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대변형율 시험을 위한 공진주 비틂전단 시험기의 수정

Modifications of RC/TS (Resonant Column and Torsional Shear) Device for the Large Strain

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Abstract

Conventional RC/TS (resonant column and torsional shear) device usesa specimen with an aspect ratio (height-to-diameter) of 2:1 and this generates a maximum shear strain in the sample of about 1.5 % at the maximum rotation of the drives system. The objective of this study is to modify RC/TS device to generate higher strain amplitude. The modifications include a new base pedestal to overcome the limitations in the travel of the drive system and modification of coil wiring to increase torque. The effects of the new coil wire on torque in the electro magnetic drive system were evaluated and the application of modified device was illustrated using sand soil.

Keyword: RC/TS device, electro magnetic, large strain, torque

요 지

기존의 공진주 비틂 전단 시험기는 길이와 지름의 비율이 2:1의 시료를 사용하고 이는 가진 시스템의 최대 회전시 대략 1.5 %의 최대 전단 변형율을 일으킨다. 이번 연구의 목적은 대변형을 일으킬수 있는 공진주 비틂 전단 시험기의 수정이다. 수정 작업으로는 가진시스템의 왕복거리 한계의 극복을 위한 새로운 기초 받침 개발과 비틂력을 증가시키기 위한 코일 감는 방법의 변형이다. 가진 시스템의 새로운 코일감는 방법이 전자석 시스템에서 비틂력에 미치는 영향이 평가 되었고 모래를 시험한 수정된 장치의 응용이 기술되었다.

핵심용어: 공진주 비틂전단 시험기, 전자석, 대변형율, 비틂력

1. INTRODUCTION

A combined resonant column and torsional shear (RC/TS) device was developed by Dr. Stokoe and his graduate students at the University of Texas, Austin. The Stokoe-type RC/TS device is used in the solid dynamics laboratory at Utah State University. The USU device was modified in two ways to increase the maximum strain that can be generated during testing. First, modifications were made to the base pedestal to allow testing of shorter specimens. And, second, modifications were made to the drive system to the drive system to allow for higher torques.

Torsional shear testing was primarily investigated in this study to determine the laboratory cyclic behavior of soils. Simply switching from one type of test to the other is one of advantages of the Stokoe device. In torsional shear mode, a cyclic torsional force with

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a given frequency, generally in the range of 0.01 to 10 Hz, is applied at the top of specimen. Hence, the stress–strain hysteresis loop is determined from measuring the torque–twist curve. Shear modulus is calculated from the slope of a line through the end points of the hysteresis loop and material damping is determined from the hysteresis loop as the ratio of the total amount of energy dissipated and the peak strain energy stored in the specimen in one complete loading cycle.

Conventional RC/TS devices use a specimen with an aspect ratio (height–to–diameter) of 2:1. At the maximum rotation of the drives system this generates a maximum shear strain in the sample of about 1.5 %. The base pedestal of the USU device was modified to allow for testing shorter specimens. Using a specimen with an aspect ratio of 1:2, shear strains as high as 6 % can be generated.

Conventional RC/TS devices employ 8 coils wired in series in the electromagnetic drive system. The USU device was modified so that four pairs of coils are connected in parallel. This makes it possible to generate four times the torque of the conventional system.

2. FACTORS LIMITING THE STRAIN LEVELS IN RC/TSTESTING

The torsional shear test is used to measure shear modulus and damping ratio. Additionally, the test canbe used to track the reduction in modulus with number of cycles, and the effect of strain amplitude on this reduction.

Torsional testing is the ideal way to load a specimen in pure shear, with the caveats that strains vary with radius in torsional testing, and that it is difficult to develop large rotations in the conventional apparatus. It is easier to obtain high strains in the simple shear test. However, this method is impaired by non–uniform normal stresses and even gapping at the platens, and the lack of complementary shear stresses at the edges of the specimens.

There are three factors that limit the strain levels that can be obtained in RC/TS testing. First, limited torque in the drive system; second, limited travel in drive system; and third, limits in the deflection measuring system.

Torque can be increased by modifying the RC/TS drive system. Limitations in the travel of the drive system and deflection measurement system by using shorter specimens can be overcome. The maximum shear strain in torsional loading of right circular cylinder is described with the following equation.

$$\gamma = \frac{r_0}{L} \cdot \theta \qquad (1)$$

where, γ = shear strain,
r_0 = radius of soil specimen,
L = height of soil specimen, and
q = rotation (rad).

