Cubical Pneumatic Cushion Triaxial Soil Test Unit

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ABSTRACT. *A cubical triaxial unit (CTU) was designed and built that used pneumatically pressurized flexible cushions to apply a three-dimensional, independently controlled, compressive stress state to a cubical soil sample measuring 50.8 mm along each side. The apparatus was computer controlled and could operate safely up to pressure levels of 1 MPa. The performance of the CTU was evaluated by comparing it to data obtained from an existing cylindrical triaxial device. Also, data from the CTU were used to validate Bailey and Johnson's (1989) soil compaction model. The CTU will be used to determine how soils react to three independent principal stresses, and to aid in the development of finite element techniques to predict soil and soil-machine behavior.* **Keywords.** *Soil compaction, Soil dynamics, Pneumatics, Digital controls.*

Soil compaction by agricultural machines can impede root growth, increase energy expenditures of subsequent tillage operations, increase surface runoff, and reduce crop yields (Grisso et al., 1987). A better understanding of soil reaction to applied forces could lead to improved management systems that would prevent excessive soil compaction. Also, this knowledge could be used to design more efficient and effective tillage tools and traction devices (Bailey and Johnson, 1989).

In recent years, the finite element method has been used to predict soil compaction (Raper and Erbach, 1990). The solutions obtained from this method are only as good as the constitutive equations used to describe the relationship between the applied stresses and the resulting soil deformations. The conventional triaxial device (Bailey et al., 1984) does not allow the intermediate principal stress, σ_2, to be controlled independently, since σ_2 must equal σ_3 in this device. Therefore, the soil compaction models developed from the conventional triaxial device have been restricted to the two dimensions containing the major and minor principal stresses. It has been recognized that the intermediate stress, σ_2, influences the soil strength and deformation (Dunlap, 1968; Sture and Desai, 1979).

This article describes the design and operation of a cubical triaxial unit (CTU) that is capable of independently controlling all three principal stresses (Gibas, 1992). The performance of the CTU was evaluated relative to a conventional cylindrical triaxial device. Data obtained from the CTU were also compared to Bailey and Johnson's (1989) soil compaction model.

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Construction and Operation of CTU

The CTU (fig.1) is similar to devices currently in use at several U.S. institutions (Sture and Desai, 1979; Ko and Scott, 1967; Bishop and Wesley, 1975; Dunlap, 1968; Kumar, 1972; Ko et al., 1986). These devices are used for determining the constitutive behavior of many different materials and operate over a large range of mean stress levels. However, the CTU was designed specifically to allow for the large strains which occur at low stresses in loose, unsaturated, agricultural soils.

The CTU used flexible rubber cushions to apply three independently controlled stresses to a cubical soil specimen. The resulting deformation of the six faces of the cube were measured at the center of each face using linear variable differential transformers (LVDTs). The volume of

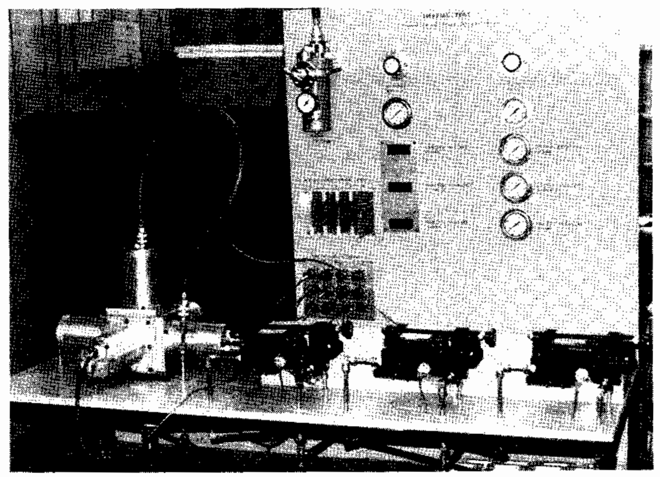

Figure 1–Assembled cubical triaxial unit (CTU) with supporting controls.

air displaced from the soil sample and the three orthogonal stresses were also continuously measured. The CTU was capable of operating at a maximum pressure of 1 MPa when $\sigma_1 = \sigma_2 = \sigma_3$.

