTL, irrespective of the initial void state is uniquely defined at an angle of 30°.

Figure 2a to 2d shows with a decrease in the void ratio, shear stress increased at QSS. Whereas, the inclination of flow liquefaction line (FLL) is uniquely defined at 28° irrespective of initial void ratio, consistent with the PTL. This implies that the PTL and FLL are material dependent, unaffected by a state of initial density.

Stress-strain response from loose to dense Toyoura sand during undrained monotonic torsional shear is presented in Figure 3. It is evident from Figure 3b to 3d, TSS (marked by state B) was observed. Exceeding the TSS, specimen showed strain softening response and reached a residual state. The peak undrained shear stress at the TSS increased from 200kPa to 298kPa with a decrease in the void ratio from 0.766 to 0.693. Loose specimen (Figure 3a) did not reach the TSS (state B) after exceeding the peak shear stress at FLL, consequently development of large shear strain. The shear strain continues to develop and gradually recovered after a shear strain of 60% (Figure 3a, top right mini window). The inclination of the critical state line on effective stress path (Figure 2) increased with a decrease in the void ratio, representing an increase in the friction angle from 32° to 34°.

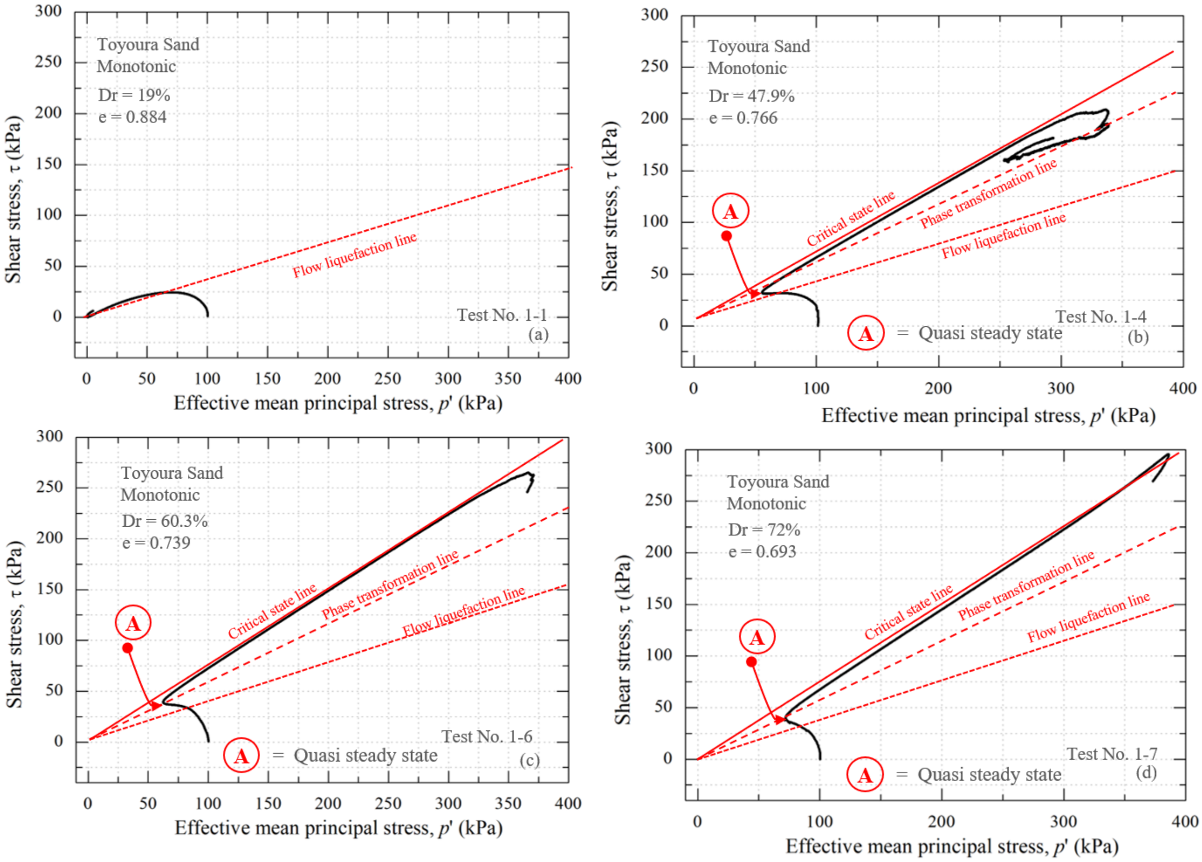


Figure 2: Effective stress path during undrained monotonic loading a) Dr = 19% b) Dr 47.9%, c) Dr = 60.3% d) Dr = 72%