By decreasing the length of the specimen, a higher strain can be achieved for the same rotation of the drive in a RC/TS test. By fabricating taller base platens shorter specimens can be employed. An additional benefit to using short specimens in torsional shear testing is that the resonant frequency of the specimen and drive plate system will be higher. This allows testing to higher frequencies without inducing significant inertial effects.

The third limitation on strain in torsional shear testing is limits in the deflection sensor. The use of shorter specimens largely mitigates this limitation. Micro–proximeters are typically employed to measure rotations of the RC/TS drive plate, from which strains can be calculated. The proximitor calibration was performed using a milling machine to obtain an accurate measurement between the proximitor and target (Sasanakul, 2005). Sasanakul showed that the average linear range for the two proximitors is about 0.216 cm and the strain levels up to about 1.5% can be measured for soil specimen with an aspect ratio of 2:1. One solution to measure higher strains would be to employ a less sensitive proximeter with a large linear measurement range. Another solution is to make a local strain measurement using a strain gage attached to the specimen membrane. Safaqah and Riemer (2004) have developed a very good local strain gage for their in situ testing device. More research is needed for improved strain measurements.

3. MODIFICATION OF BASE PEDESTRAL

The base pedestal of a conventional RC/TS device is shown in Fig. 1. This pedestal is designed for a specimen with an aspect ratio of 2:1. To remain within the linear range of the proximitors, the maximum shear strain that can be measured is about 1.5 % with an aspect ratio of 2:1. Decreasing the height of soil sample can increase the shear strain for a given rotation, as can be seen from Eq. 1.

A modified base pedestal was fabricated at the Civil and Environmental Engineering Department machine shop, at Utah State University. It consists of one base plate, one bottom platen and one or two cylindrical rod(s) as shown in Figs. 2 and 3. The base plate, cylindrical rod(s), and bottom platen are fastened with a bolt. O-rings are used to prevent leakage from the drain port. The base plate, cylindrical rod(s), and bottom platen are fastened with a bolt shown in Figs. 2 and 3.

The rigidity of the driving system and fixity at the bottom of the specimen is critical to maintain proper boundary conditions during testing. Tightening two connecting bolt in the modified pedestal to a high torque provides a rigid base condition.

Figs. 4 and 5 show drawings of parts of the modified base pedestal and Fig 6 shows the two bolts required for different specimen heights.

Figs. 7 (a), (b), and (c) show the side view of a fixed-free resonant column test with specimen aspect ratio of 2:1, 1:1, 1:2, respectively.

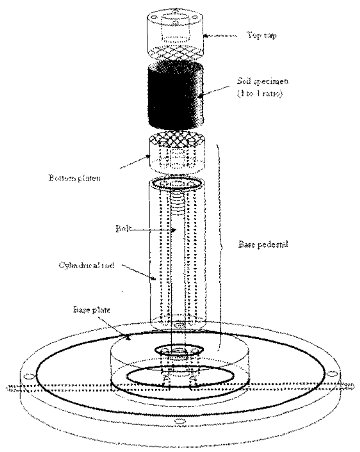

Fig. 1 Conventional RC/TS base pedestal (specimen aspect ratio of 2:1)

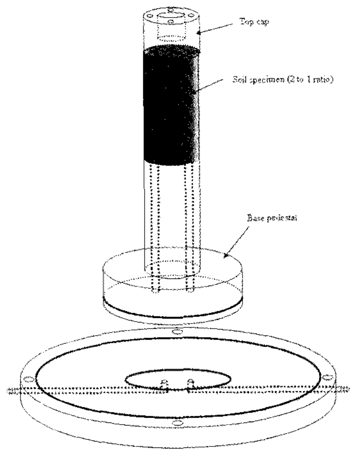

Fig. 2 Modified base pedestal I (specimen aspect ratio of 1:1)

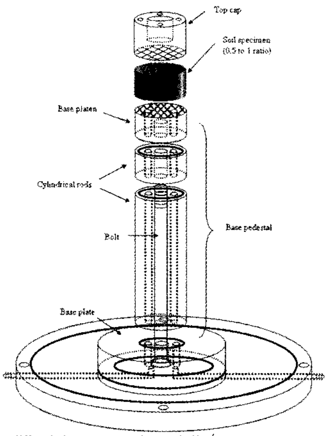

Fig. 3 Modified base pedestal II (specimen aspect ratio of 1:2)

