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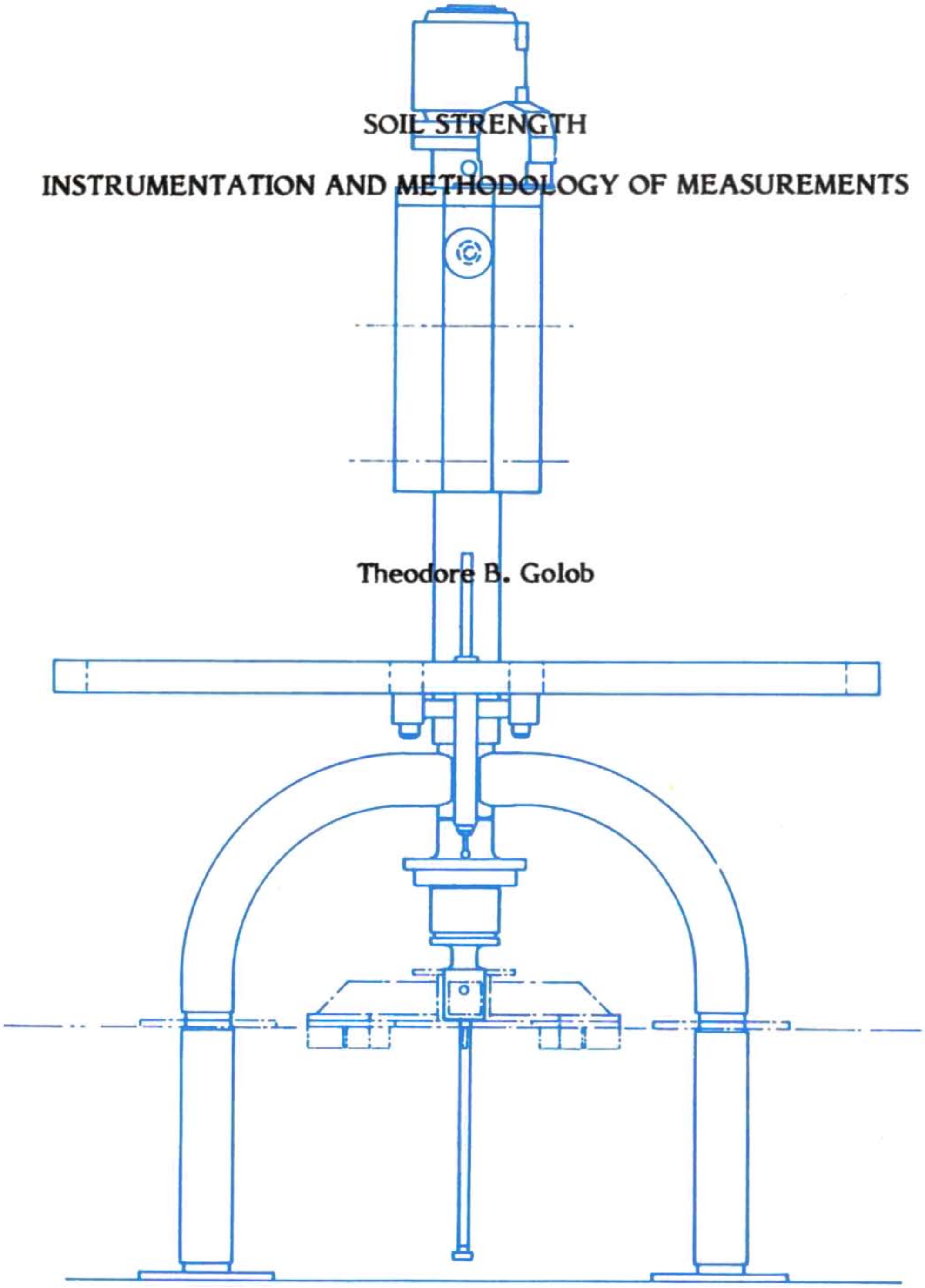
SOIL STRENGTH
INSTRUMENTATION AND METHODOLOGY OF MEASUREMENTS



Theodore B. Golob

Information
Report
PI-X-2

Issued under the authority
of the Minister, Environment Canada

Catalogue No. Fo46-11/2-1982E
ISSN 0706-1854
ISBN 0-662-11810-3

Additional copies of this publication can
be obtained from:

Technical Information and Distribution Centre
Petawawa National Forestry Institute
Environment Canada
Chalk River, Ontario
K0J 1J0

Cette publication est aussi disponible en français
sur demande.

Cover: Equipment for the measurement of
terrain strength

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SOIL STRENGTH

INSTRUMENTATION AND METHODOLOGY OF MEASUREMENTS

Abstract
A report on the development of experimental equipment and methodology capable of recording terrain strength tests carried out with a variety of soil probes. The equipment and instrumentation were designed as a special type of bevameter (Bekker Value Meter) that can analyze soil strength values.

