# PID Controlled Combined Axial Torsional Testing System for Cohesive Soil

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Abstract

The present paper summarizes the details of a testing system developed for performing combined axial torsional loading on hollow cylinder cohesive specimens. The axial-torsional loading system used in this research employs a MTS loading frame with Testware-SX control. The frame is operated hydraulically through the use of a servovalve that feeds actuators which can independently control the axial load/displacement and/or torque/angular rotation. Stress paths ranging from triaxial compression to pure shear to triaxial extension can be obtained using this testing apparatus by rotating the fixed inclination of the major principal stress ($\beta$) with the axis of rotational symmetry. The ratio between the torsional shear stress increment and the vertical stress increment is maintained a constant value to achieve a desired $\beta$ value. A new approach using PID control was implemented to achieve precise control. To implement this into the control procedure, calculated control channel was used throughout the test using updated specimen dimensions. Undisturbed hollow cylinder specimens were obtained using high water content kaolinite slurry, and custom built consolidometer. Typical test results for stress path corresponding to $\beta = 30$ degrees were presented for isotropically consolidated kaolin clay under undrained conditions.

## Previous Hollow Cylinder Axial-Torsional Devices

Triaxial testing of hollow cylinder soil specimens subjected to torque was first performed by Cooling and Smith [1936]. In their study, torque was applied to unconfined hollow cylinder specimens to evaluate the resistance of soil under pure shear conditions. The use of specimens having a hollow cylinder shape in soil testing became more widely used recently. The effects of the intermediate principal

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stress, $\sigma_2$, and the effects of principal stress rotation was studied by Broms and Casbarian [1965]. They concluded that the principle of superposition could be used to predict the shear strength and pore pressure parameters for any rotation of the principal stress axes.

In the mid 1960's, Saada introduced an automated testing apparatus which could be used to perform hollow cylinder axial - torsional testing [Saada 1967 and 1968]. The inclination of the principal stresses created by subjecting the soil specimens to a combination of axial and torsional stresses was used to study anisotropy in soils. This device was used in many subsequent investigations to examine the behavior of anisotropic clays [Saada 1967, Saada and Zamani 1969, Saada and Ou 1973, Saada and Bianchini 1975]. Saada discusses his findings as well as the advantages and limitations of hollow cylinder testing in a state of the art paper [Saada 1988]. Ishibashi and Sherif [1974] developed a torsional simple shear apparatus to study soil liquefaction.

Hollow cylinder specimens in Saada's studies were obtained by coring full cylinder specimens. Preparing samples in this manner can lead to handling and some disturbance to the specimens. In this research, specimens were made using the slurry consolidation method and trimming of the specimens was avoided. Saada's device was limited to load control. This prohibits the possibility of investigating the post failure conditions of the soil. Pore pressure equilibration and strain rate become major issues at failure under load control. Failure is sudden in load control mode; the strain rate becomes very fast. In clay specimens, the pore pressure may not have a chance to equilibrate when this happens.

Lade developed a torsion shear apparatus with an outside diameter of 22 cm, an inside diameter of 18 cm and a height of 5 cm [Lade 1975]. Further examination revealed that these specimen dimensions created nonuniform stresses and strains in the hollow cylinder [Lade 1976] and a specimen height of 25 cm was found to create a uniform stress state in the hollow cylinder [Lade 1981]. Lade's work with kaolin clay using the torsion shear apparatus revealed that the failure surface obtained from experiments on $K_o$ consolidated hollow cylinder torsion shear tests could be modeled using an isotropic failure criteria [Hong and Lade 1989]. Hong and Lade also examined the strain increment and stress directions in torsion shear tests on $K_o$ consolidated kaolin clay. They observed that the clay behaved as an elasto-plastic material [Hong and Lade 1989].

A hollow cylinder torsion shear testing device which was capable of applying different internal and external cell pressures was introduced in 1983 [Hight et al. 1983]. Their hollow cylinder device tested sand specimens with an inside diameter of 20.3 cm, an outside diameter of 25.4 cm and a height of 25.4 cm. The large sample size was necessary to be able to monitor displacements over a central gauge length and measure pore pressure of the specimen at its mid height. They used finite element analysis to determine the optimum specimen dimensions. The authors were able to follow complex stress paths using manual control of the apparatus.