Cubical Main Frame Assembly

Figure 2 shows a cross-sectional view of the assembled CTU. The 139.7-mm cubical main frame, the main walls, and the LVDT protection cylinder were machined from aluminum. The cubical cavity's internal dimension was 63.5 mm. The main walls (fig. 2) served to hold the stress applying cushions in place and complete the pressure chamber.

The LVDT protection cylinder enclosed the LVDT within the pressure chamber. Both ends contained a circular recess which housed an O-ring. These O-rings formed axial compression seals on both sides of the protection cylinder when the main wall and protection cylinder cap were bolted to the protection cylinder. The protection cylinder cap accommodated a pressure inlet, electrical feedthrough, and a pressure transducer.

Soil Sample Holder

A soil sample holder was used to isolate the sample from the flexible rubber pressure cushions and to allow air forced from the sample to be collected and measured. The soil sample holder was made of a 1:1 volume ratio of Dow Corning 1890 and VM&P naphtha. The VM&P naphtha was used to thin the silicone rubber compound to a viscosity conducive to a dipping process. This rubber material was chosen because it cured quickly at room temperature, had excellent moisture resistance, abrasion resistance, and memory, and was extremely elastic. Another advantage was that molds could be dipped into it to create the soil sample holder.

The cubical mold was made of teflon because that was one of the few materials from which the cured rubber would release. The teflon cube measured 50.8 mm along each side. A 3.18-mm outside diameter plastic tube was inserted into the middle of an edge of the teflon cube. This tube was used to transport displaced air from inside the soil sample membrane to the volumeter during the triaxial tests. The teflon cube was held by the attached plastic tube and dipped four times into the rubber compound. After the rubber was fully cured, a flap was cut into one of the faces and the rubber membrane and plastic tube were peeled from the teflon cube. A coat of Motor Mica powder, manufactured by Scientific Lubricants Company, was applied to both the inside and outside of the soil sample holder to decrease friction between all mating surfaces during a CTU test. The final thickness of the soil sample holder was 1.5 mm.

Stress Applying Cushions

Six flexible rubber cushions applied the stresses to the sample enclosed in the soil sample holder. Figure 3 shows a cross-sectional view of the two types of stress applying cushions used in the CTU. The flexible rubber cushions were made of Dow Corning Silastic E RTV Silicone Rubber (base and catalyst), and Dow Corning 20 centistoke 200 fluid (a thinner), which made the material easier to work with. The three components were mixed together using 125 mL of the base, 10 mL of the catalyst, and 10 mL of the thinner. This material was chosen because it could cure in the absence of air, it had good tensile strength, high elasticity, and good memory, it was easy to de-air, and it had low shrinkage and good release characteristics.

The mold used to make the rubber cushions was machined from aluminum. Different male members could be bolted to the wall of the male assembly to make various shaped cushions. The female member of the mold was made of stacked 19-mm thick plates of aluminum. This enabled cushions of various lengths to be formed by adding or subtracting plates.

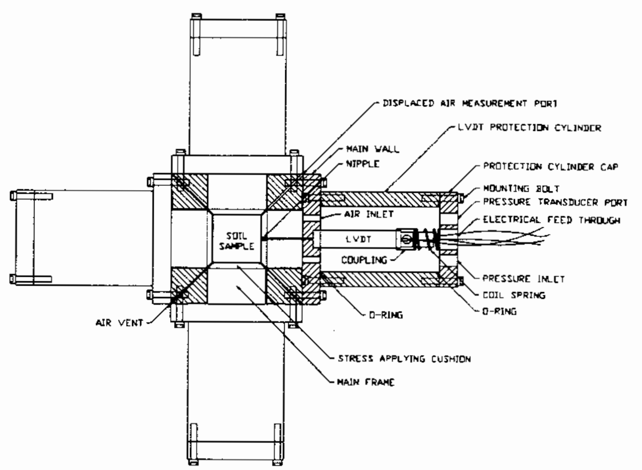

Figure 2–Cross-sectional view of the assembled CTU.