It is noteworthy the specimen that did not exhibit a phase transformation, tend to develop large deformation after exceeding small amplitude of a shear stress. Whereas for medium dense to dense sand, a large shear strain was developed after exceeding the undrained shear stress at TSS. Therefore, it can be concluded that the loose, as well as dense sand, are prone to large deformation depending on the density state as well as the amplitude of a shear stress.

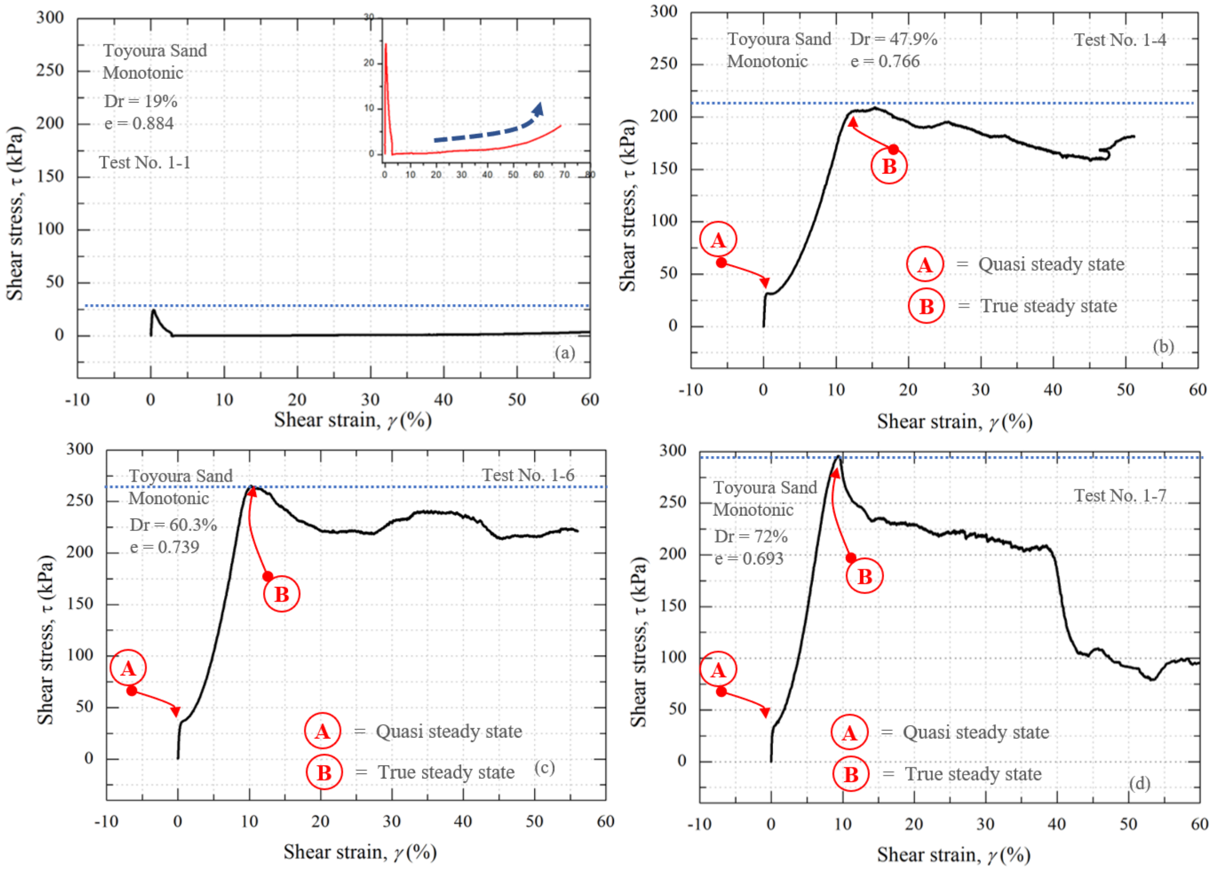


Figure 3: Stress strain relationship during undrained monotonic loading a) Dr = 19% b) Dr 47.9%, c) Dr = 60.3% d) Dr = 72%