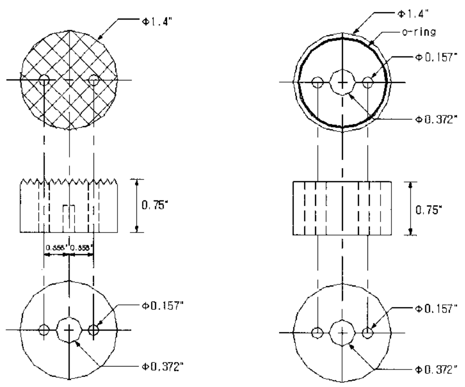

Fig. 4 Drawings of base pedestal parts (note: 1"=2.54cm)

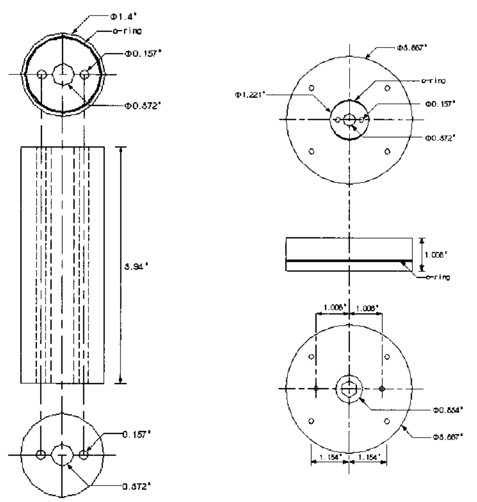

Fig. 5 Drawings of base pedestal parts (note: 1"=2.54cm)

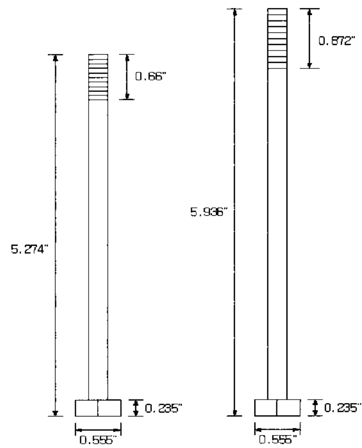

Fig. 6 Drawing of two screws to tighten cylindrical rods (note: 1"=2.54cm)

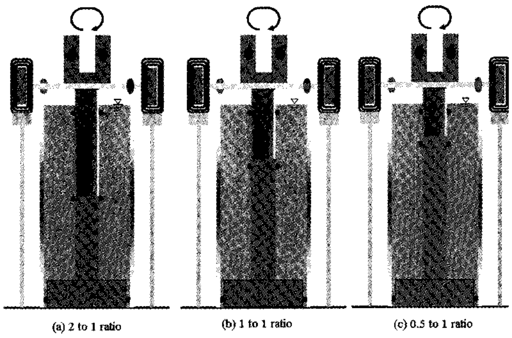

Fig. 7 Simplified side views of a RC/TS equipment with conventional and modified base pedestal

4. MODIFICATION OF RC/TS DRIVE SYSTEM

Limited torque is one of factors that limit the strain levels that can be obtained in RC/TS testing. The torque can be increased by three ways; first, by amplifying the drive signal, second, by using strong drive magnets, and, third by modifying the drive coils.

By using a precision, high-power amplifier, more current can be applied to the drive coils, greatly increasing the torque. Care must be taken to in staging testing to allow time intervals for the coils to cool when testing at high torques. With the amplifier used in the lab, torques up to 2 N−m can be generated, with practically no harmonic distortion.

By replacing Alnico 5 magnets in the current drive system with stronger rare earth magnets, the drive torque could be increased even more. This modification was not made to the USU device.

The 8 drive coils in a conventional RC/TS device are wired in series. The coils in the USU system were modified so that can be connected in the conventional manner (8 in series) or as 4 pairs of coils in parallel. Using parallel wiring allows for four times the torque of a conventionally wired drive system. However, rewiring the drive system changes the electromagnetic properties of the drive system. The following section presents the properties of the modified system.

4.1 Calculation of torque in series/parallel connection

The drive system in RC/TS equipment consists of a drive plate and eight drive coils. The drive plate is a four−armed aluminum plate that has rectangular shaped magnets attached to the end of each arm as shown in Fig. 8.