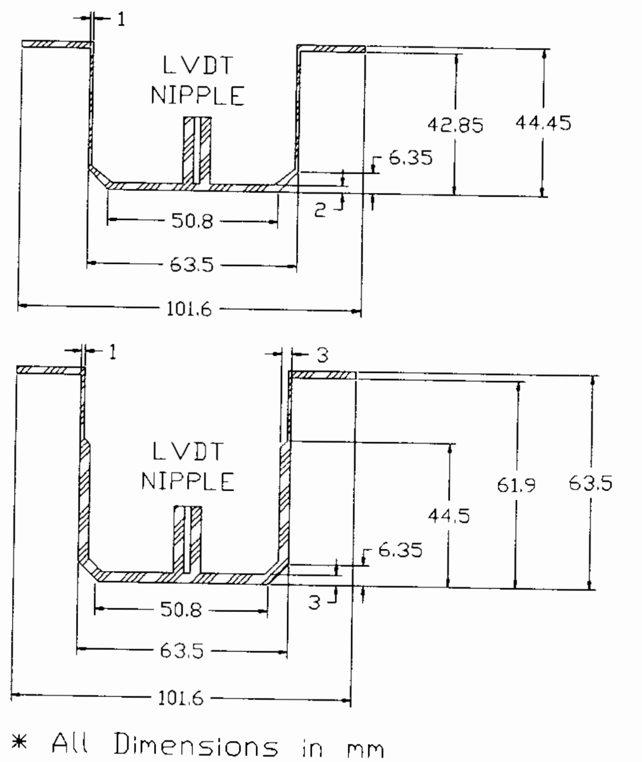

Figure 3–Cross-sectional view of the two types of rubber membranes used in the CTU.

Two different types of cushions were needed due to the pressure differential created between adjacent cushions during some of the stress paths. The low pressure axis or axes needed extremely flexible cushions to maintain contact with the soil sample holder during the large strains created by the adjacent high pressure axis or axes. The 45° bevel allowed all of the cushions to meet flush and limit the amount of open space between the flexible rubber cushions and the soil sample holder.

The high pressure flexible cushions needed to be rigid to stop the cushions from protruding into adjacent low pressure cavities and wrapping around the soil sample. A problem which was encountered was designing a cushion rigid enough to keep it from wrapping around the soil sample and flexible enough to handle the large strains. This problem was solved by adding a 19-mm extension to the flange end of the cushion. This extension was 1-mm thick while the rest of the sidewall, the 45° bevel, and the face were 3-mm thick. The thin bands of the high pressure cushions were folded similar to an accordion when the wall assemblies were bolted to the main frame. The high pressure flexible cushions were capable of withstanding a pressure differential of 375 kPa.

The flexible rubber cushions were coated on the outside with Motor Mica to decrease the friction between all mating surfaces. The inside of the cushions were coated with a thin layer of Dow Corning high vacuum grease and a thin layer of petroleum jelly. This was done to ensure that the high pressure air could not permeate into the soil sample holder and influence the volume measurements.

Displacement Measurement

The displacements of all six faces of the soil sample were measured using Trans-Tech, model 243, LVDTs. A 12 bit analog to digital converter (ADC) limited the smallest detectable displacement to 0.01 mm. The tips of the LVDTs were inserted into nipples on the deformable rubber cushions that were used to apply the stresses to the soil samples. There was very little friction between the core of a LVDT and the outer casing, which allowed the LVDT tip to move freely. A coupler and a spring were attached to the rear of each LVDT to ensure that the LVDT remained seated in the main wall. The working range of the LVDT was ±12.7 mm.

Stress Measurement

The three orthogonal stresses were monitored using Sensotec, model TJF/708-11, pressure transducers. Only one pressure transducer was needed for each axis because opposite sides of the device were assumed to be at the same pressure. Pressure transducers were mounted on the protection cylinder cap. The pressure measuring system was capable of distinguishing a 0.5-kPa pressure change within a working range of 0 to 1 MPa.