Influence of relative density on stress ratio

To have a more precise interpretation of a Quasi steady state (QSS) and true steady state (TSS), Figure 4 report test result in terms of stress ratio and shear strain from loose to dense Toyoura sand. Consistent with the increased in the shear stress with the decrease in a void ratio (Figure 3), the stress ratio initially increased to a peak value and with a further increase in shear strain, it reached a residual stress ratio (Figure 4b to d). For the dense specimen with the void ratio of 0.693, peak stress ratio of 0.74 was observed. Whereas for very loose specimen exceeding peak stress ratio, the collapse was observed, which is associated with flow failure during liquefaction. Therefore, a stress ratio of 0.54 provides a threshold. Exceeding this threshold value stress ratio, specimen will show initially a stain hardening followed by strain softening leading to residual state. Whereas, below this threshold value the specimen will show a strain hardening accompanied by a loss in shear strength.

Specimen deformation at several states (numbered as to 1 through 4) is shown in Photo 1 to 3 for a void ratio of 0.884, 0.766 and 0.693 respectively. State 1 corresponds to the initial state (γ_{SA} = 0%) – a reference vertical line marked in red color.

Dense specimen (Photo 2 and 3) from state 2 (γ_{SA} = 5%) to 3 (γ_{SA} = 10%), the deformation was uniform throughout the height of the specimen. The shear band(s) appeared between state 3 (γ_{SA} = 10%) and 4 (γ_{SA} = 20%). At state 5 (γ_{SA} = 30%), the region near the top cap experienced larger deformation than that near pedestal indicating a non-uniform deformation distribution along the height of the specimen. Whereas loose specimen (Photo 1), after exceeding a shear strain of 2% (state 2), the region near the pedestal collapsed (Figure 3a). This collapse is associated with the loss of a shear stress in the specimen, and consequently development of extremely large strain.