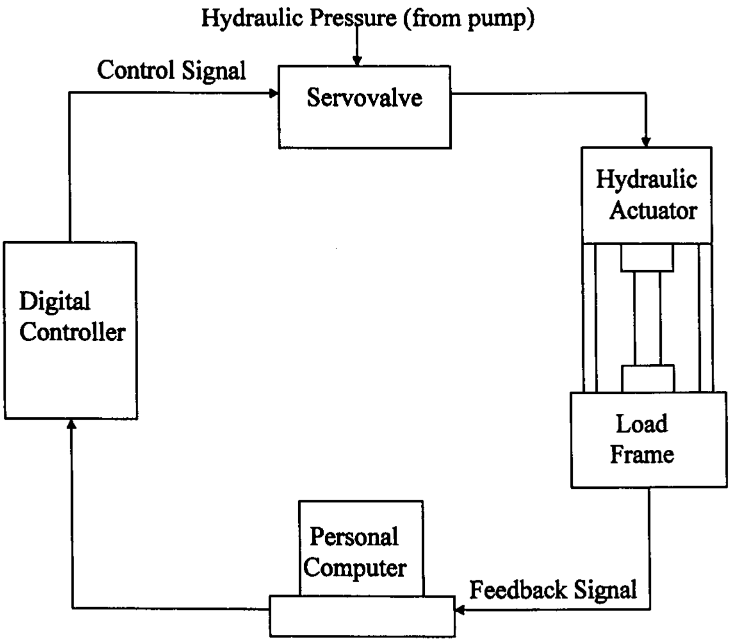
Problems associated with past test data have been discussed recently [Tatsuoka et al. 1986, Sayao and Vaid 1991, Frost and Drnevich 1994]. The major issues that primarily deal with testing procedures are: 1) measurement of axial and torsional forces without any coupling effects or cross-talk, 2) neglecting the inclusion of half the specimen weight in the calculation of vertical stress at the center of the specimen, 3) correction of forces carried by the membrane and filter paper strips for a given cell pressure, 4) provision of full friction surfaces to the specimen to avoid slippage at the interfaces with end-platens, and 5) obtaining homogeneous and repeatable hollow cylinder soil specimens.

## Axial - Torsional Shear Frame and Control Software

The axial-torsional loading system used in this research employs a MTS loading frame with Testware-SX control. The frame is operated hydraulically through the use of a servovalve that feeds actuators which can control the axial load/displacement and/or torque/angular rotation. Along the axial direction the system is capable of applying ±9.8 kN load or 12.7 cm displacement (full stroke). Along the torsional axis, the system is capable of applying ±113 N-m torque or ± 45° rotation. The stress or strain controlled actuators can be programmed in Testware-SX to have accurate, automated, and repeatable control of the axial and torsional loads or displacements. With this testing system, any desired stress path involving the rotation of the major principal stress can be accurately achieved for soil specimens. The MTS system (Fig. 1) uses a closed loop servo-control for achieving the desired stress or strain path. The control loop has a very fast update rate of 5 kHz and is capable of supporting up to ten input signals and eight calculated control channels. The controlling elements are the personal computer and the digital controller; they determine what the actuator does. The control signal being generated represents the action the actuator should take to apply load or deformations to the specimen. The control signal is transmitted to the controlled element consisting of the servovalve, the hydraulic actuator, and the specimen itself. The feedback is a response from the appropriate sensor(s) that indicates how the controlled element has performed for the new conditions of variables (e.g. stress or strain). The digital controller then reacts to the relative difference between the desired signal and the feedback signal and adjusts the control signal to correct the difference. The control software specifically developed to perform combined axial torsionsal tests on kaolin clay will be discussed in a later section.