Volume Measurement

Measurement of the displaced volume of air was accomplished by using a volumeter as described by Grisso (1985). The volume measurement system was capable of distinguishing a 0.5-cm^3 change in sample volume within a working range of 0 to 60 cm^3.

Stress Control System and Data Acquisition

One axis of the stress control system is shown in figure 4. This system converted the control voltage from the computer to a proportional pneumatic pressure to operate the CTU. Air from a 1-MPa compressor was filtered to protect the downstream regulators and transducers from moisture and dust. The high pressure line was then routed to two manual pressure regulators. One regulator, set to 0.14 MPa, supplied the control pressure required by the voltage-to-pressure converter. The second regulator, set to 1 MPa, supplied the high pressure required for the pneumatic amplifier.

The system worked as follows: A desired pressure was calculated by the controlling program. This pressure value was compared to the pressure measured by the pressure transducer in the feedback loop. If there was a difference between the desired pressure and the measured pressure, then the control voltage was increased or decreased to drive this error to zero. The control pressure was then amplified by the pneumatic amplifier and the test pressure was applied to opposite sides of the CTU. This control system allowed the three axes of the soil sample to be loaded at different rates.

Control Program

Analog Devices Turbo Pascal software for the RTI-800 series of boards, Quinn-Curtis Real-Time Graphics & Measurement/Control Tools, and Borland Turbo Pascal 6.0 were used to develop a control program. The control program prompted the user to enter the path and file name to save the test data, name of the test, maximum mean normal stress in kPa, ratio between σ_1 and σ_3, ratio between σ_2 and σ_3, and initial confining pressure to apply to the soil sample (10 kPa was used for all tests). After entering these values, the program took a bias reading of all 10 transducers. Then the program output a digital signal which engaged shunt resistors across the three pressure transducers and the differential pressure transducer (part of the volumeter). These four channels were read by the program and their scale factors were adjusted accordingly. The full scale of each of these transducers was also calculated. These data were then written to the desired file and to the printer. The program then disengaged the shunt resistors and applied the initial confining pressure. After the initial confining pressure was applied, the desired pressure ratios between the three orthogonal axes were established. Then the real-time graphics were initialized.

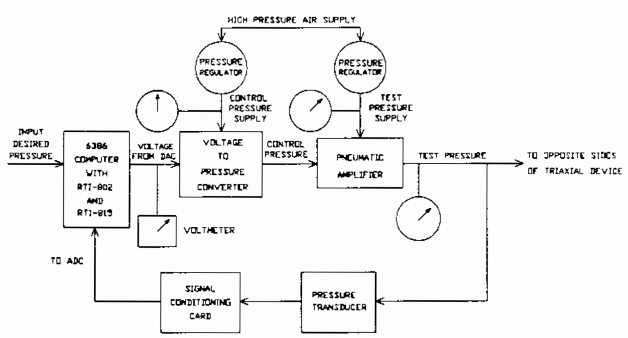

Figure 4–One of the three stress control paths in the CTU.

The real-time graphics display consisted of four graphs. The first graph plotted displacement versus time for three of the LVDTs. The second graph plotted displacement versus time for the other three LVDTs. The third graph plotted pressure versus time for the three pressure transducers. The fourth graph plotted volume of air displaced versus time. All four graphs appeared on the computer screen until the test was completed.

Soil samples were loaded at a rate of 20 kPa per minute until the maximum mean normal stress was reached. Measurements of time, the six displacements, the three pressures, and the volume of displaced air were saved in an array every 6 s. The soil sample was then unloaded over a 2-min period.

The program had three safety features. First, the program automatically unloaded the soil sample and aborted if any key on the keyboard was pressed during the loading or unloading of the soil sample. Second, the program automatically unloaded the soil sample and aborted if the full scale of any of the pressure transducers was reached. Third, the program automatically unloaded the sample and aborted if there was a 40-kPa change between successive pressure readings during the loading cycle. The second and third safety features protected the transducers, in case of an air leak or loss of control, and allowed tests to run unattended.