Résumé
Rapport sur la mise au point de matériel et de méthodes expérimentaux capables d'enregistrer la résistance du sol mesurée au moyen de diverses sondes pédologiques. Le matériel et les instruments ont été conçus de façon à servir comme type spécial de "bevamètre" (appareil de mesure developpé par M.G. Bekker) pouvant analyser les mesures de la résistance du sol.

INTRODUCTION

The interaction of forest vehicles and soil-working tools with different soils is of concern to forestry and to the manufacturers of forestry equipment. This interest is increasing with our efforts to mechanize forest operations on an ever-expanding scale, and as new technology is gradually moving into the forests, we face problems that cannot be solved without our understanding the very basic principles of the interaction of these new machines with the sensitive forest environment. The manufacturers of tree-harvesting equipment are in the process of reevaluating their past developments, reluctant to embark on new ventures until existing problems are dealt with. Also, we have come to realize that natural regeneration is not going to restock our forests to the levels and quality needed to maintain a sufficient flow of lumber and pulp to the national economy. This realization brought pressure on provincial and federal officials to increase the rate of artificial forest regeneration. However, the projected new goals can be achieved only through an increased mechanization of forest operations requiring soil-working tools.

Research work dealing with the strength of soils is generally concerned with the analysis of experimental data and prediction of vehicle and tool performance based on soil parameters or on comparative experimental results. There seems to be a great deal of disagreement as to what instruments should be used for any given set of analytical requirements. The former Forest Management Institute of Ottawa developed experimental equipment (Golob, 1978) capable of recording soil strength tests carried out with a variety of instruments. The equipment and instrumentation were designed as a rather special type of bevameter, chosen because it could analyze soil strength values.[1] This work is now being carried on by the Petawawa National Forestry Institute, Chalk River, Ontario.

Soil is a complex, nonhomogeneous substance unlike most engineering construction materials; it is almost impossible to define it in simple terms of stress

Manuscript approved for publication: August 1980.

Theodore Golob is a research scientist, now affiliated with the National Research Council, Energy Division, Ottawa, Ontario, K1A 0R6.

[1] The term "bevameter" is derived from Bekker Value Meter, a device for measuring soil strength, developed by Dr. M.G. Bekker, Santa Barbara, California.

and strength. Homogeneous soils, normally used in laboratories, have so far provided little information on problems encountered by vehicles and tools working in forest and agricultural soils. The Forest Management Institute (FMI) and now the Petawawa National Forestry Institute (PNFI) decided to develop instrumentation and equipment to study and analyze different forest soils and to provide information needed for the design of vehicles and tools for use in the forest.

This report deals primarily with the development of the equipment and instrumentation, including hydraulic and electronic systems. It discusses different techniques for measuring force and displacement, their advantages and disadvantages, and the reasons for choosing these particular systems and tools. In the context of variations on the established bevameter theory (Bekker, 1969), the methodology of measurement is also discussed. This was thought necessary because of specific forestry problems.

EQUIPMENT

General

The design for the test equipment was based on well-established theory and design criteria (Bekker, 1969; M.G. Bekker;[2] J.Y. Wong[3]); these criteria, however, were somewhat modified (Golob, 1978) to accommodate specific forestry and agricultural requirements and provide better mobility of the equipment. The original bevameter developed by Bekker is made up of two separate cylinders, one designed for measuring pressure-sinkage relationship and the second for a simulated soil shear test based on the concept of grousers on a tracked vehicle. The down force and displacement of the test plate in the pressure-sinkage tests are applied and measured in any one of the conventional methods; however, the simulated ground pressure in the soil shear test is somewhat more difficult to apply and maintain, because it must remain constant throughout the test.

Keweenaw Research Center, a research agency of Michigan Technological University, is the only establishment known to make bevameters commercially (G.J. Irwin[4]). They make instruments mounted on vehicles and also a smaller and lighter bevameter that can be carried to the test site. However, three men are required to operate the latter and, at the same time, act as counterweights. The latest experimental bevameter design is a quite small, hand-operated device not unlike the Waterways Experiment Station (WES) cone penetrometer (Knight and Freitag, 1961) or the vane cone penetrometer by Yong (Yong, Youssef, and Fattah, 1975). However, whatever is gained in portability and flexibility is usually lost in ability to maintain a uniform force and to provide consistent and accurate measurements — the prerequisites for any serious research work.