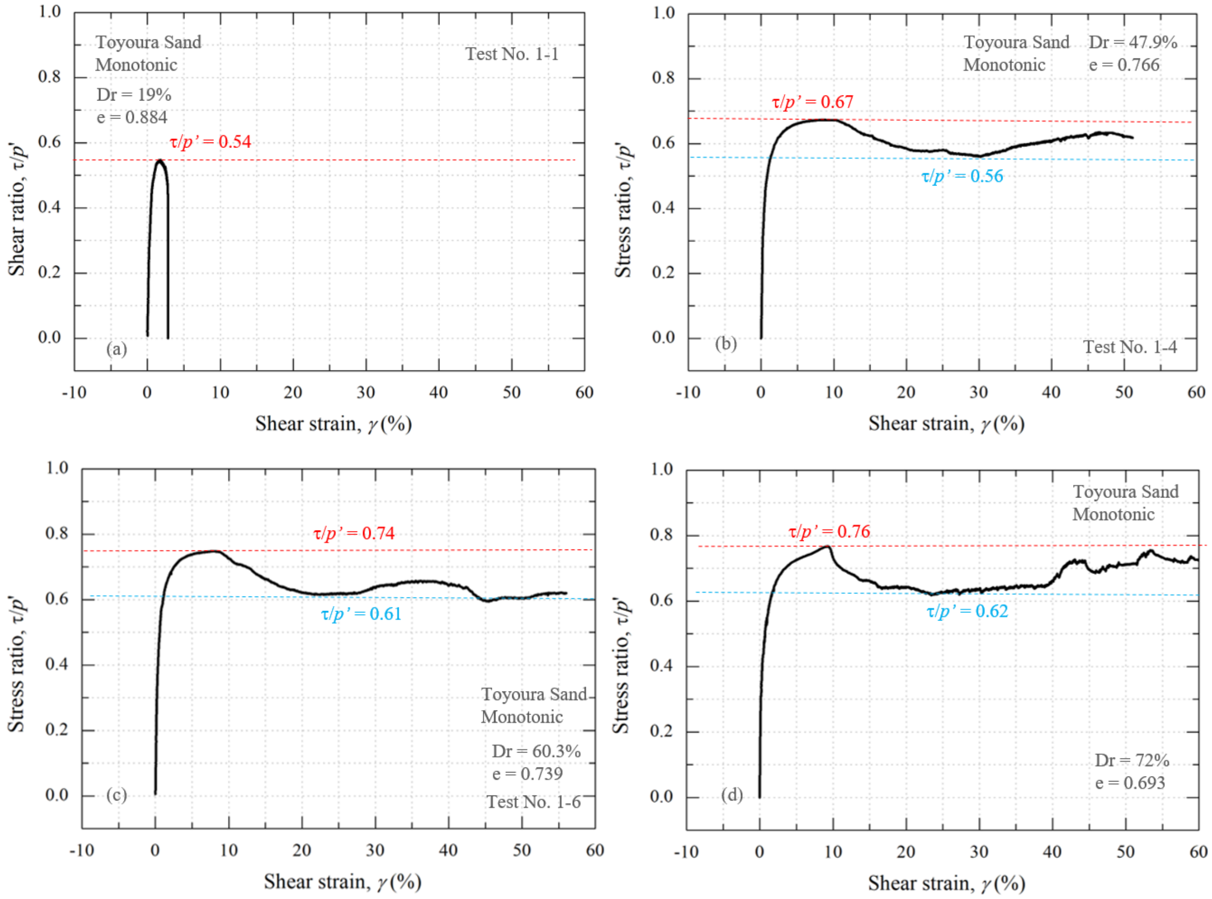
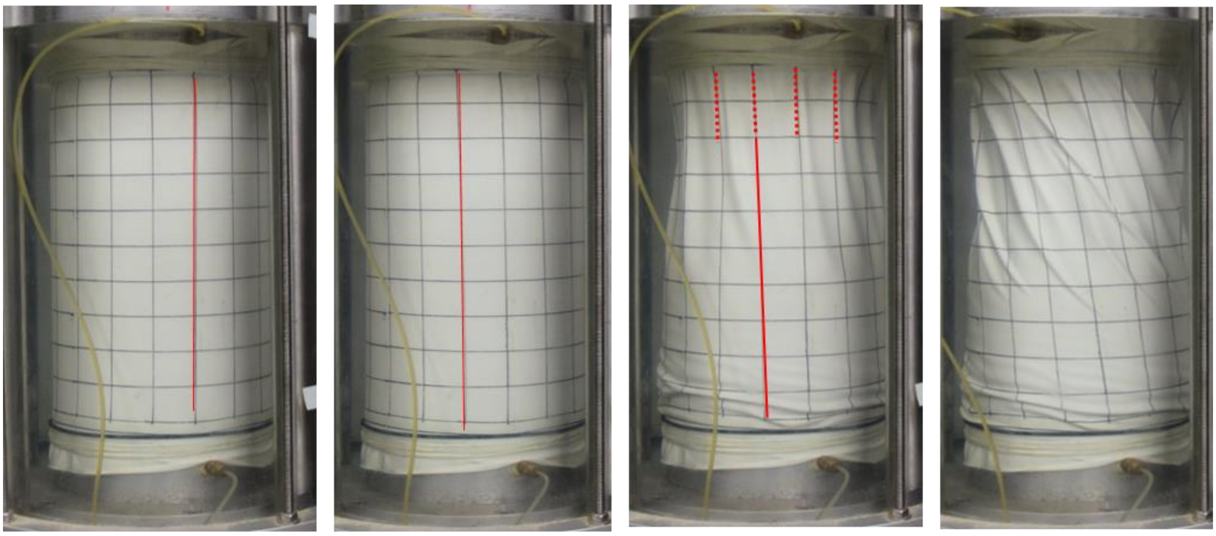