Experimental Procedures

Three different types of CTU tests were conducted. Six replicates of each test type were run with Hiwassee Clay (CH unified soil classification system). Two of the test types can be run with a conventional triaxial test and data were available as a base of comparison. These were a hydrostatic test, $\sigma_1 = \sigma_2 = \sigma_3$, and a proportional test with the ratio between σ_1 and σ_3 equal to 1.5 and $\sigma_2 = \sigma_3$. A completely randomized design experiment was chosen to conduct these two tests. The third test was a proportional test with the ratio between σ_1 and σ_3 equal to 1.5 and $\sigma_1 = \sigma_2$. The third test type cannot be run with a conventional triaxial device because σ_2 must equal σ_3. The six replicates for the third test were run consecutively. All tests were run to a maximum mean normal stress of 500 kPa. An identical experiment was conducted (Gibas, 1992) using Norfolk Sandy Loam (SP-SM3).

Sample Handling

All of the soil samples in this experiment were constructed from loose soil with the soil sample holder in place inside the CTU. First, the plastic tube of the soil sample holder was inserted between two of the flexible pressure cushions and through the main frame of the triaxial device. This tube was then pulled from outside of the device until the soil sample holder was sitting snugly between the flexible pressure cushions. Then 130 g of soil was spoon fed into the sample holder while being stirred periodically with a wire to ensure that the sample was uniform. The flexible rubber cushions were rigid enough to support the soil sample throughout this process. Dow Corning 1890 silicone rubber was brushed on the sample holder lid's seam to make it airtight. The soil sample was allowed to sit for 30 min to allow the rubber to cure, before the top wall assembly was bolted to the main frame. The control program was then initiated.

At the conclusion of a CTU test, the top wall assembly was removed from the main frame. Then the soil sample holder, containing the compressed sample, was removed from the CTU. The silicone rubber seal, on the top of the soil sample holder, was then peeled off with a razor blade. This allowed one soil sample holder to be used for multiple CTU tests. The compressed soil sample was then removed from the soil sample holder. Several small clumps of soil were always left in the sample holder. These clumps broke off of the edges of the soil sample when the sample was pulled out of the sample holder. It was assumed that the density of these clumps were the same density as the remaining compressed soil sample. This assumption was necessary to determine the final volume of the entire soil sample. The compressed soil sample density was determined using the clod method as described by Grisso (1985). The final volume of the entire soil sample was calculated by multiplying the initial mass of soil, 130 g, by the inverse of the density of the compressed soil sample.

A second method was also used to determine the final sample volume. It involved using a micrometer to measure the compressed soil sample dimensions at three points along each axis. The results of these two final sample volume calculations were always within ±5% of each other. The compressed soil sample was then oven dried to obtain the moisture content of the soil sample. The average dry basis moisture content was 18.5%.

The final sample volume calculated from the clod method was used in all bulk density calculations. The soil sample volume at each point in time was back calculated using the final sample volume and the volumeter measurements. The dry weight of soil divided by these soil sample volumes allowed calculation of the bulk density of the soil sample throughout the test.

Verification of Device

To examine if there was a difference between the actual stress applied to the soil sample and the stress measured by the pressure transducer, a Sensotec, model F/2349-02, wafer pressure transducer was placed inside the triaxial device and two tests were run. The wafer transducer was first mounted on the σ_1 axis of a teflon cube. The first test was conducted to examine the effects that the thicknesses of the high pressure flexible cushion and soil sample holder were having on the applied stress. A patch of the sample holder membrane was placed over the wafer transducer and a $\sigma_1 > \sigma_2 = \sigma_3$ proportional test was run. The combined thickness of the soil sample holder and high pressure cushion had a slight effect on the applied stress at the low stresses. At the maximum pressure (643 kPa) there was a 0.43% difference between the two curves. Duncan's multiple range test showed no significant difference between the means of the pressure readings of the two transducers at the 5% significance level.