## Axial - Torsional Shear Cell

An axial torsional triaxial cell was custom designed and fabricated in a previous study by Abrantes [1998] under the direction of the primary author. The main characteristics of this cell are: the ability to apply normal and shear stresses on a hollow cylinder specimen without coupling or slippage, individual control of pore,




| Slot | Conditioner | Type | Range/Capacity |
|---|---|---|---|
| J1 | AC | LVDT (axial displacement) | 12.7 cm |
| J2 | DC | Load Cell | 9.8 kN |
| J3 | DC | Extensometer | 12% Full Scale |
| J4 | DC | Torque | 113 N-m |
| J5 | DC | Angle Rotation | +/- 45 degrees |
| J6 | DC | Differential Transducer | 5.6 kPa |
| J7 | DC | Cell Pressure | 1379 kPa |
| J8 | DC | Load Cell | |
| J9 | DC | Torque | |
| J10 | DC | Pore Pressure | 1379 kPa |
| J11 | | External Sensor (open) | |
| J12 | | Servovalve Connector (E/P Transducer) | |
| J13 | | Servovalve Connector (Torsion) | |
| J14 | | Servovalve Connector (Axial) | |

Digital Controller

Fig. 1: Combined Axial Torsional Test System

cell, axial and shear stresses to the specimen, and ease of assembly. The cell can accomodate specimens with an inside diameter of 7.1 cm, an outside diameter of 10.2 cm and a height of 20 cm. In this research, the pressure on the inside and the outside of the hollow cylinder specimen were always kept equal. Radial drainage is provided through holes drilled on the sides of the end caps and through the use of filter paper strips. Porous plastic plugs were placed in the drainage holes to prevent them from clogging with clay during saturation and consolidation. The filter paper pattern, following the recommendations of Berre [1982 was used for compression, extension, and torsion shear tests. For β equal to 0°, 30°, and 45°, the filter paper pattern suggested for triaxial compression was used because the specimen was being compressed axially. For β equal to 60° and 90°, the filter paper pattern recommended for triaxial extension was used because the specimen was being extended axially. The lack of prior recommendations in the literature regarding filter paper for three-dimensional testing lead to this. The filter paper was orientated on the sample such that it would unwind with an increase in torque. To provide frictional resistance at the end caps, short, metal tabs were glued to the end caps. These tabs are very thin and have a height of 5mm and caused minimal disturbance to the specimen during the process of attaching the end platens. This cell was also used to perform tests on solid cylinder specimens by employing a different set of end caps. The solid cylinder end caps have radial drainage and are designed to be used as lubricated ends with thin latex membranes and vacuum grease. The specimens had a diameter of 10 cm and a height of 10 cm (H/D = 1.0). The lubricated end caps have a diameter of 10.8 cm and allow the specimen to deform as a right cylinder during shearing, resulting in negligible frictional end boundaries during the application of deviator stress. A complete drainage path from the sample to the drainage lines was provided using filter paper strips. Lubrication is provided through the use of 0.6 mm thick membranes and a thin layer of vacuum grease. The inclination of filter paper strips used in this research were based on the recommendations of Berre [1982].

A design modification was made to the cell to allow for long-term drained testing. Over the course of several days required for drained testing, air was found to diffuse into the confining fluid, across the latex membrane, and into the pore water lines. An impermeable air bladder was added between the cell and the pressure supply to prevent the diffusion of air across the latex membrane and into the sample. A thin layer of silicone oil was added to the top of the burette, part of the volume change device. This was done to prevent the loss of water through evaporation during drained testing and minimize air diffusion under back-pressure.

## Hollow Cylinder Specimen Preparation

Undisturbed hollow cylinder kaolin clay specimens were obtained using the slurry consolidation method. The slurry had an initial water content of 125%. The slurry was consolidated one dimensionally. A custom built consolidator was used to consolidate the specimens. The consolidator was lined with Teflon to minimize surface friction effects. Using double drainage, specimens were consolidated under a vertical stress of 207 kPa (30 psi) for approximately 48 hours under $K_o$ conditions, well beyond the end of primary consolidation. The specimens had a final inside diameter of 7.1 cm, an outside diameter of 10.2 cm, and a height of 20.3 cm. These dimensions provide a zone of uniform stress and strain distribution by minimizing the effects of the frictional end platens in axial – torsional testing [Lade 1981].