Because there is no real standardization of equipment and instrumentation, most researchers design and build their own bevameters to suit their particular requirements. Some of these instruments are mounted on tracked vehicles for application on very soft terrain (Bekker, 1975), some on an agricultural tractor (Sohne, 1969), and some are built into a frame that can be mounted on any vehicle (Wong, 1979). The FMI (now the PNFI) bevameter and instrumentation have been modified to suit our particular requirements, to provide greater mobility and flexibility of measurements under forest conditions, and to make it possible to test a range of forest soils under dry summer conditions. The objective of our investigations is not only the mobility of vehicles over a marginal terrain but also the interaction of soil-working tools with different soils and the effect of compaction and disturbance of the top soil under hard and dry conditions. These conditions will require test plates of considerably smaller diameters for the given down force and

[2] Correspondence, 1974; consultant, Santa Barbara, California.

[3] Correspondence, 1976; professor, Mechanical Engineering Department, Carleton University, Ottawa.

[4] Correspondence, 1977; defence scientist, Suffield, Alberta.

test-vehicle weight; also, special attachments and adaptors have been designed to accommodate the smaller test tools.

Carrier vehicle

Argo 8 was chosen for the carrier vehicle.[5] It is a small all-terrain recreational vehicle, equipped with eight solid-mounted wheels for normal operation and a set of optional tracks for soft terrain. The vehicle is powered by a Tecumseh four-cycle, single-cylinder, air-cooled engine that develops a maximum brake power of 13 kW at 3600 rpm. The maximum recommended operating power at 3600 rpm is 9.5 kW, with a torque rating of 31 N/m. The engine has a recommended operating speed range between 1800 and 3600 rpm.

Weight distribution

An approximate distribution of the weight of the basic vehicle and the test equipment, shown in Figure 1, is expressed in newtons of force vectors acting on the vehicle wheels and at the bevameter test tool. The vehicle components of the force are shown above the centerline and the equipment below the line, representing the weight of the vehicle, equipment, and bevameter— all together amounting to a total of 910 kg.

The force applied by the bevameter test plate to the ground tends to raise the vehicle and rotate it theoretically about the front axle at the point R_1. When all the weight is theoretically supported by the front axel (R_1) and by the bevameter (R_2), the maximum possible force applied by the bevameter at R_2 is 4723 N. The recommended maximum design force (M.G. Bekker[6]) of approximately 6500 N can be obtained by placing an additional weight of 180 kg on the platform attached to the bevameter cylinder, just above the reference structure (Figs. 1 and 2).

The final equipment mounting arrangement is somewhat different from the original design (Golob, 1978) because of the weight distribution and the required maximum bevameter force of approximately 6500 N (M.G. Bekker[7]). The total weight of the equipment and instrumentation exceeded the original estimate by 200 kg, which made it necessary to reexamine the concept in order to assure an even weight distribution over all wheels when travelling and also to provide a sufficient counterweight for the maximum bevameter force. This requirement was partly satisfied by installing the instrument pack and hydraulic controls on sliding tracks so that they could be shifted to the back of the vehicle for additional weight when testing soil and forward again when moving from site to site. The added weight also affected the steering of the vehicle, which had to be redesigned and replaced by a more positive system.

Supporting structure

The bevameter's supporting structure and parallelogram, designed to maintain it at a right angle to the ground, are of a simple but functional design. A special counterbalance platform was attached to the bevameter cylinder to provide room for additional counterweight, should it be required because of exceptionally hard ground conditions.

The reference structure and pads, shown in Figure 2, are floating freely on the cylinder rod and serve as a ground level reference point, used to record movement of the bevameter tools relative to the reference structure by means of two displacement transducers mounted on the structure.

Just above the reference structure is a platform used to add counterweight when needed. The initial design provided for two operators to sit on it during the test, but this was later modified when the reference structure was made higher to allow for smaller test tools.

Test tools

Since our objectives are not only to study forest terrain as a function of vehicle mobility but also to study the interaction of soil-working tools with different forest soils, we designed the additional test tools

[5] Ontario Drive and Gear Limited, of New Hamburg, Ontario, manufacturer of Argo all-terrain vehicles.

[6] See note 2 above.

[7] See note 2 above.

