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FINAL REPORT: PART 3

CONSTITUTIVE MODELLING OF JOINTS UNDER CYCLIC LOADING

PART 3: CYCLIC MULTI DEGREE-OF-FREEDOM SHEAR DEVICE WITH PORE WATER PRESSURE

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CYCLIC MULTI DEGREE-OF-FREEDOM SHEAR DEVICE
WITH PORE WATER PRESSURE

INTRODUCTION

The previous device described in Part 1 of this Final Report allowed testing of joints and interfaces under dry conditions. This device needed certain modifications such as inclusion of pore water pressure, need to reduce or avoid moment effects due to the eccentricity of the normal and shear loads, need to increase the loading capacity, and need to install devices to measure pore water pressures at the joints and additional devices to measure displacements and stresses.

Thus a new loading frame and circular test device were designed and fabricated. It was found that the task of designing such an improved device with application and measurement of pore water pressures was indeed a formidable task! As a consequence, the design was a process of continuous refinement and modification involving bottlenecks in terms of personnel and material, and hence, a significant amount of additional time was required beyond what was expected.

The device was designed and fabricated partly supported by this AFOSR grant and a grant from the NSF. At his writing (August 1980), the device is just completed. However, it would need some initial dry runs before it becomes operational. This brief report describes details of the frame, test device and electronic control and data acquisition system. Figure 1 shows a schematic line drawing of the device.

REACTION LOADING FRAME

A very stiff frame was designed so as to allow direct shear testing as well as planned torsional and testing under a high rate of loading. It was installed in an existing hydraulic channel with appropriate foundation design, treatment and additional reinforcement. Figure 2 shows the reaction loading frame with the pressure vessel and test device installed.