A second test was run to see what effect the low pressure flexible cushions were having on the applied stress during a hydrostatic test with a soil sample. The wafer transducer was mounted on the σ_1 axis of a soil sample holder. The low pressure flexible cushions caused a −12 kPa (2.37%) difference between the measured stress and the actual stress being applied to the soil sample at the maximum pressure of 500 kPa. Duncan's multiple range test showed no significant difference between the means of the pressure readings of the two transducers at the 5% significance level.

To check the integrity of the sample volume calculations, the sample volume was calculated using the LVDT measurements and the volumeter measurements. Figure 5 shows the average sample volume versus mean normal stress for the hydrostatic stress path. The average percent difference between the two curves was 0.52% and was most likely due to the inaccuracy of the volume calculations using the LVDTs. For this calculation to result in accurate volume values, all faces of the sample would need to be orthogonal and perfectly flat throughout a test.

The larger overall change in volume shown by the LVDTs was due to the soil sample's faces being slightly convex at the beginning of the test.

Results

Figure 6 shows the average curves of bulk density versus mean normal stress for five different sets of data. Curves represent data form the CTU or data from conventional triaxial tests reported by Grisso et al. (1987). It is obvious that the conventional triaxial samples reached a higher bulk density than the CTU samples, but they also started at a higher density. To study the effects of varying the initial bulk density, an experiment was conducted, in the CTU, using three different initial weights of Hiwassee Clay for a hydrostatic test. Figure 7 shows how the bulk density versus mean normal stress curves shifted upwards as the initial bulk density was increased. Figure 8 shows the bulk density versus mean normal stress curves ($\sigma_1 > \sigma_2 = \sigma_3$) for the CTU data, the shifted CTU data, and the conventional triaxial device data. This figure shows that the CTU curves are basically the same shape as the conventional triaxial device curves except for the shift due to the differences in the initial bulk density of the soil samples. The hydrostatic load path (not shown) yielded similar results. The initial bulk density of the soil in the conventional triaxial device was always higher, which may be due to an initial stress on the soil sample caused by the confining cell water.

The proportional tests ($\sigma_1 > \sigma_2 = \sigma_3$) attained a higher bulk density than the hydrostatic tests ($\sigma_1 = \sigma_2 = \sigma_3$), which was expected due to the lack of octahedral shear stress during the hydrostatic load path. Duncan's multiple range test, at the 5% significance level, showed significant differences between all pairs of means of the final bulk density except between the two proportional tests.

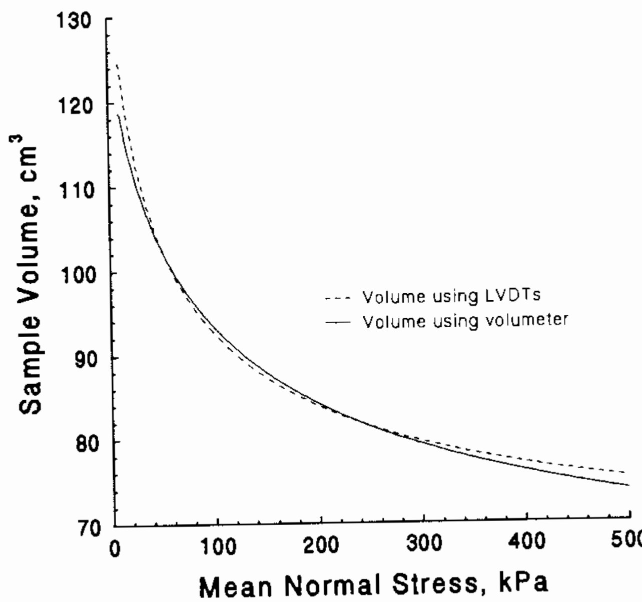

Figure 5–Soil sample volume vs. mean normal stress for the hydrostatic load path.