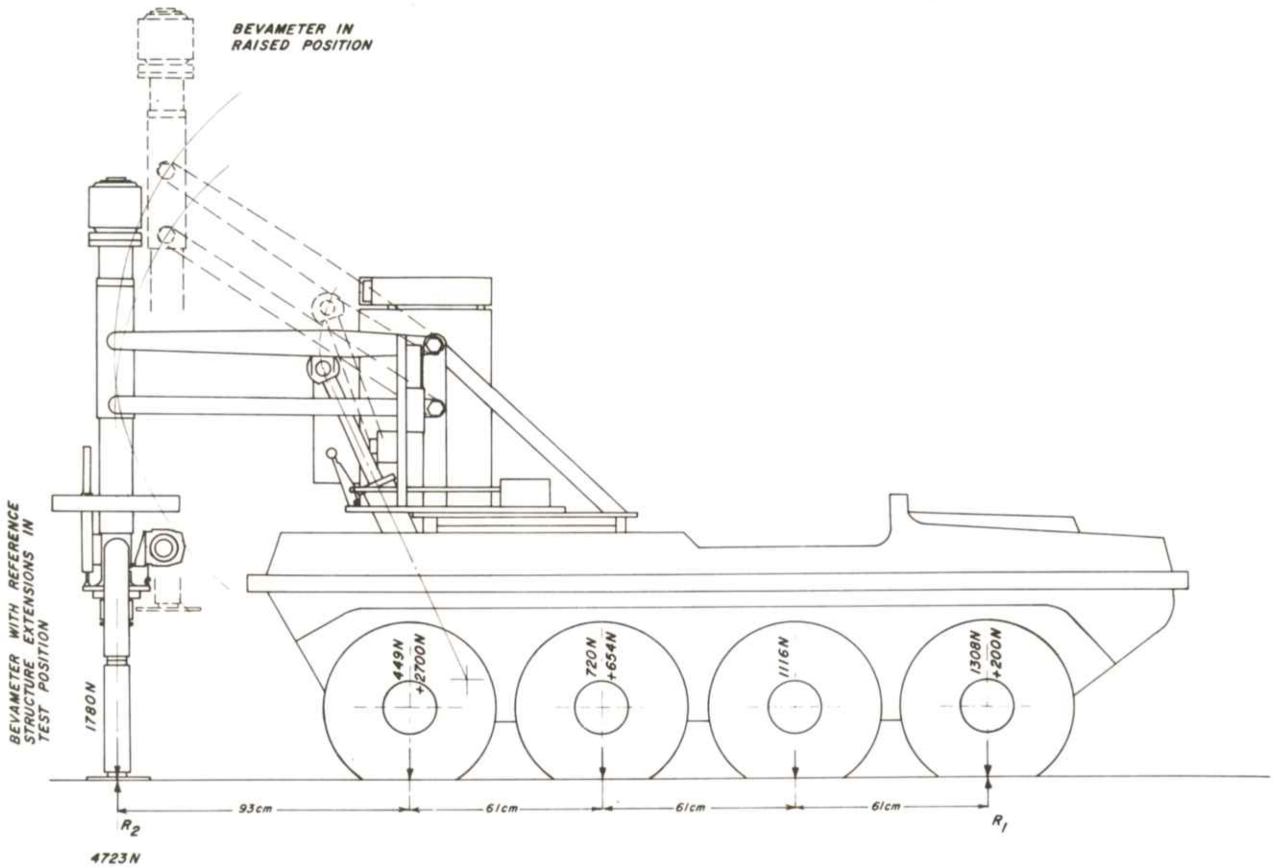

Figure 1. PNFI bevameter installation and weight distribution.