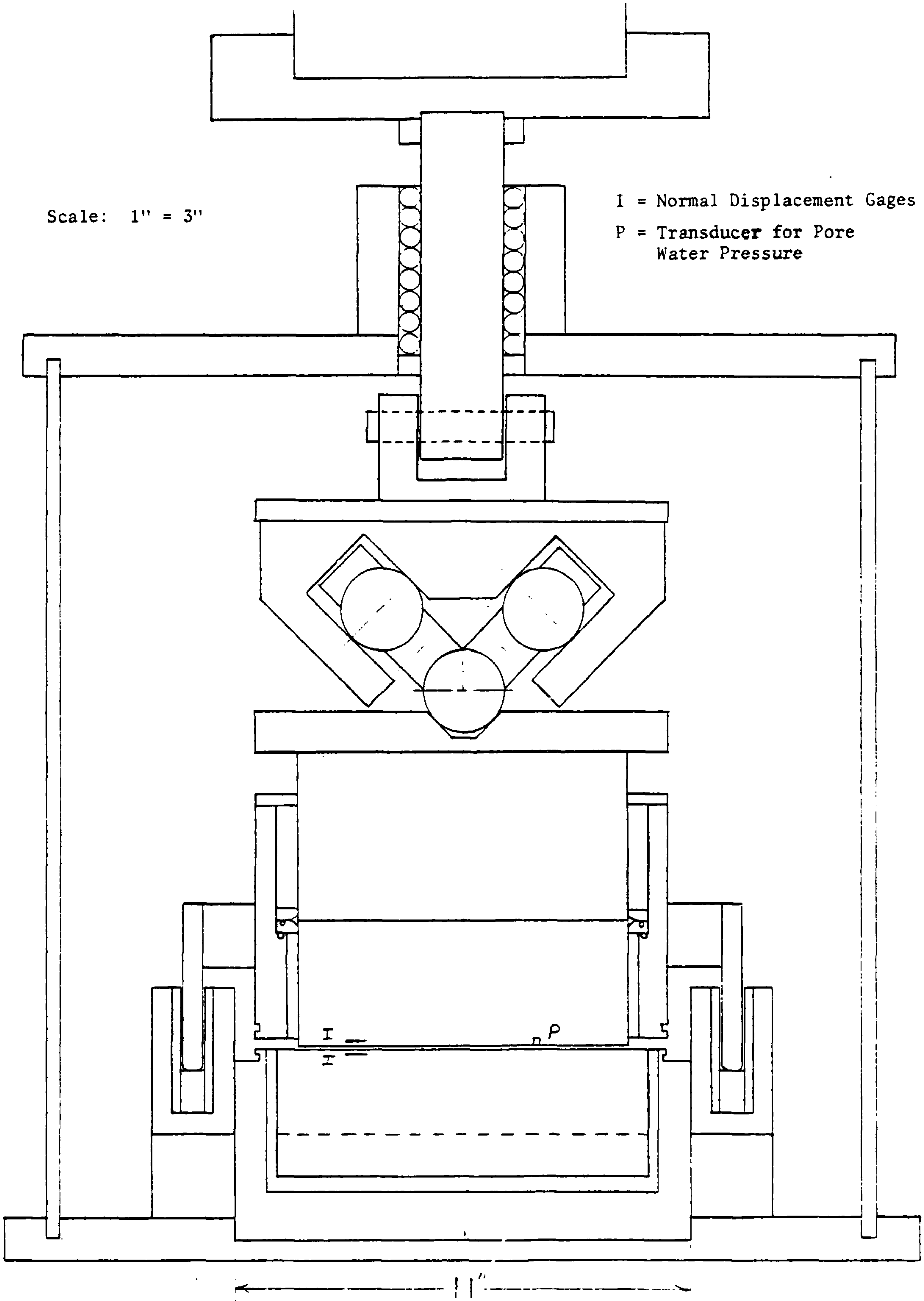


Fig. 1 Schematic Outline of CYMDOF Device With Pore Water Pressure

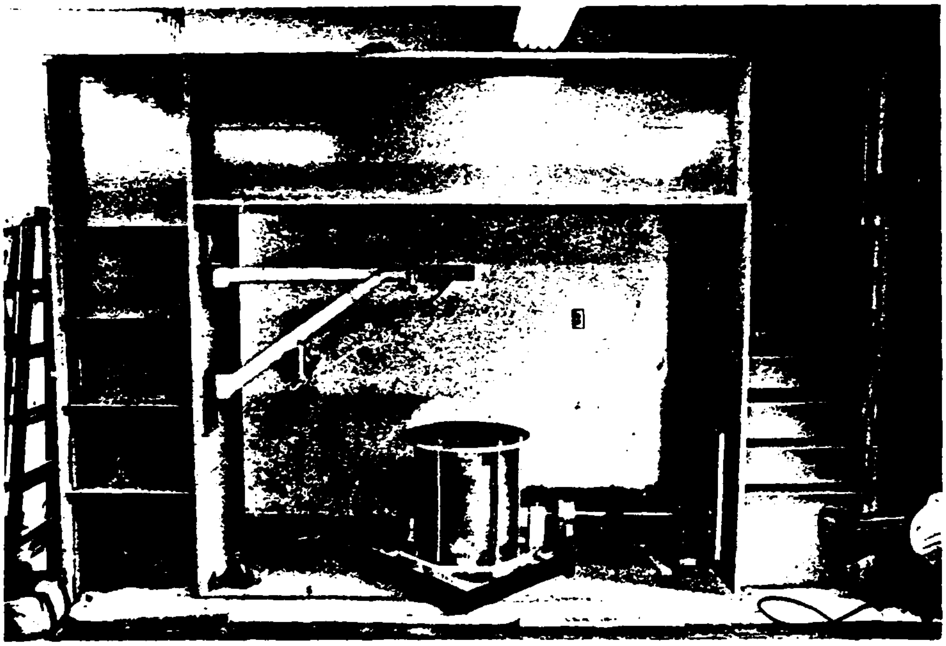


Fig. 2 Reaction Loading Frame

TEST DEVICE

The newly developed dynamic direct-shear device is designed to hold an 7.5-inch diameter 3-inch thick upper sample and a 9-inch diameter 3-inch thick lower sample. As the lower sample is larger than the upper sample, the interface area always remains constant during the test. A normal stress of 400 psi (2.7 MPa) and a shear stress of 550 psi (3.9 MPa) can be applied and developed at the interface. Both of these stresses may be increased by modification of the device. The horizontal actuator attaches right at the level of the interface so no significant moment is induced at the interface by the push or pull of the top box. Keywords: Computers, Control Systems, Hydraulic Systems, Friction, test equipment. (AW)

The lower sample is fixed and the upper sample is allowed to move both horizontally, vertically, and if desired, to rotate about an axis in the plane of shear perpendicular to the direction of shear. The range of shear displacement is +/- 0.5 inch. The range of normal displacement is +/- 0.75 inch. A rotation at the center of the interface of +/- 3 degrees (0.25 inch at the sample edge) is permitted. As has been mentioned previously, pore water pressures can be measured at the interface.

The following types of material joints and interfaces can be tested in the new device:

1. rocks and soils
2. soil and manufactured materials such as concrete, steel, wood, soil cement, asphalt, rubber, geogrids, geotextiles, geomembranes, components of ground anchor systems
3. components used in laboratory testing and other materials such as latex rubber and silicone grease on steel
4. bonded interfaces (adhesives or cementing agents)

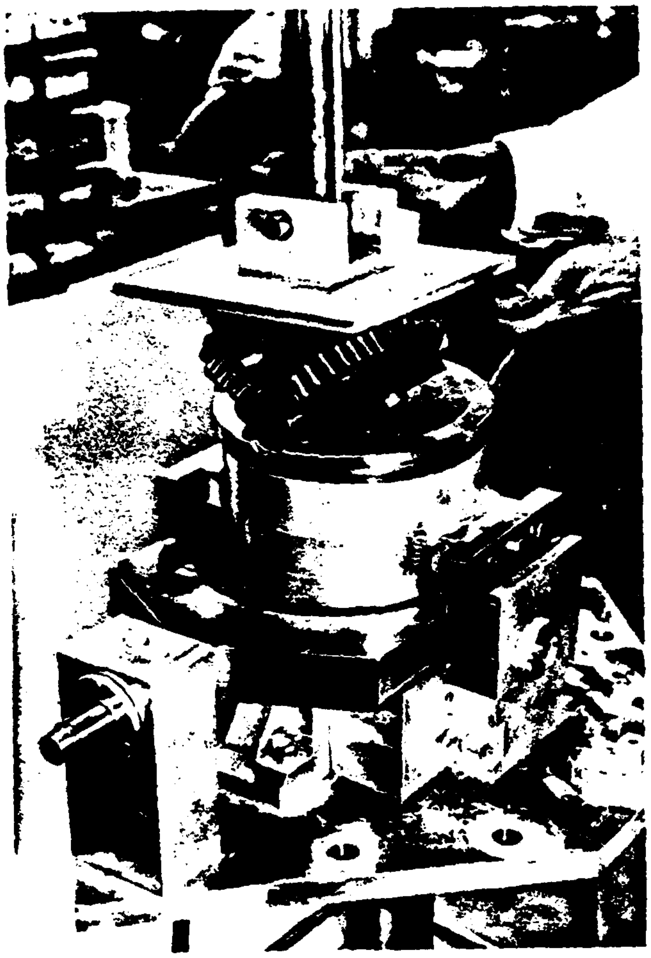
The interface properties that can be measured or calculated include the normal stress, shear stress, normal displacement, shear displacement, interface rotation, coefficient of friction, angle of internal friction, apparent cohesion, and the fluid pressure.