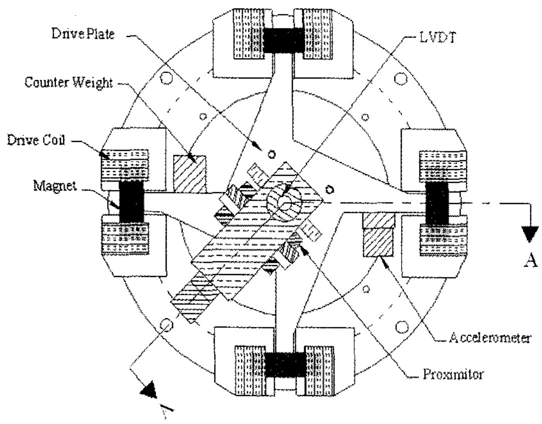

Fig. 8 Top view of the drive plate (from Sasanakul 2005)

Sasanakul (2005) showed that the torque created in the system can be calculated with the following equation.

$$T = k_i * i, \qquad (2)$$

where, ki = torque−current factor, and
i = current.

Figs 9 and 10 show the drive system of eight coils in series connection and parallel connection, respectively. The total resistor in series connection, Rseries is calculated by summation of the resistor, Rc from each magnet:

$$Rseries = 8 * Rc \qquad (3)$$

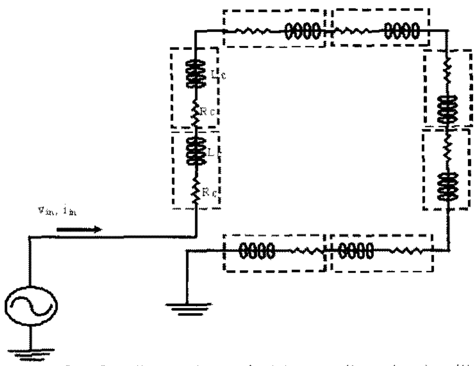

Fig. 9 Configuration of drive soils wired with series connection

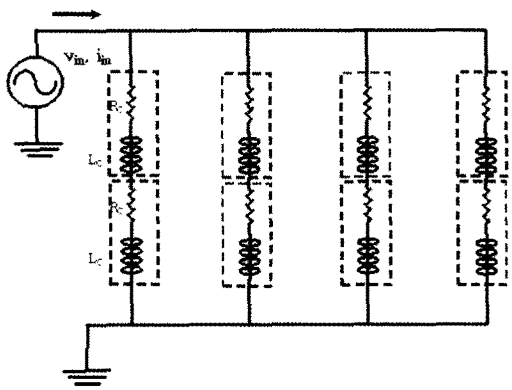

Fig. 10 Configuration of drive soils wired with parallel connection

By Ohm' s law, the total current in series connection, Iseries is calculated with the following equation:

$$I_{series} = v_{in} / R_{series} = v_{in} / (8*R_c) \quad (4)$$

where, vin is voltage suppied into coils. Hence, torque created in series connection is calculated from Eq. (2):

$$T_{series} = (k_i)_{series} * I_{series} = (k_i)_{series} * v_{in} / (8* R_c) \quad (5)$$

where, (k_i)series is the torque-current factor in series connection.

The total resistor in parallel connection, $R_{parallel}$ is calculated from the following equation:

$$R_{parallel} = 1/2* Rc \quad (6)$$

By Ohm' s law, the total current in parallel connection, $I_{parallel}$ is calculated with the following equation:

$$I_{parallel} = v_{in}/R_{parallel} = v_{in}/(1/2* R_c) = 2*v_{in}/R_c = 16*I_{series} \quad (7)$$

The current in series connection, I_{series} is equal to the current supplied into coils, I_{in} shown in Fig. 9:

$$I_{series} = I_{in} \quad (8)$$

And the current in parallel connection, $I_{parallel}$ is equal to the quarter of current supplied into coils, $¼*i_{in}$ shown in Fig. 10:

$$I_{parallel} = I_{in} / 4 \quad (9)$$

From Eqs. (8) and (9), the current in series connection, I_{series} is equal to four times the current in parallel connection, $I_{parallel}$. Therefore, the relationship between torque-current factor, (k_i)series in series connection and torque-current factor, (k_i)parallel in parallel connection is represented by:

$$(k_i)_{series} = 4 * (k_i)_{parallel} \quad (10)$$

The torque created in parallel connection is calculated from Eq. (2):

$$T_{parallel} = (k_i)_{parallel} * I_{parallel} \quad (11)$$

Using Eqs. (7), (10), and (11) the torque created in parallel connection, $T_{parallel}$ is four times the torque created in series connection, T_{series}.