In a previous research program performed using this consolidator [Abrantes 1998], a difference in the water contents of 4.5 % was noticed for hollow cylinder specimens after slurry consolidation. The slurry consolidation procedure involved pouring kaolinite slurry into the teflon lined consolidometer and subjecting it to 210 kPa by a loading piston at the top. Drainage was allowed through the top and bottom of the consolidometer. For these specimens, the water content varied from 43% (top of sample) to 47.5% (bottom of sample) at the end of $K_0$ consolidation (Fig. 2). The average water content was 45.7% and the void ratio varied from 1.13 at the top of the specimen to 1.24 at the bottom of the specimen. This was attributed to friction due the large height to wall thickness ratio. After isotropic consolidation in the cell, the water content, and correspondingly, the void ratio, was constant across the height. However, this results in a change in the cross sectional area because the change in the void ratio is different at each point along the height of the sample. At the top of the sample, the void ratio changes from 1.13 to .947 and from 1.24 to .947 at the bottom of the specimen. This corresponds to the cross sectional area of the specimen ranging from 39.4 cm$^2$ at the top to 36.1 cm$^2$ at the bottom.

An alternative method was devised in an attempt to minimize the water content variation across the height of the specimen. The main idea was to consolidate the sample by applying vertical stress from both ends of the slurry consolidometer. The modified procedure involved consolidating from one direction for several hours, then remove the base and use two pistons and consolidate from both directions simultaneously. The reason for the specimen to be consolidated in one direction initially was to transform the slurry to a semi-solid state for facilitating consolidation from both directions. The resulting variation of the water content using this method is also shown in Fig. 2. The average water content was 45.2%. The water content is still higher in the middle, but is more uniform in the representative zone free from the end platens. Full cylinder specimens were also prepared using the slurry consolidation method. Powdered kaolinite was mixed with de-aired water to make a slurry with an initial water content of 155%. The slurry

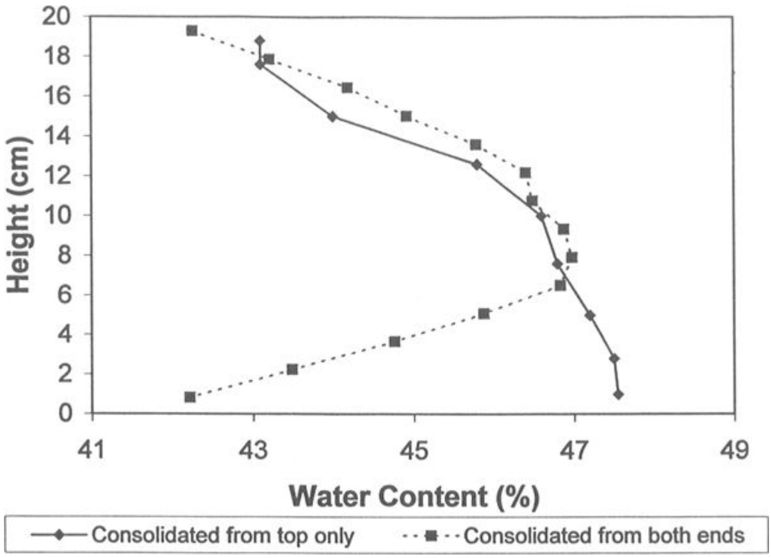



Fig. 2: Water Content Variation Across Hollow Cylinder Specimen Height

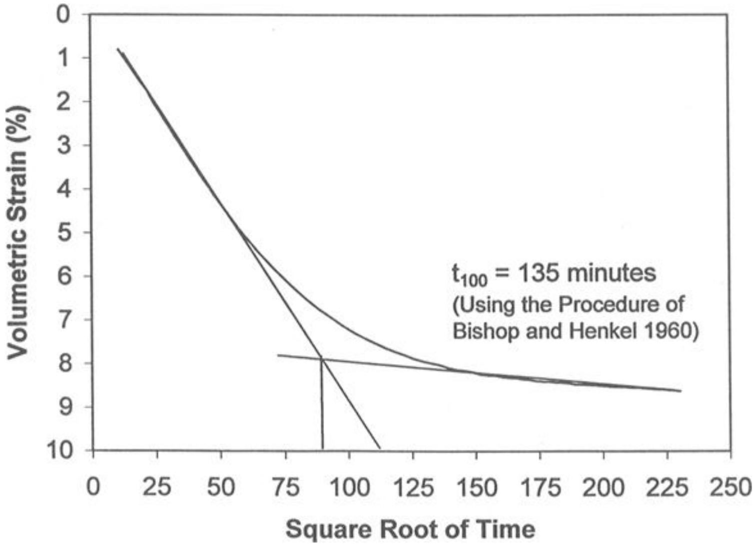



Fig. 3: Isotropic Consolidation Curve (276 kPa)