Vertical Loading Linkage

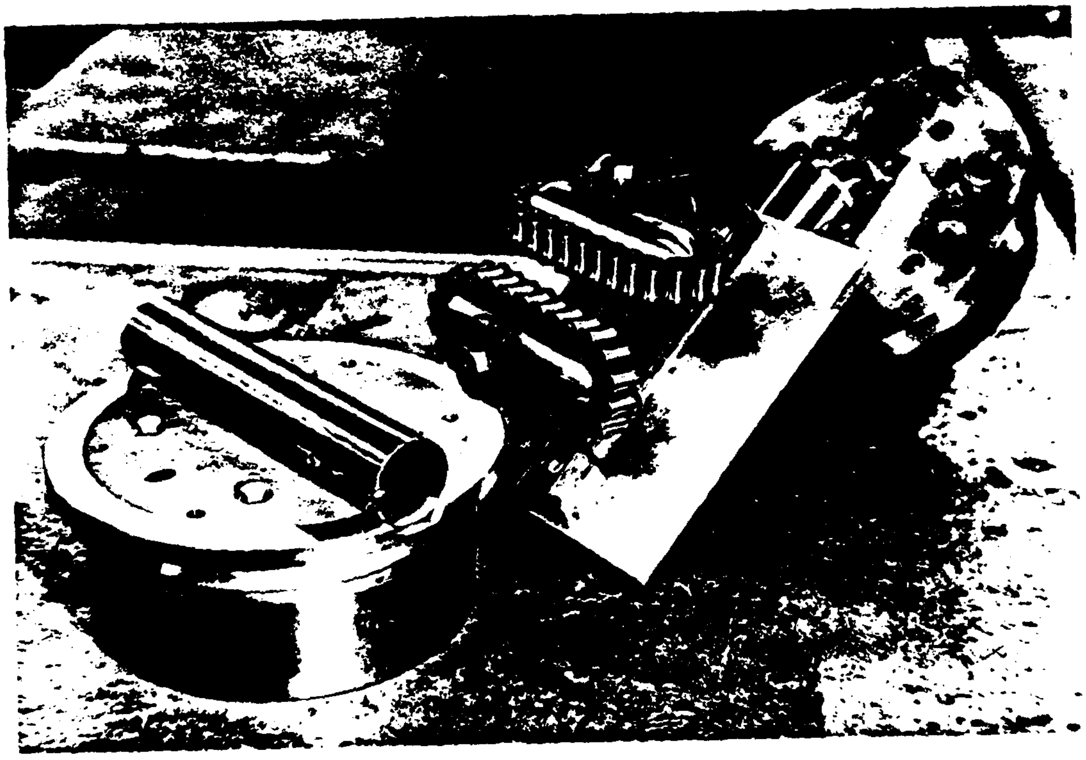
The normal loac is applied to the interface by means of the following components (see Figures 3a and 3b):

1. A 30-kip actuator is mounted by one end to the frame.
2. The threaded end of the actuator screws into a Strainsert 30-kip flat load cell which is attached by 8 bolts to a 2-inch thick, 9-inch diameter steel back plate.
3. A 2-inch diameter, 8.25 inch long stainless steel shaft inserts 0.5 inch into the underneath side of the back plate. The other end of the shaft is pinned with a 0.75 inch diameter pin into a clevis block mounted on the roller bearing. The 2-inch shaft passes through a roller bearing mounted into the top plate of the pressure vessel.
4. The roller bearing (Thomson V-type RW-32 Dual Roundway Bearing) sits on a 10-inch long, 2-inch shaft mounted in the direction of upper box motion. This shaft is bolted onto a steel plate which is in turn bolted to an 6061 aluminum plunger. The depth of the 8-inch diameter plunger is 3.75 inches and inserts into a solid bearing mounted into the upper sample guide box. Figure 3b shows the solid bearing out of the box with the plunger assembly inserted into it.
5. The plunger assembly contacts the top of the upper sample holder (aluminum) over all of its 8-inch diameter area which then puts pressure on the upper sample itself.
6. The bottom sample is held within a lower sample holder (aluminum) which is held rigidly by the lower box component of the device.
7. The lower box is bolted to a 1-inch thick bottom plate which is held down to large steel plates mounted on the frame.

The plunger assembly and upper sample slide freely (vertically) within the upper sample guide box, allowing all of the transmitted force to go to the interface. Obviously, the upper sample is restricted to being a solid material. The weight of



(a) Top Box and Loading Gear



(b) Details of Loading Gear

Fig. 3 Components for Normal Loading

the 6061 aluminum guide box is supported by vertical wings welded to the side of the box which rest on rollers mounted in the bottom box.

Horizontal Loading Linkage

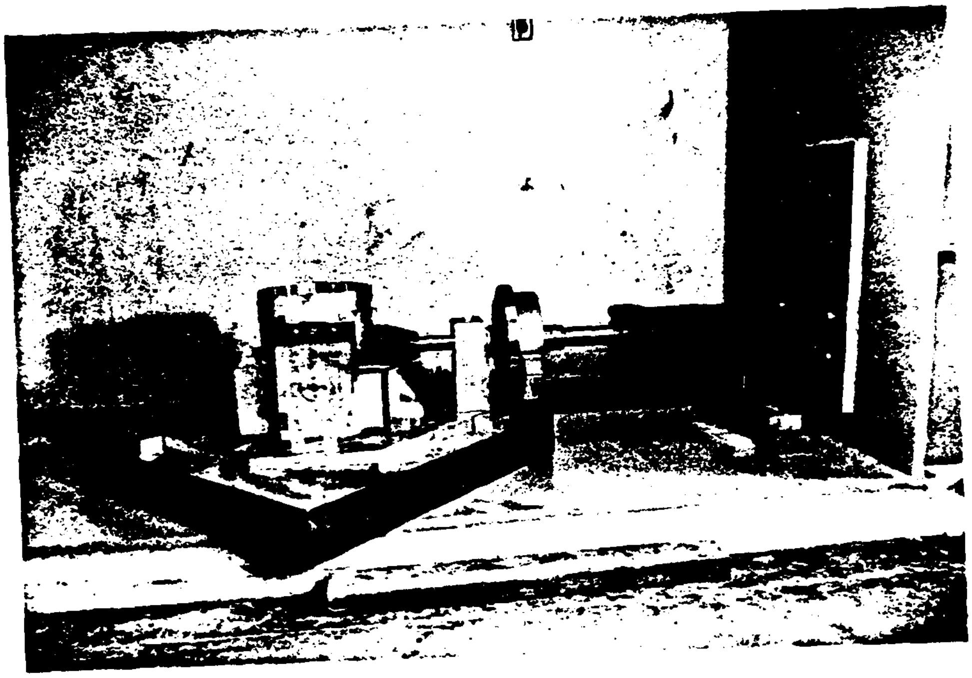
The shearing load is applied to the interface by means of the following components (see Figures 4a to 4d):

1. A 30-kip actuator is mounted by one end to the frame.
2. The threaded end of the actuator screws into a Strainsert 30-kip flat load cell which is attached by 8 bolts to a 2-inch thick, 9-inch diameter steel back plate.
3. A 1.25-inch diameter, 10 inch long stainless steel shaft screws into the one side of the back plate. The other end of the shaft passes through a bearing and is pinned with a 0.5 inch diameter pin into the yoke. The 1.25-inch diameter shaft passes through the side of the pressure vessel between the bearing and the yoke.
4. The steel yoke is pinned to the vertical support wings of the upper sample guide box. The yoke is centered right at the interface.
5. The upper sample guide box transmits load to the upper sample holder and thus to the upper sample itself.