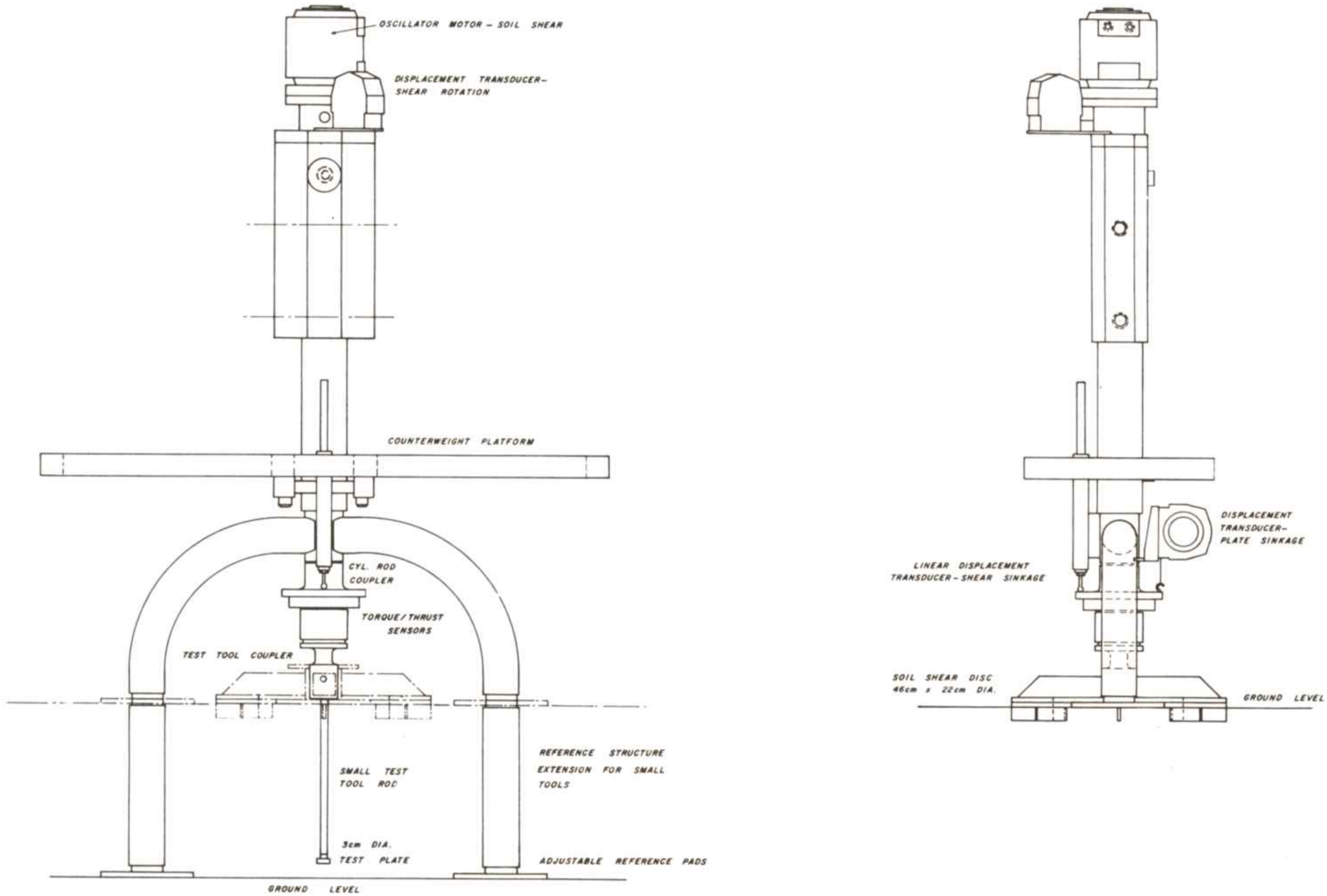

Figure 2. Bevameter in test position with and without reference structure extension.

shown in Figure 3. The intermediate *(c)* and small *(b)* plates require coupling adaptors so that they can be attached to the bevameter rod. The other test tools shown *(d)* — e.g., the conventional WES cone- and tree-planting containers of various shapes and sizes — will be used in the analysis. The large bevameter plates *(a)* will be used for conventional bevameter analysis of soft forest soils like muskeg and others during the spring breakup period. Other test tools and experimental equipment will be added when required.

Auxiliary equipment

An important piece of auxiliary equipment is the trailer, designed to carry other components that can be detached from the carrier vehicle and thus improve its mobility. The trailer is a converted all-terrain Argo 6 chassis[5] modified so that it can be pulled behind the Argo 8. In addition to all tools, it will carry a portable generator (1.5 kW, 120 V, 60 Hz), powered by a four-stroke engine directly coupled to the generator. It will also be loaded with several weights, which will be used to provide additional counterweight when needed.

Bevameter

Because of the limited space on the vehicle, several bevameter mounting arrangements and different bevameter concepts were evaluated by the FMI until the present concept provided a solution. The pressure-sinkage test is a simple soil strength experiment that dates back to 1913, when Bernstein (Bekker, 1969) first proposed the use of a plate to measure soil strength. However, we decided to combine the two pieces of equipment developed by Bekker into one device capable of performing both tests, pressure-sinkage as well as soil shear test. This was achieved by developing an hydraulic cylinder in combination with an hydraulic motor; as the rod extends, it can simultaneously rotate. Each function is independently controlled, providing either simultaneous linear and rotary motions or independent linear motion for the pressure-sinkage test. This device is illustrated in Figure 2: in the illustration on the left we see the bevameter from the rear in the operating position, equipped with extensions to the reference pads for use with small test plates and other tools. The pressure plate shown is a test plate 3 cm in diameter, and above it in phantom outline is shown the shear test ring, of 46-cm diameter, in the normal operating position, without extensions. The same shear test ring is shown on the right, where the bevameter is seen from the side.

The variable force in the pressure-sinkage test and the constant force required to simulate a given ground pressure are applied on the piston side of the bevameter cylinder. The shearing test rotation and soil-shearing torque are generated in the oscillating motor mounted at the top of the bevameter cylinder, forming an integral hydraulic component whose cylinder rod is rotated by the oscillating actuator through a splined shaft freely sliding inside the rod through the piston. The device has been tested by the manufacturer for performance and reliability,[8] and although some reservations were expressed because of inherent internal friction, the bevameter was found functional and within its design parameters. Some further work in the area of hydraulic seals has been done to determine the possibility of reducing friction between the seal and the cylinder; the friction can be reduced considerably by using a newly developed material for seals and by allowing minimal oil seepage between the rod and the piston.

Hydraulic system

The bevameter power and control system is energized by a system of hydraulic circuits, illustrated in Figure 4. These circuits provide power and control the bevameter cylinder (item 1), oscillating motor (item 2), and hoist cylinder (item 3), whose function it is to position the bevameter for soil tests or to raise it for transportation, as shown in Figure 1. The power is supplied by a double hydraulic pump with separate inlets and outlets, one section delivering hydraulic fluid at a rate of 0.5 dm^3/s and the other at a rate

[8] Hyd-Mech Engineering Ltd., Woodstock, Ontario.