was consolidated one dimensionally at 207 kPa (30 psi). The final dimensions of the cylinder were 10 cm (4 in) in diameter and 10 cm (4 in) in height. The final water content was 44%. The maximum water content variation across the specimen height was less than 2%, resulting in very uniform specimens.

## Specimen Assembly

The triaxial cell used for this research permits easy assembly of both hollow and full cylinder specimens with minimal disturbance. The following steps were used in the assembly process for hollow cylinder specimens:

1) The bottom cap is attached to the base of the cell.
2) A latex membrane with a diameter of 7.1 cm and a thickness of .6 mm is sealed to the inside of the bottom cap.
3) The specimen is lowered around the membrane and is seated on the bottom cap.
4) The top cap is placed on the specimen and the inner membrane is sealed around the inside of the top cap.
5) Filter paper, used to provide radial drainage, is placed on the specimen. The filter paper is designed so that no corrections are needed for the axial load. The angle of the filter paper differs for compression and extension tests [Berre 1982]. Great care was taken to ensure that the filter paper is always in contact with the porous plugs in the top and bottom caps.
6) At this point, the outside membrane is placed around the specimen and is sealed with O-rings.
7) The pore lines are attached to the top cap.
8) The Lucite chamber is set into place and the top cap is attached to the piston.

After the specimen is fully assembled in the triaxial cell, the saturation process was started. The system is flushed with $CO_2$ and then purged with de-aired water. The active back pressure method is used to dissolve any $CO_2$ trapped in solution. A back pressure of only 35 kPa was sufficient to reach full saturation in few hours. Full saturation was assumed when the B-value ($\Delta u/\Delta\sigma_{cell}$) reached a value of 0.99. The next step in the process was to perform isotropic consolidation. Valves connecting pore lines to the volume change device were closed and the cell pressure was increased steadily. When the cell pressure reached the desired level, the drain lines were opened and the consolidation process started. During consolidation, the volume change of the specimen was measured with a burette and the change in height of the specimen was measured with a dial gauge. This was required to calculate the correct dimensions of the specimen at the end of consolidation. At the end of consolidation, Eq. 1 was used to find the new outside radius and the new inside radius of the hollow cylinder [Tatsuoka, 1986]:

$$R_o = \sqrt{\frac{1-\varepsilon_v}{1-\varepsilon_a}} \cdot \left(R_o\right)_{initial} \tag{1}$$

A typical example of volume change behavior for a hollow cylinder specimen during isotropic consolidation is shown in Fig. 3. The consolidation process was allowed for 14 hours which is well beyond the time of completion for the primary consolidation.

In drained triaxial testing, the consolidation curve is also used to find the appropriate deformation rate during shearing. Bishop and Henkel's [1960] procedure was used to find the appropriate strain rate to ensure that no excess pore pressure is built up during the application of shear stress. Using their method, the time to failure was found to be 35 hours. Assuming that failure occurs at about 10% axial strain, a strain rate of .0045 %/min (deformation rate of .0009 cm/min) was used. This rate was found to be slow enough to prevent the generation of excess pore pressures during shearing. A strain rate of .05%/min was used for the undrained tests and permitted equalization of the pore pressures during undrained testing.