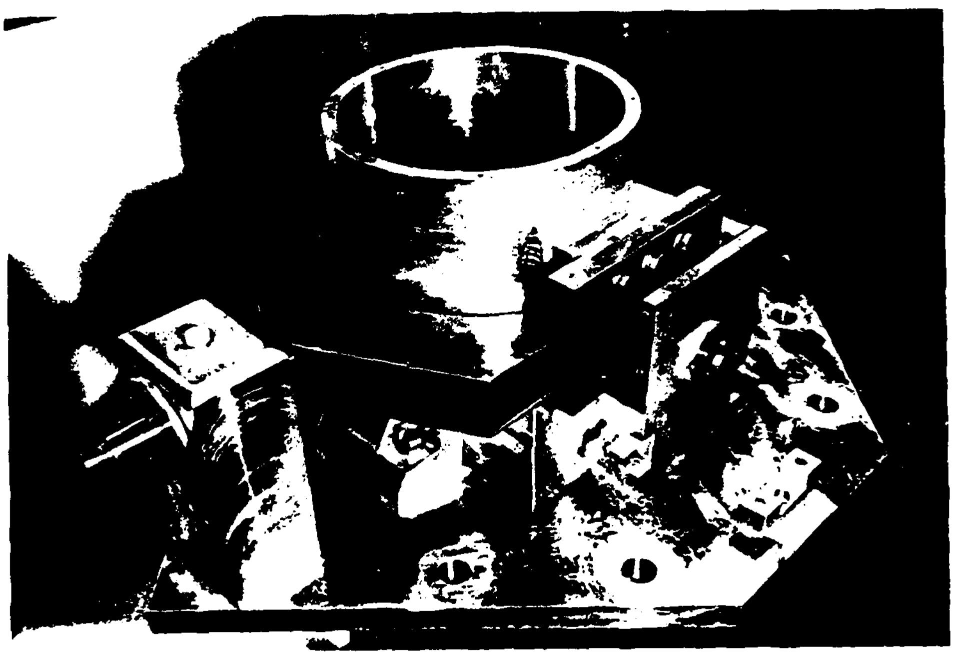
As the upper sample is pushed back and forth over the stationary lower sample, the upper sample is free to move up, down, and rotate around an axis perpendicular to the direction of translation. Additional rollers can be inserted under the vertical support wings (part of the upper sample guide box) to not allow freedom of rotation of the upper sample.

Pressure Vessel and Sealing System

A flexible membrane is attached to the outside of the upper and lower boxes of the device so that fluid pressure at the interface can be introduced and measured. To work properly, this requires the outside as well as the inside of the membrane to be pressurized. The outside of the membrane is pressurized by housing the entire device within a pressure vessel. Water is used within the membrane at the interface and oil is used outside the membrane within the pressure vessel. The components of this system are described below (see Figure 5a and 5b):