The above equations neglects inductance of coil, L_c, however, inductance is decreased in exactly the same proportion as resistance when going from series to parallel so at any frequency the torque for parallel wiring will be four times the torque for series wiring at the same driving voltage.

Figs. 11 and 12 show the photos of the drive plate and magnet in connection of series and parallel, respectively.

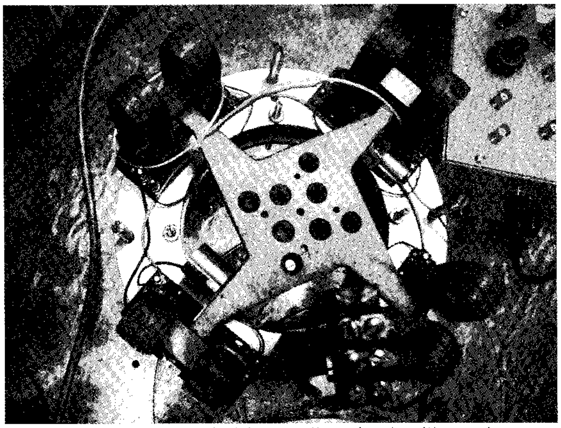
Fig. 11 Photo of drive coils wired with series connection

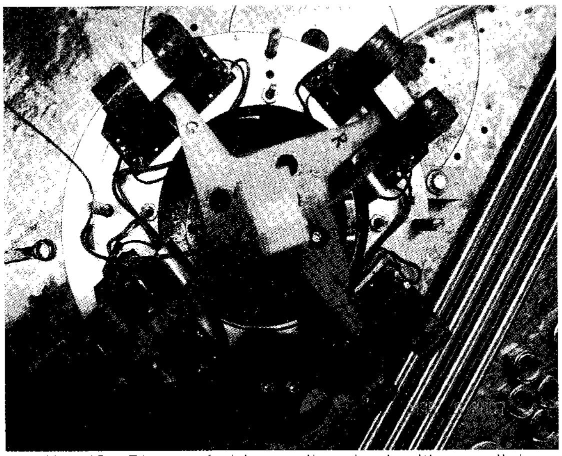
Fig. 12 Photo of drive coils wired with parallel connection

4.2 Measurement of torque-current factor in parallel connection

In this section, it is verified that the torque-current factor in series connection, (k_i)series is 1/4 times the torque-current factor in parallel connection, $(k_i)_{paralle}$ shown in Eq (10).

Sasanakul (2005) determined torque-current factor in series connection by the measurement of torque and current. The current was measured using a current proportional signal from the power amplifier and the torque was determined by performing the torsional shear tests on calibration specimens with known torsional stiffness and measuring torque directly using a torque sensor. Torque-current factors determine for the coils in series is presented in Table 1. Sasanakul noted that slight differences in the results can be attributed to errors in the stiffness of each specimen.

Table 1. Factors of ki Determined from Drive Coils Wired with Series Connection, unit:N-m/A (from Sasanakul, 2005)

Frequency (Hz)	14-Hz Specimen	62-Hz Specimen	128-Hz Specimen	188-Hz Specimen
0.01	0.413	0.434	0.440	0.434
0.05	0.413	0.434	0.437	0.436
0.1	0.413	0.434	0.436	0.435
0.5	0.414	0.434	0.435	0.436
1	0.415	0.434	0.438	0.435
Average	0.414	0.434	0.437	0.435

The torque-current factor in parallel connection was determined by the measurement of torque and current in the same manner. In this study the torque was calculated based on the stiffness of the 14-Hz calibration specimen and 62-Hz calibration specimen. Figs. 13 and 14 show the 14-Hz calibration specimen and 62-Hz calibration specimens, respectively.Tables 2 and 3 present the torque-current factor, $(k_i)_{parallel}$ determined from drive coils wired with parallel connection on 14-Hz calibration specimen 62-Hz calibration specimens, respectively. It can be seen that that the torque-current factor in series connection, (ki)parallel is almost exactly 1/4 times the torque-current factor in series connection, (ki)series.