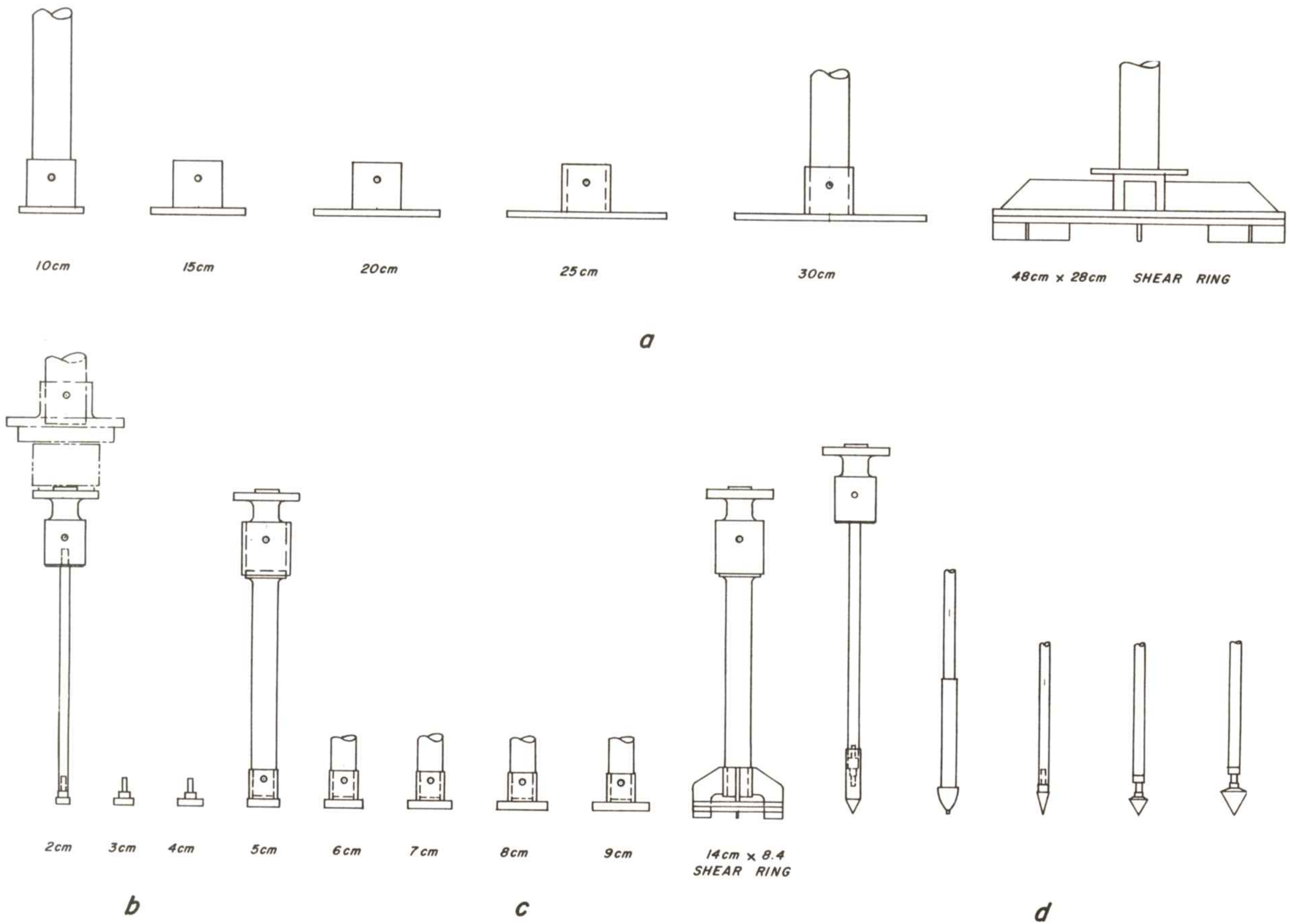

Figure 3. Tools for bevameter soil tests. *a*: Large plates, to be used for conventional bevameter analysis of soft forest soils. *b*: Small plates; require coupling adaptors so that they can be attached to the bevameter rod. *c*: Intermediate plates; require coupling adaptors for same reason as small plates do. *d*: Other tools, e.g., WES cone- and tree-planting containers, to be used in the analysis.