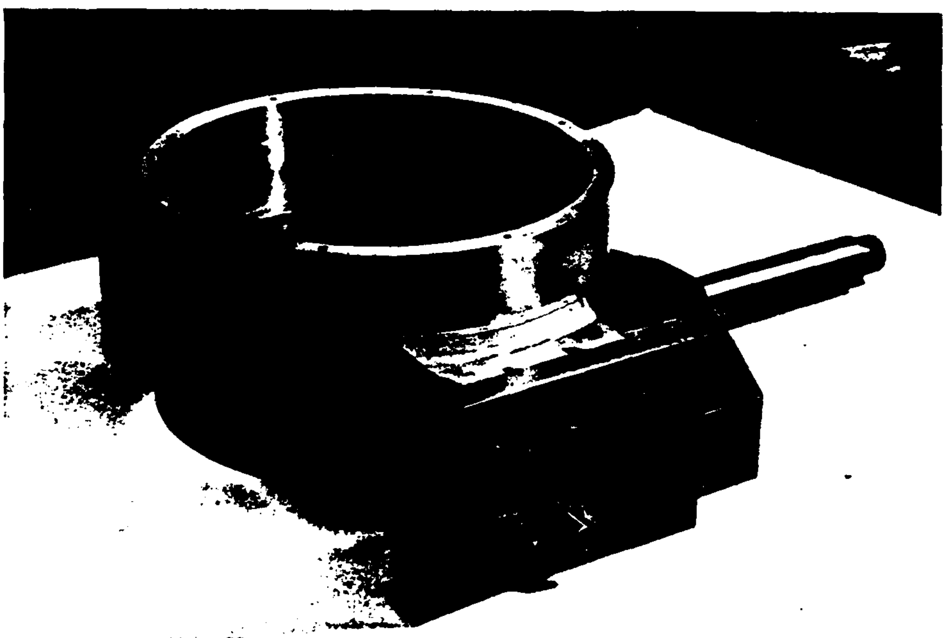
(a) Shear Loading Components



(b) Upper Box Pulled Off Center Over Lower Box

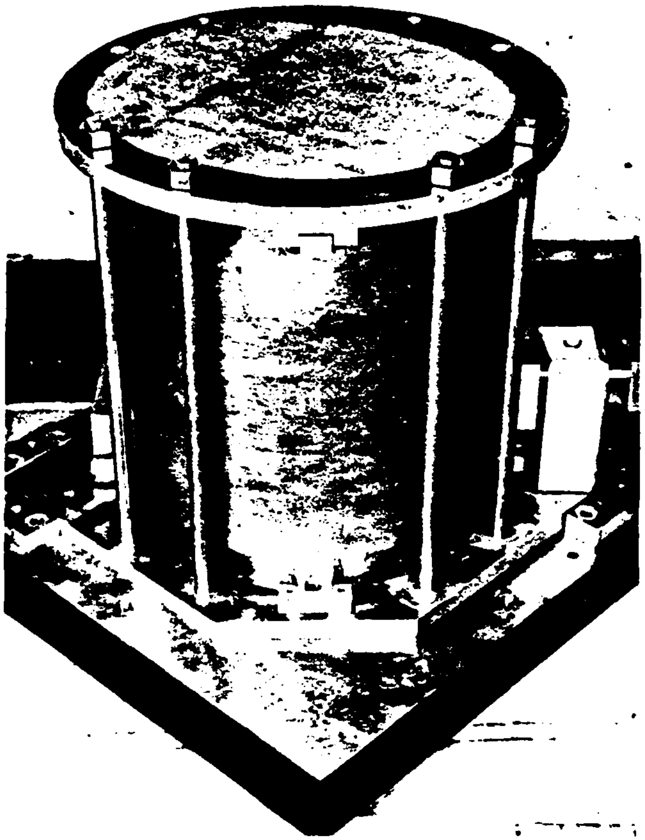
Fig. 4 Details of Bottom Part

(c) The Yoke-Bearing Surface on Outside

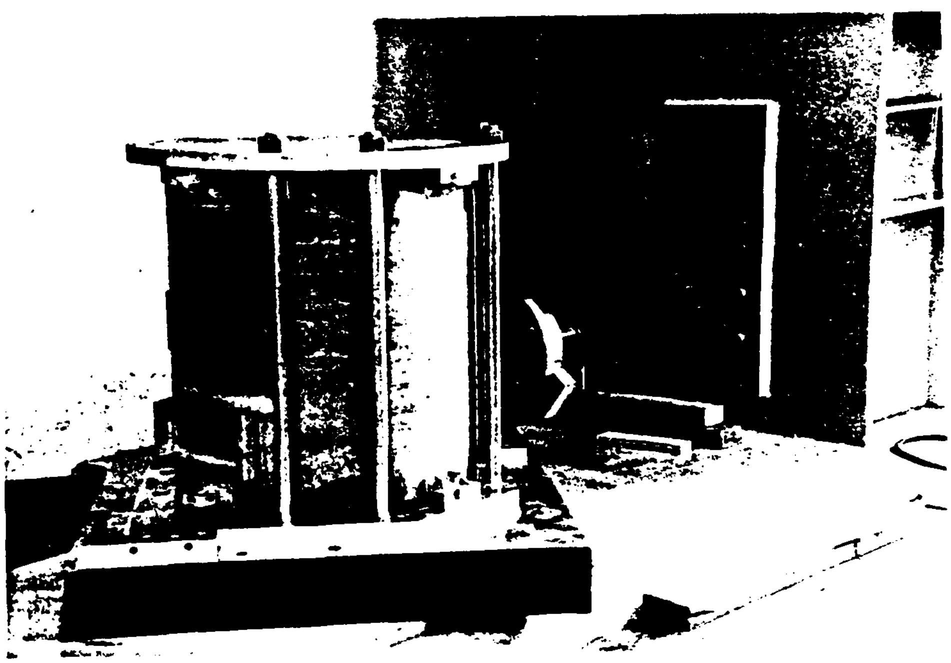


(d) Attachment of Yoke to Upper Box

Fig. 4 (Cont'd.)



(a) Pressure Vessel



(b) With Shear Loading

Fig. 5 Details of Pressure Vessel

1. The circular pressure vessel wall is rolled 6061 aluminum plate which is 0.375 thick. Two 1-inch thick 6061 aluminum flat plates mount with a 0.125 inch seal to the top and bottom of the circular vessel. These components are held together by 8 1-inch diameter steel pillars and 8 0.625-inch bolts. The pressure vessel assembly is designed to withstand 100 psi at a high factor of safety.
2. The vertical 2-inch diameter and horizontal 1.25-inch diameter shafts need to be sealed at the point they enter into the pressure vessel. At each location a sealing assembly as been designed using standard wipers and Parker PolyPak seals.
3. Electrical instrument wires from the device are passed through the pressure vessel using Pave Technology's "Hermetically Sealed Wire Passthru Harnesses."
4. There are attachments on the device and the pressure vessel to allow the water and oil to be introduced, maintained under a specified pressure and removed. Using air pressure, the oil is pumped from a holding tank into the pressure vessel and then through a 10 micron filter back to the holding tank.
5. The interface membrane is made of thin rubber to allow for motion of the upper box. The membrane is 10 inches in diameter and is attached to both the upper and lower boxes (also 10-inch diameter) using adjustable steel straps.

Instrumentation

Measuring the Applied Loads

1. One Strainsert flat load cell mounted in-line with the shear actuator
2. One Strainsert flat load cell mounted in-line with the normal actuator

Measuring the Normal Stresses

1. Three total pressure gages to measure the force being transmitted to the top of the upper sample at 3 chosen locations (mounted within the loading ram)

Measuring Normal Displacements

1. One mechanically-linked AC LVDT mounted on the normal actuator
2. Three hermetically-sealed, spring-loaded DC LVDT's to measure the normal movement and rotation of the upper sample at the top of the loading ram

relative to a rigid reference base (mount 2 on the side of the stabilizer-arm guide blocks and the third on the bottom box opposite the shear actuator with the LVDT gage heads extending to horizontal plates attached to the chain-bearing/load-ram plate)

3. Two hermetically-sealed, spring-loaded DC LVDT's to measure the normal movement and rotation of the upper sample-holder guide box relative to a rigid reference base (mount one LVDT on the actuator side of one of the stabilizer-arm guide blocks and the 2nd LVDT on the side opposite the actuator on the other stabilizer-arm guide block with the LVDT gage heads extending to horizontal plates attached to the upper sample-holder guide box)
4. Three (1 at least) bison (induction-type) gages about a half-inch from the interface to measure normal deflection between the upper and lower sample, aligned in a mounting block within the upper sample (3 will allow the interface plane to be defined)

Measuring Shear Displacements

1. One mechanically-linked AC LVDT mounted on the shear actuator
2. Two hermetically-sealed, spring-loaded DC LVDT's to measure the shear movement of the upper sample-holder guide box (mount on the stabilizer-arm guide blocks with the LVDT gage heads extending to the stabilizer arms)
3. One hermetically-sealed LVDT arrangement to measure shear displacement at the interface

Measuring Normal Strains in the Soil

1. Two (1 at least) additional bison gages to measure the normal displacements (and strains) in the rock or soil

Measuring Shear Strains in the Soil

1. Two bison gages to measure the shear displacements (and strains) in the rock or soil

Measuring Rocking Motions in Direction of Shear

1. Calculate from the normal displacement measuring devices

Measuring Fluid Pressures in Vessel and at Interface

1. One fluid pressure transducer to measure the pressure of the vessel fluid (screwed into pressure vessel at the elevation of the interface)
2. Two (1 at least) fluid pressure transducers at the interface (can use porous stones and tubes at the interface and mount the transducers outside the vessel -- mount transducers within vessel outside of sample)
3. One fluid pressure transducer to measure water pressure in the soil away from the interface (soil)

Measuring Critical Movements to Prevent Device Damage

1. One hermetically-sealed RVDT mounted on the normal bearing hinge

Calibration

Calibration of the LVDT's will be performed within the device in their operating positions as far as is possible.