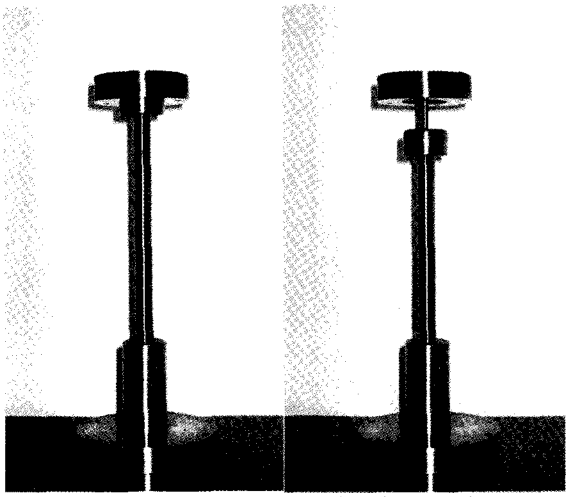

Fig. 13 Photo of 14-Hz calibration specimen

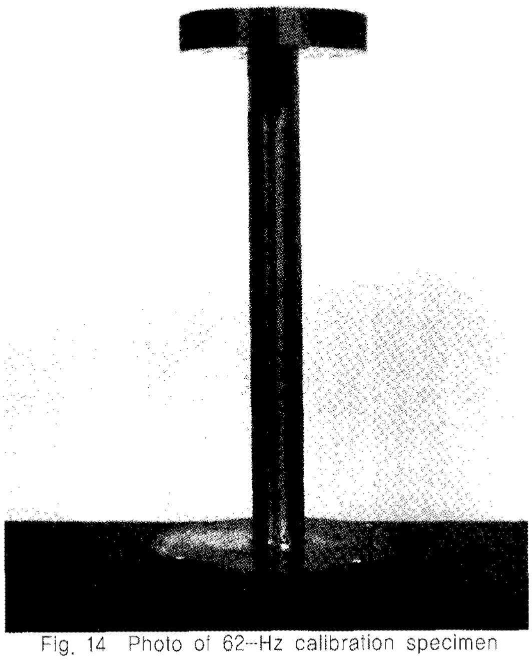

Fig. 14 Photo of 62-Hz calibration specimen

Table 2. Factors of k_i Determined from Drive Coils Wired with Parallel Connection on 14-Hz Calibration Specimen, unit:N-mt/A

freq=1Hz

θ (rad)	K_θ (N-m/rad)	Torque (N-m)	current (A)	Ki (T/A)
0.035	24.329	0.862	8.209	0.105
0.036	24.329	0.873	8.210	0.106
0.034	24.329	0.831	8.195	0.101
0.035	24.329	0.862	8.275	0.104
0.034	24.329	0.825	8.272	0.100
0.035	24.329	0.845	8.257	0.102
			avg	0.103

freq=0.5Hz

θ (rad)	K_θ (N-m/rad)	Torque (N-m)	current (A)	Ki (T/A)
0.034	24.329	0.833	8.140	0.102
0.034	24.329	0.822	8.124	0.101
0.034	24.329	0.816	8.105	0.101
0.033	24.329	0.811	8.206	0.099
0.033	24.329	0.809	8.190	0.099
0.033	24.329	0.806	8.167	0.099
			avg	0.100

freq=0.1Hz

θ (rad)	K_θ (N-m/rad)	Torque (N-m)	current (A)	Ki (T/A)
0.032	24.329	0.790	7.933	0.100
0.032	24.329	0.782	7.859	0.100
0.032	24.329	0.779	7.790	0.100
0.032	24.329	0.774	7.972	0.097
0.032	24.329	0.772	7.899	0.098
0.031	24.329	0.766	7.834	0.098
			avg	0.099

freq=0.05Hz

θ (rad)	K_θ (N-m/rad)	Torque (N-m)	current (A)	Ki (T/A)
0.032	24.329	0.784	7.946	0.099
0.032	24.329	0.778	7.782	0.100
0.031	24.329	0.766	7.651	0.100
0.031	24.329	0.762	7.953	0.096
0.031	24.329	0.752	7.806	0.096
0.031	24.329	0.749	7.692	0.097
			avg	0.098
			total avg	0.100