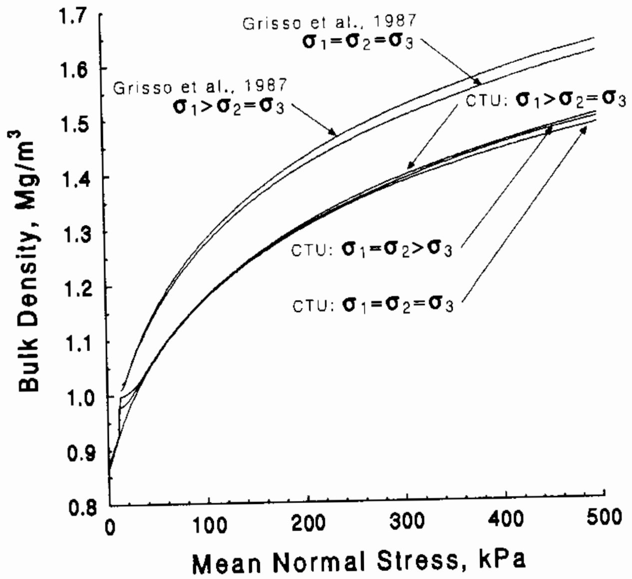

Figure 6–A comparison of cylindrical triaxial data and CTU data.

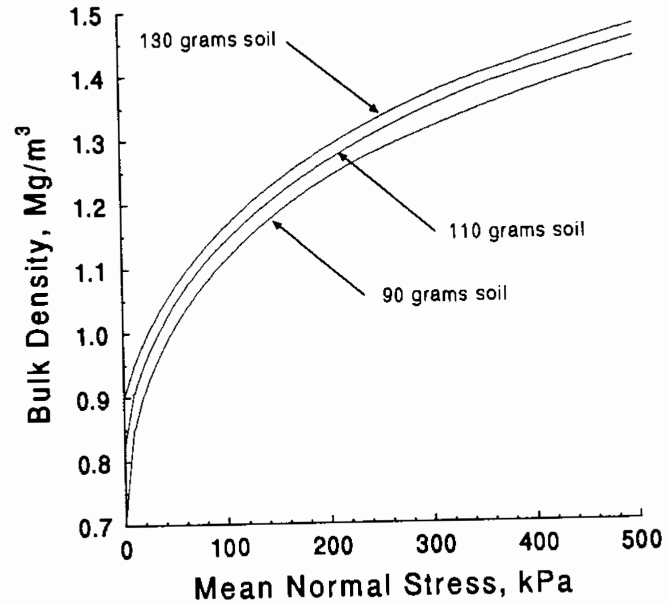

Figure 7–A hydrostatic load path showing the effects of varying the initial bulk density of the soil sample.

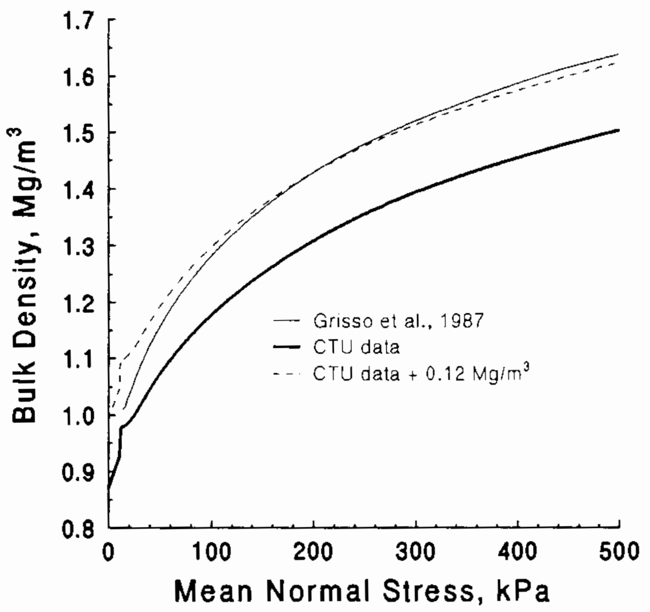

Figure 8–A comparison of cylindrical triaxial data and CTU data for the proportional load path with $\sigma_1 > \sigma_2 = \sigma_3$.