Calibration of the total and the fluid-pressure transducers will be accomplished by leaving the interface open to the pressure vessel and then filling the chamber with water and then subjecting the water to a series of known values of hydrostatic pressure.

AUXILIARY SYSTEMS AND EQUIPMENT

Electro-Hydraulic Control System

The hydraulic loading actuators are controlled with a closed-loop servo-controlled system. The electronic part of the existing system consists of a MTS model #436 master control unit connected to a MTS model #406 controller for each actuator (see Figure 6).

For each actuator, the computer control system needs to send the appropriate analog command (set-point) signal (+/-10 VDC, resolution of 1 mV) to a 406 controller which in turn sends another analog signal to the servovalve, controlling the hydraulic fluid to move the actuator. The hydraulic actuators may be controlled in either displacement-controlled mode or load-controlled mode. This is determined by a setting on each of the 406 controllers. The 406 compares the

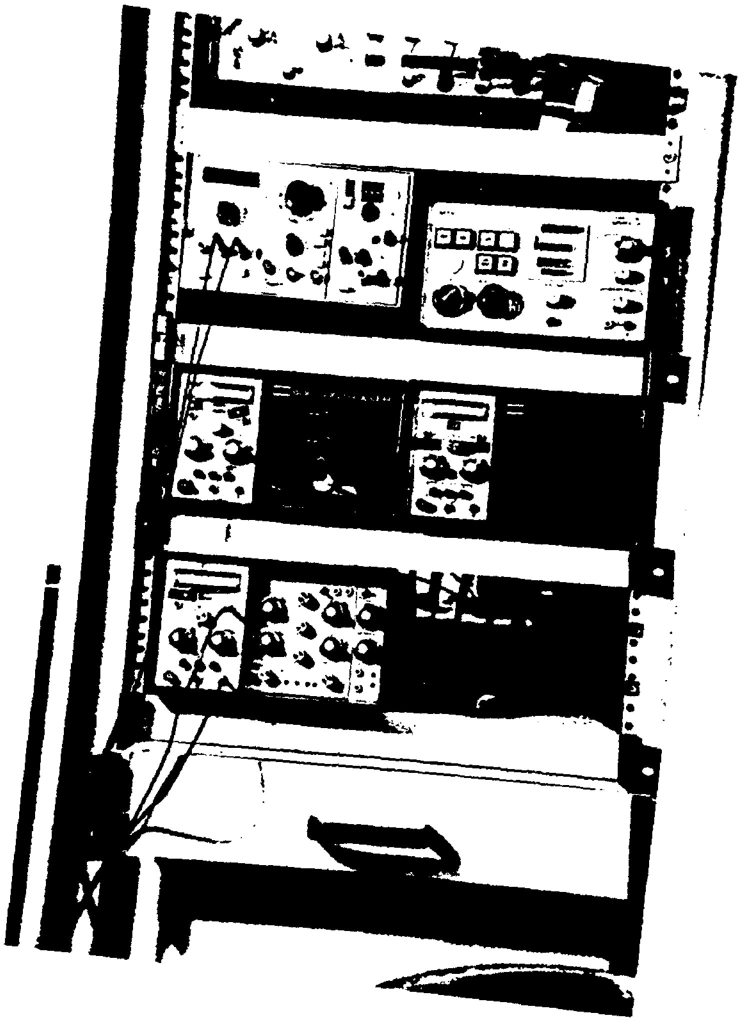


Fig. 6 Electro-Hydraulic Control System.
436 Controller is Upper Left;
406 Controllers are the Lower Three Units

input command signal (desired motion or force) with a feedback signal from the measuring instrument (actual motion or force) and corrects the signal to the servo valve as necessary. The response time for this part of the existing system is about 15 micro seconds.

At present, the system electronics can be used to apply constant normal load (stress) or varying load according to the command signal input (for instance, constantly increasing ramp mode or even a sine wave mode). However, the system has a provision to also perform tests under a "constant stiffness" condition in which normal movement affects normal load (stress).

Electrical and Hydraulic System Components

The hydraulic fluid used in the pump and hydraulic system is Mobil DTE 25 -- this same brand and type of fluid should always be used as mixing different brands of hydraulic fluid can create contaminants that will damage the hydraulic system. An operating temperature of the hydraulic fluid between 100-125 degrees F(38-52 degrees C) is required to give consistent results and prevent fluid breakdown. The system is designed to control the fluid temperature in this range.

The following components are part of the hydraulic system: Hydraulic actuators capable of applying a 30 kip (133 KN) force; Moog servo-control valves; a 6000 psi PALL filtration filter, 20 gpm, 0.45 micron nominal, 3 micron absolute filter unit, model #HH9800B16UPSBP; a Hayden cooler-heat exchanger model #TT3241, 20 GM capacity; a Young water-based heat exchanger; a temperature control water valve; a Fenwal overtemperature switch; several temperature and flow indicator gages; an hour meter; a CYMDOF Service Manifold is model # 290.13, serial # 908; and from Norman Equipment Co., an Abex Denison 1A84 adjustable flow pump which is capable of applying a pressure of up to 3000 psi (21 MPa) at a flow rate of 20 gallons/min.

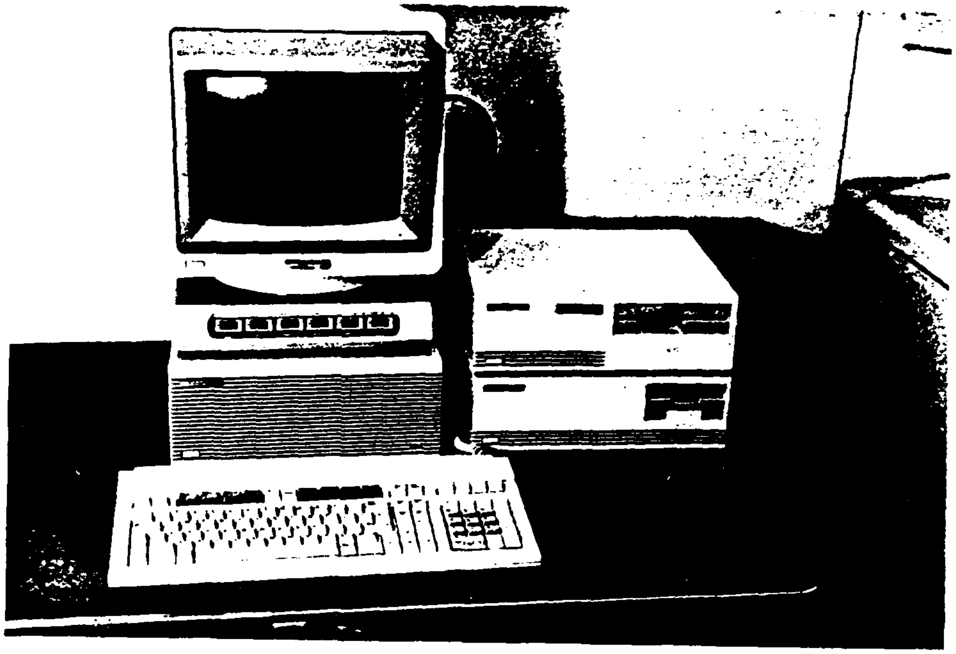
AUTOMATIC DATA ACQUISITION AND CONTROL SYSTEM