## Calculation of Stresses and Strains

The kaolin clay hollow cylinder specimens were subjected to a combination of axial load and/or torque at the end of isotropic consolidation. During testing, the inner and outer pressures ($P_i$ and $P_o$) were kept equal throughout testing. Fig. 4 shows the states of stress produced on a hollow cylinder specimen subjected to a combination of axial load and torque. After correcting for the inner and outer membrane stiffness, piston friction, piston uplift, and system compliance, Eqs. 2 through 9 were used to calculate various stresses and strains on the hollow cylinder specimen [Saada 1988]. A single load cell measured the axial load and torque. No measurable "cross-talk" was noticed between the axial load and torque readings.

$$\sigma_z = \frac{F_{ax}}{\pi(R_o^2 - R_i^2)} + \sigma_{cell} \tag{2}$$

$$\sigma_r = \sigma_{cell} \tag{3}$$

$$\sigma_\theta = \sigma_{cell} \tag{4}$$

$$\tau_{\theta z} = \frac{3M_t}{2\pi(R_o^3 - R_i^3)} \tag{5}$$

$$\varepsilon_z = \frac{\Delta H}{H} \tag{6}$$

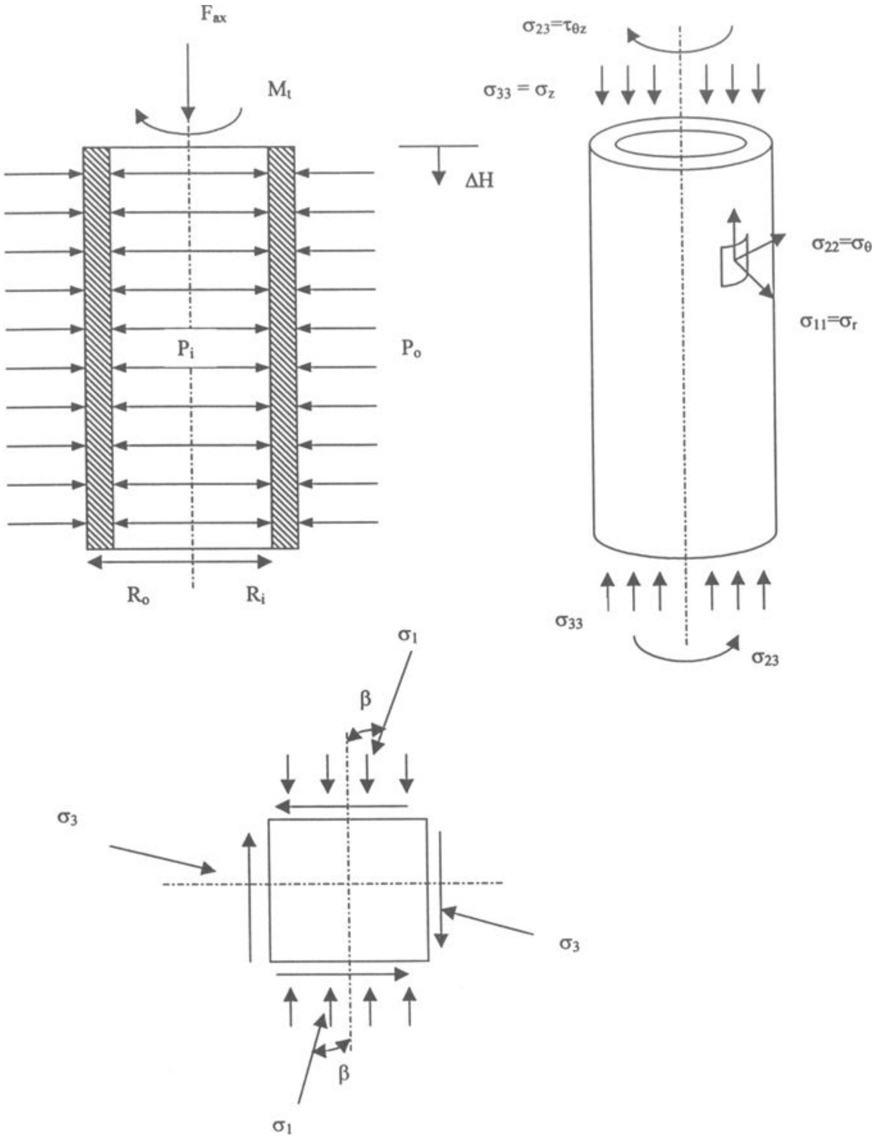



**Fig. 4: State of Stress in Hollow Cylinder Specimen**