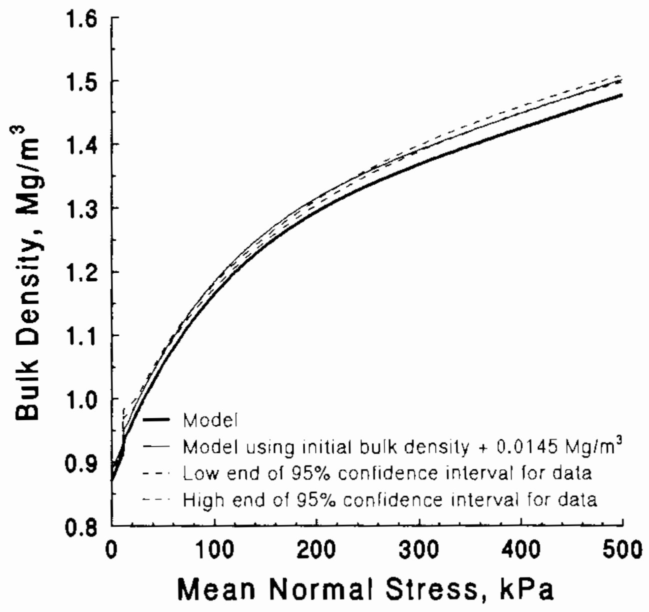

Figure 9–Proportional loading of the soil sample ($\sigma_1 > \sigma_2 = \sigma_3$) showing the deviation of the Bailey and Johnson soil compaction model from the CTU data.

VERIFICATION OF SOIL COMPACTION MODEL

Bailey and Johnson (1989) proposed the following soil compaction model.

$$\ln(BD) = \ln(BD_i) - \left((A + B\sigma_{oct})\left(1 - e^{(-C\sigma_{oct})}\right) + D(\tau_{oct}/\sigma_{oct})\right) \quad (1)$$

where

BD	=	bulk density
BD_i	=	initial bulk density at zero stress
A,B,C	=	compatibility coefficients
D	=	coefficient for the component of natural volumetric strain due to shearing stress
σ_{oct}	=	octahedral normal stress (i.e. mean normal stress)
τ_{oct}	=	octahedral shear stress
$\tau_{oct}/\sigma_{oct} \le k$	=	plastic flow limit

The A, B, C, and D coefficients used in equation 1 were from Bailey and Johnson (1989). The initial bulk density at zero stress, BD_i, was the average of six replications obtained from the CTU data. Figure 9 presents a comparison of the CTU data and bulk densities predicted from the model for the proportional load path with $\sigma_1 > \sigma_2 = \sigma_3$. The ranges shown in the figure are the 95% confidence intervals for the data. The soil compaction model predicted bulk densities which were lower than the CTU data. This was probably due to the lower initial bulk density values which characterize the CTU data. However, if a small value was added to the initial bulk density value used in the model, the predicted bulk densities would lie within or just outside of the 95% confidence interval for the CTU data. This shows that the model is capable of predicting bulk densities accurately, but the model is sensitive to the initial bulk density value. Similar results were obtained for the hydrostatic load path and the proportional load path with $\sigma_1 = \sigma_2 > \sigma_3$.

SUMMARY

The CTU performed well in both conventional and complex load paths and should prove to be a valuable tool in the research of the stress-strain behaviors of agricultural soils. The data obtained with the CTU compared well with conventional triaxial data where such comparisons could be made. The initial bulk densities of the soil samples using the conventional triaxial device were higher than the CTU samples causing an upward shift of the bulk density versus mean normal stress curves for the conventional triaxial device relative to the CTU curves.

A wafer transducer was used to examine the difference between the actual stress applied to the soil sample and the stress measured by the pressure transducer. It was found that the soil sample holder and stress applying cushions did not have a significant effect on the applied stress.

Sample volumes were calculated using both LVDT measurements and the volumeter measurements. The average percent difference between the volume calculations was 0.52% and was most likely due to the inaccuracy of the volume calculations using the LVDT measurements.

Bailey and Johnson's (1989) soil compaction model predicted bulk density values lower than the CTU data. However, by adding a small value to the initial bulk density value used in the soil compaction model, the predicted bulk densities would lie within or just outside of the 95% confidence interval for the CTU data. This shows that the model is capable of predicting bulk densities accurately, but the model is sensitive to the initial bulk density value.

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