The newly acquired data acquisition and control system can be divided into two parts, the main Hewlett Packard (HP) 330 Computer and the HP 3852 Data Acquisition Mainframe (see Figure 7a to 7c).

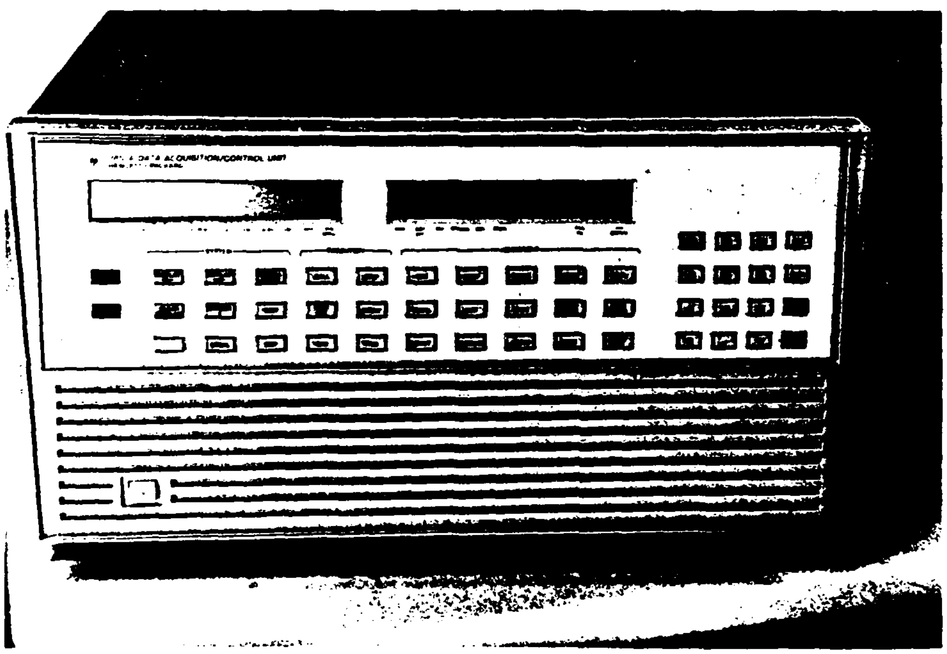
HP 330 Computer System

The HP 330 Computer System consists of the following components:

1. One HP 9000 Model 330MMA Monochrome Instrument Controller computer -- has a Motorola 16.67 MHz MC68020 processor (2 MIPS), MC68881 floating point coprocessor, MC68851 Paged Memory Management Unit, a 32-bit Memory Bus, 32-bit DIO-II I/O bus, 4Mb of ram memory, keyboard, direct memory access (DMA) at a rate of 349 Kbytes/sec, 98644 RS-232 serial port, 98625B high speed HP-IB disk interface, 12-inch monochrome display, 98542A medium resolution monochrome graphics board, 98643 LAN network, virtual memory
2. One 98515B Opt 045 UNIX 6.0 Operating System -- manages hard disk files; enables DOS Coprocessor to run; enables next version of BASIC to run directly with UNIX; UNIX allows multi-tasking, windowing
3. One 9153C 40 Megabyte Hard Disk with integrated 2 Megabyte 3 1/2 inch Floppy Drive
4. One 9127A 5.25 inch Floppy Drive
5. One 98622A 16-bit GPIO Parallel Interface -- for high speed data transfer
6. One 2227A QuietJet Plus Printer with RS-232C interface -- 15-inch wide carriage, ink jet graphics printer
7. One 98616A Opt. 045 BASIC 5.1 Language and Operating System -- gives the highest performance found in interactive instrument control systems on the market today; gives tree-structured directory and subdirectories; interactive file editor; share files with HP-UX files; extensive debug and trace tools; allows for independent subprograms, allows for dynamic variable allocation; has labeled common; has numerous predefined mathematical and matrix commands; allows up to 15 levels of prioritized software interrupt; Real precision is -1.798E+308 to -2.225E-308; Integer precision is -32768 to +32767; Complex precision consists of two real precision components

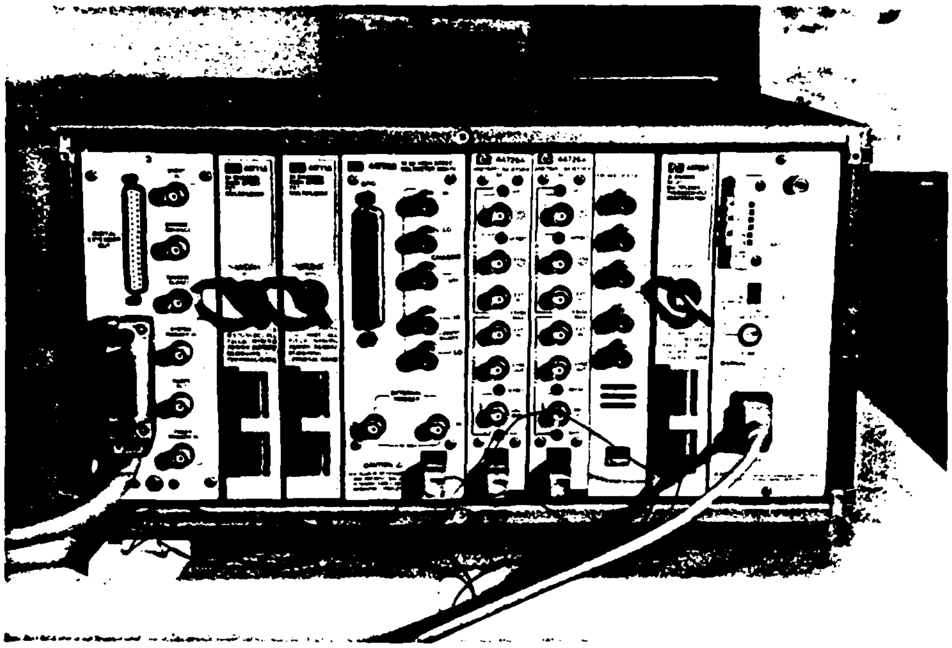


(a) HP 330 Computer



(b) Main Frame

Fig. 7 HP 3852 Data Acquisition System



(c) HP Data Acquisition and Control Hardware
Components Installed in the 3852 Mainframe

Fig. 7 (Cont'd.)