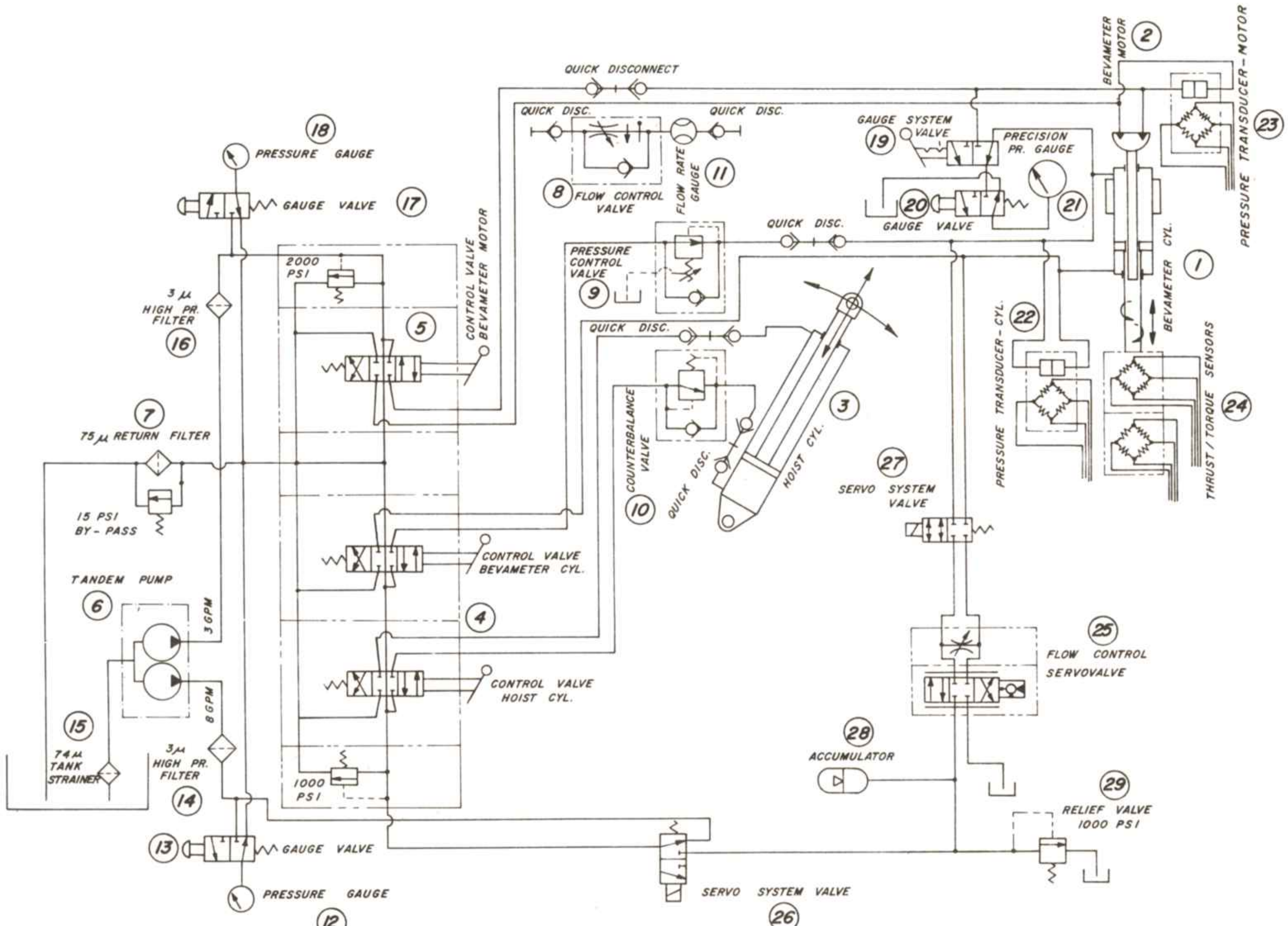

Figure 4. Hydraulic system schematic. See Appendix B for list of components.

of 0.19 dm^3/s. The tandem pump is mounted on the transmission input, which is coupled to the torque converter output shaft; it rotates at the converter output speed. The rate of flow mentioned is based on the pump input speed of 3450 rpm at the system pressure of 4800 kPa, for a power output of 3.3 kW for the two pumps. At 14 MPa, the rate of flow is reduced by 74 per cent. The flow of 0.5 dm^3/s from the larger pump is directed to a two-spool open-centre valve, controlled by a pressure relief of 7 MPa for a maximum power requirement of 3.5 kW, and the flow from the smaller pump goes to a single-spool valve set at 14 MPa for a maximum power of 2.6 kW.

The two-spool valve (item 4) controls the hoist cylinder and the bevameter cylinder. A counterbalance valve (item 10) is installed on the piston line of the hoist cylinder to prevent slippage and provide a positive positioning of the bevameter equipment. The bevameter cylinder is controlled by the second spool of the two-spool valve, with the flow to the piston end of the cylinder passing through a pressure control valve (item 9) intended to provide a constant simulated ground pressure, required for the soil shear test. The valve is manually adjusted for the desired system pressure, which is then maintained during the shear test. This approach can provide an infinitely variable control of desired ground pressures. In other bevameter designs, the ground pressure is controlled by a dead load, which must be changed for different ground pressures.