Figure 4: Stress ratio vs shear strain during undrained monotonic loading a) Dr = 19% b) Dr 47.9%, c) Dr = 60.3% d) Dr = 72%



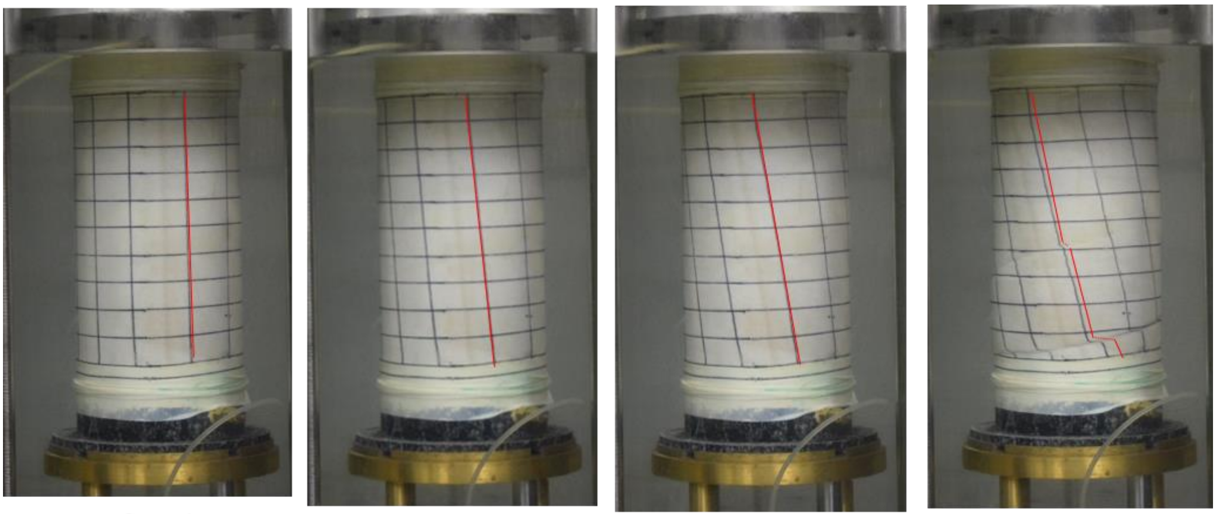
State1
γ = 0%

State 2
γ = 2%

State 3
γ = 3%

State 4
γ = 15%

Photo 1: Specimen deformation at various stages for Test 1-1, Dr=19%



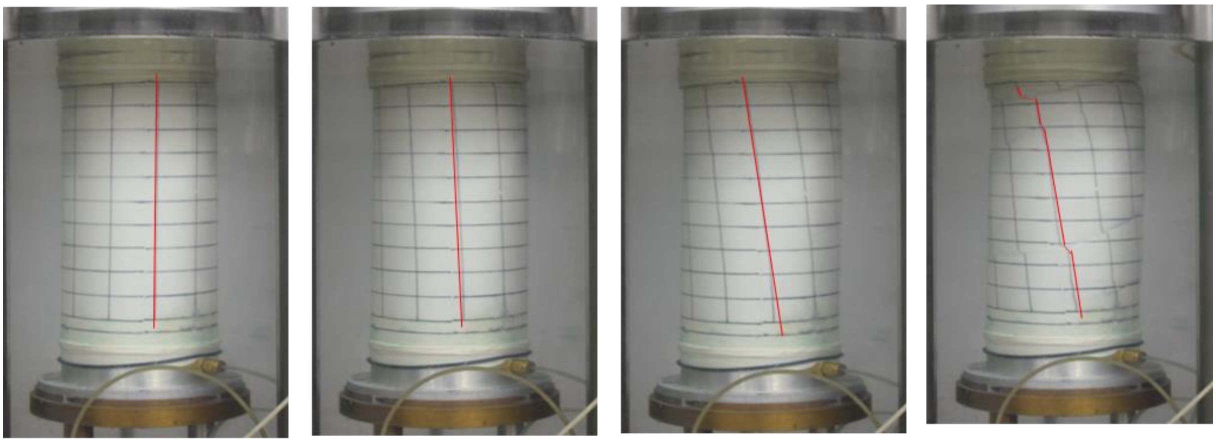
State 1 $\gamma = 0\%$

State 2 $\gamma = 5\%$

State 3 $\gamma = 10\%$

State 4 $\gamma = 21\%$

Photo 2: Specimen deformation at various stages for Test 1-4, Dr=47.9%



State A $\gamma = 0\%$

State B $\gamma = 5\%$

State C $\gamma = 10\%$

State D $\gamma = 21\%$

Photo 3: Specimen deformation at various stages for Test 1-7, Dr=72%

Undrained shear strength during monotonic loading

The undrained shear strength at QSS is taken by plotting at a vertical tangent at PTL. Whereas the shear strength at TSS is taken at the beginning of non-uniformity in the specimen (Kiyota et al. 2008). Figure 5 shows the correlation of undrained shear strength at QSS and TSS with the increase in the void ratio. It can be observed that, at the void ratio of 0.857, the shear strength at QSS and TSS are 5kpa and 32kPa respectively. Whereas, as the void ratio decreases, the difference between shear stress at QSS and TSS becomes significant i-e at void ratio of 0.693, shear strength is 40kPa and 297kPa at QSS and TSS respectively. This implies that denser specimen exhibits higher shear strength at QSS an TSS with the decrease in the void ratio.