8. One 44458A Data Acquisition Manager Software Package -- consists of compiled subroutines that can be used by HP BASIC programs to handle many data management functions:

   - data management -- set up a data base; storage to or retrieval from data bases; data collection over HP-IB interface, GPIO interface, from a program, or the keyboard; time-stamp data; document data
   - data analysis -- scaling (mx + b), limit checking, statistics, math, strain gage conversions, user-defined look-up tables
   - data presentation -- printing, plotting with graphs, real-time stripcharting
   - process control -- can control as many as ten processes in a program through proportional gain control, integral control or derivative control
   - task scheduling -- assists you in scheduling tasks by creating a table of up to 99 tasks in which you can designate for each task a name, number, starting time, time interval between task runs, number of times the task is to be run and its priority
   - configuration/verification -- a menu driven program that you can use to help document your equipment set-up and to help ensure that a needed configuration is completely attached and working

HP 3852 Data Acquisition Mainframe System

The HP 3852 Data Acquisition Mainframe system consist of the following:

1. One 3852A Data Acquisition/Control Unit or "Mainframe" -- functions are described below:

   - has eight slots for plug-in function modules
   - has a built-in system clock (1 msec resolution) with alarms and a programmable pacer (0.25 micro second resolution) -- supports multi-tasking and allows real-time interrupts to be given at any time for a high priority tasks
   - has 11Kb RAM memory for storing data readings and subroutines
   - has an HB-IB interface for uploading to and downloading from HP computer
   - analog throughput is rated at more than 100,000 readings per second and you can get 1 microvolt sensitivity in the presence of noise

- has a keyboard and display on the front panel
- on-board intelligence allows use of structured programming to obtain the maximum speed of collecting measurements, making control decisions, and sending out control data
- down-loaded subroutines and internal calculations (math operations, fast scaling [mx + b] and statistics) can be used as post-processing routines to return only the data you need to the computer, saving disk and storage space
- permits user-defined tables of X,Y pairs to be used for fast linear interpolation
- limit checking of analog measurements can be performed in real time or after measurements have been stored in main-frame memory
- has built-in transducer conversions for strain gages
- supports asynchronous communication with the HP computer through buffering
- supports multiple data-gathering voltmeters working simultaneously

2. One 44703B Mainframe Extended Memory Card — 1 Mbyte of additional RAM memory
3. One 44702B 13-bit High-Speed Voltmeter -- directly measure DC voltage or DC resistance; measurement rate of 100,000 readings per second with auto-ranging; buffer for over 64,000 readings that can be transferred to mainframe internal memory or to hard disc via GPIO and a DMA controller while taking measurements; dedicated triggering with on-board pacers
4. Two 44711A 24-Channel High-Speed FET Multiplexers -- directly multiplexes voltage, resistance, strain gages over 24 channels (the two give us 48 channels); high and low switch for each channel; signal plus common mode noise must be less that 10 V peak; works with the HP 44702B voltmeter
5. One 44701A 5 1/2 to 3 1/2 Digit Integrating Voltmeter -- directly measures DC voltage, resistance, AC voltage; can accurately measure small signal changes in noisy environments; can choose the resolution, accuracy, and noise rejection needed, while maximizing measurement speed
6. One 44708A 20-Channel Relay Multiplexer -- directly multiplexes voltage, resistance, strain gages; circuitry to reduce the effects of real-world measurement errors in a multi-channel system; works with the HP 44701A voltmeter

7. Two 44726A Arbitrary Waveform Digital to Analog (D/A) Converters -- two channels (four total) with 32 Kbytes of memory per channel; directly outputs arbitrary waveforms stored in its own memory and DC voltages; each channel has enough memory for 32,000 waveform points in which each point is defined as both a voltage level and length of time at that level; has 16-bit resolution with a step rate of up to 800 kHz; range is +/- 10.235 volts DC; channels have independent timebases that can be synchronized with each other or with external events or external timebases can be used; sine, triangle and square waveforms can be calculated and loaded from the HP 3852A with one command; waveforms can be single shot or continuous

A description of a sample laboratory test will now be given as an example of the capabilities of the electro-hydraulic control system. The critical test will be a fully instrumented cyclic test running at 10 Hz. A cycle is defined as a physical back and forth movement of the upper sample. We start at zero (0 VDC), move forward say 1/4 inch (+8 VDC) then reverse direction back to zero (0 VDC), continue moving past zero 1/4 inch (-8 VDC), reverse direction and come back to the zero point (0 VDC). Readings from all of our 15 instruments are taken very quickly at 60 different times spread over each of these cycles. At 10 Hz then, we have a reading from all (each) of our instruments at the rate of 60 readings per cycle x 10 cycles per second or 600 times per second. Now at each time the instruments are read we take two successive readings from each instrument so we can average the two readings. Thus, we require 15 x 2 or 30 instrument readings each time the instruments are read. Finally then, are taking 30 x 600 or 18,000 readings per second for our critical scanning requirement. Our equipment is actually capable of handling the same test at 50 Hz which is approximately 100 thousand readings per second. Up to 1000 cycles may be performed over the duration of the test.

PLANS

The device described above is just about to undergo its first test runs. The programming and wiring of the new data acquisition and control system is underway. The frame and hydraulic systems are now complete. Future work will entail the following:

- Investigative analysis of the reaction frame
- Calibration and adjustment of all equipment
- Investigative analysis of the direct shear device
- Verification of proper data acquisition and control
- Documentation of testing procedures for the new CYMDOF device
- Development and accomplishment of laboratory testing plan
- Improved theoretical constitutive modelling and testing of joints and interfaces
- Implementation of the improved modelling in Finite Element programs
- Carry out Finite Element analysis of actual problems