Table 3. Factors of ki Determined from Drive Coils Wired with Parallel Connection on 62-Hz Calibration Specimen, unit:N-m/A

freq=1Hz

θ (rad)	K_θ (N-m/rad)	Torque (N-m)	current (A)	Ki (T/A)
0.002	466.193	0.876	8.073	0.109
0.002	466.193	0.739	8.068	0.092
0.002	466.193	0.872	8.171	0.107
0.002	466.193	0.735	8.161	0.090
			avg	0.099

freq=0.5Hz

θ (rad)	K_θ (N-m/rad)	Torque (N-m)	current (A)	Ki (T/A)
0.002	466.193	0.871	8.056	0.108
0.002	466.193	0.734	8.039	0.091
0.002	466.193	0.864	8.145	0.106
0.002	466.193	0.728	8.127	0.090
			avg	0.099

freq=0.1Hz

θ (rad)	K_θ (N-m/rad)	Torque (N-m)	current (A)	Ki (T/A)
0.002	466.193	0.823	7.711	0.107
0.001	466.193	0.685	7.652	0.089
0.002	466.193	0.817	7.780	0.105
0.001	466.193	0.677	7.721	0.088
			avg	0.097

freq=0.05Hz

θ (rad)	K_θ (N-m/rad)	Torque (N-m)	current (A)	Ki (T/A)
0.002	466.193	0.814	7.646	0.107
0.001	466.193	0.671	7.530	0.089
0.002	466.193	0.803	7.687	0.104
0.001	466.193	0.660	7.582	0.087
			avg	0.097

freq=0.01Hz

θ (rad)	K_θ (N-m/rad)	Torque (N-m)	current (A)	Ki (T/A)
0.002	466.193	0.806	7.586	0.106
0.001	466.193	0.638	7.449	0.086
			avg	0.096
			total avg	0.098

4. APPLICATION OF MODIFIED RC/TS DEVICE

The application of modified RC/TS device was illustrated using sand soils. Torsional shear (TS) test was performed to obtain hysteresis loops based on saturated sand soil. The grain size distribution of the tested sand soils is shown in Fig. 15 and the basic soil properties are summarized in Table 4. Using the modified device, the shear strains were generated successfully as high as 5.2 % as shown in Fig. 16. At high strain levels, it was known that the stiffness of the saturated sand soil is reduced due to cyclic degradation as is expected (Kim, 1991). This is observed as the slope of hysteresis loop begins to flatter with increasing number of cycles as shown in Fig. 16. This means that the secant shear modulus decreases as the number of cycle increase. Many researches are required to determine the relationship between cyclic shear, γ, and cyclic degradation of modulus with various soil types.

Table 4. Soil Properties Index of Tested Sand Specimen

USGS	SP
Curvature coefficient, C_c	1.423
Uniformity coefficient, C_u	3.1
PI	NP
Median particle size, D_{50}, mm	0.57

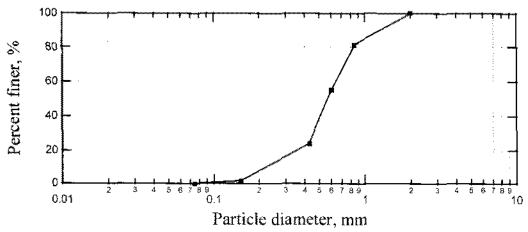

Fig. 15 Grain size distribution of the tested sand soil

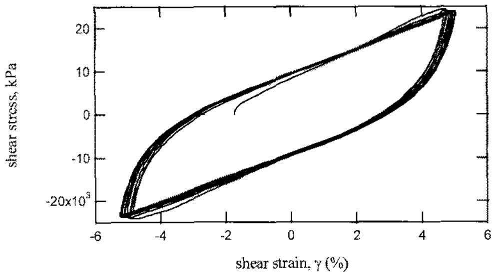

Fig. 16 Hysteresis loops of ten cycles of loading on sand soil specimen tested at a confining pressure of 101.3 kPa

5. CONCLUSIONS

It was attempted to modify RC/TS device to generate higher strain amplitude. There are two factors that limit the strain levels: Fist, limited travel in drive system; second, limited torque in the drive system. The first limitation was dealt with by decreasing the length of the specimen a higher strain can be achieved for the same rotation of drive system and the high strain level is measured within linear proximitor measurement range. And the second limitation was dealt with by fixing the eight coils in series connection modified to parallel connection, which generates four times much torque at given voltage source. Using the modified device, the shear strains were generated as high as 5.2 %, which is almost four times the shear strain of the conventional system.

6. ACKNOWLEDGMENTS

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