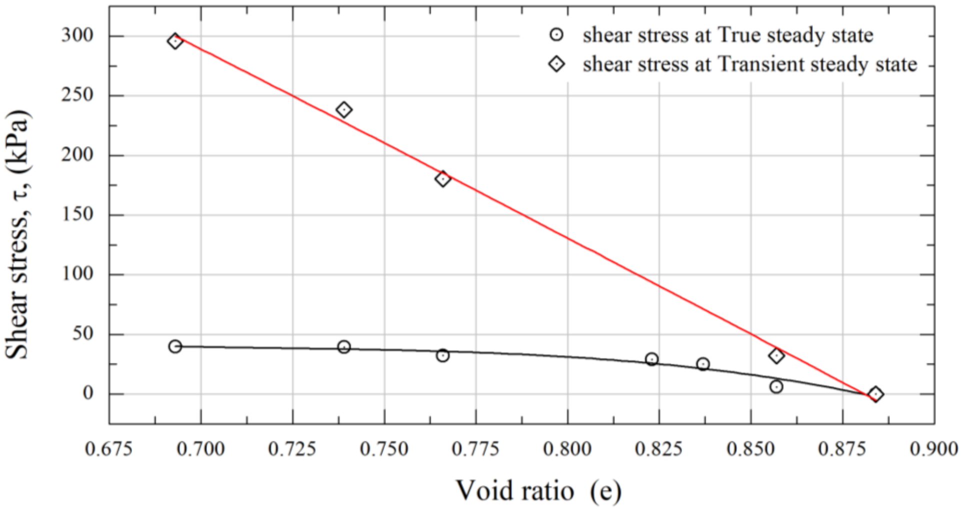


Figure 5: void ratio and shear stress at true steady state and transient steady state

CONCLUSIONS

In this study, the influence of relative density on undrained monotonic is investigated using large strain hollow cylindrical torsional shear apparatus. Except for very loose specimen, the true critical state was observed for medium dense and dense Toyoura sand. Influence on two types of undrained shear strength encountered during undrained monotonic loading showed that the shear strength at flow quasi-state increased with the increased in the density, as well as shear strength at true steady state. The increment of undrained shear strength at true critical state is significant as compared to undrained shear strength increase at quasi-state. Large deformation developed after exceeding the undrained shear strength at a true critical state. Whereas for loose sand, large deformation developed after exceeding shear stress at flow liquefaction state. The specimen will exhibit in a contractive way below the stress ratio of 0.54, whereas above this threshold stress ratio it will behave initially contractive followed by dilative response.

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