The oscillating bevameter motor (item 2) is controlled by the single-spool valve (item 5), which controls the rotation of the soil shear rings. The shear test is done in the clockwise rotation of the oscillator, having a limited rotation of 280 degrees.

Item 8 is a flow control valve, manually adjustable, designed to provide a controlled flow either to the cylinder or to the oscillator, for a constant penetration or for a constant rotation of the soil shear disc. The flow is shown on the flow rate gauge (item 11), downstream from the flow control valve. The switch from one circuit to the other is done by the use of quick disconnects on the two power lines, the one leading to the cylinder and the other to the motor. During the pressure-sinkage test the flow control is connected to the cylinder, and for the shear test it is switched to the oscillating motor. The second alternate circuit is designed to connect either one of the two power lines to the precision pressure gauge (item 21), calibrated for pressures of up to 7000 kPa. The manually operated gauge system valve (item 19) is switched to the desired circuit, cylinder or motor, and the gauge valve (item 20) is then depressed for reading. The system provides good protection for the very sensitive precision gauge that is used for the initial setting of the pressure as it may be required for the simulated ground pressure during the soil shear test or just to double check the system pressure.

Smaller (14-MPa) pressure gauges (items 12 and 18) are installed on the pressure lines coming out of the two pumps, between the high-pressure 3-micron filters (items 14 and 16) and the two power-control valves. The pressure loss in the system can be determined by subtracting the pressure taken at the equipment gauge (item 21) from the pressure taken at the pump gauges (12 and 18).

A differential pressure transducer (item 22) connected to the two lines leading to the bevameter cylinder is used to provide a continuous record of the bevameter ground force by subtracting the back pressure in the return line from the pressure in the pressure line, leaving the internal friction in the cylinder as the only unknown force in the bevameter cylinder circuit. The maximum calibrated pressure in the cylinder transducer is 5000 kPa. The differential pressure transducer (item 23) in the bevameter motor circuit has a capacity of 21 MPa, and it measures net pressures during the soil shear test. The loss of internal pressure due to the friction inside the motor is not recorded. These two instruments were used in the original design to record bevameter penetration forces and the soil shear torque forces. However, during the preliminary tests in the fall of 1978, it was felt that the error due to the internal friction might be too great for an accurate evaluation of test results; therefore, during the summer of 1979, an additional direct force and torque measuring device (item 24) was added.

Servo control system

The constant ground pressure required for the soil shear test is critical to the test. The constant down force was maintained in the original design by setting the pressure control valve (item 9) to a desired system pressure; however, during the preliminary tests it was felt that the pressure fluctuated beyond the acceptable error, and the simulated ground pressure could not be maintained within the desired design limits. This led to the design of an additional control circuit, featuring a servo control valve (item 25) that is controlled automatically by the electrical signals from either the differential transducer (item 22) or the thrust sensor (item 24). The valve is electrically controlled and is switched on when the two servo system valves (items 26 and 27) are activated. The two system valves are solenoid-controlled to cut into the main power system controlled by the manual valves (items 4 and 5). These two servo system valves switch the hydraulic power flow from the manual system to the servo system, which is then controlled by the predetermined ground pressure measured by the transducer.

Data acquisition system

Power for the data acquisition system is provided by a portable generator producing 1.5 kW of 120-V alternating current. The system was originally designed with hydraulic pressure transducers only,[9] but later it was expanded by adding sensors that measure bevameter cylinder force and soil-shearing torque directly through a thrust/torque measuring device.[10] The device, built into one component, is designed for a minimum of cross talk between the two transducers.

The system must also record the bevameter pressure plate displacement, rotary displacement of the soil-shearing ring, and displacement of the shearing ring caused by the sinkage during the shearing test. It therefore consists of seven transducers, or sensors, that generate electrical signals in response to changes due to displacement, varying pressures, forces, and torque. These electrical signals are transmitted to their respective signal conditioners, where they are processed, each of them matched to the type of signal output generated by the sensor/transducer.

The function of the conditioners is to convert the sensor signals to a standard 5-V signal, so that the output of the conditioner varies from 0 to 5 V, depending on the value of the input signal. The transducer bridge, when excited by the voltage from the conditioner, produces a signal of 1 to 5 mV/V of excitation voltage; this signal is then amplified and filtered so that a stable digital indication and a jitter-free control signal can be obtained and recorded. The signal conditioner outputs are fed to the display selector/controller, to a data buffer and recorder controller, and to a two-channel X-Y_1, Y_2 recorder. The system is shown in the block diagram in Figure 5, indicating the interconnection of all seven transducers (items 1–7) and their respective signal conditioners (items 8–14) with the display selector/controller (items 15 and 16) and the two recording devices (items 17 and 20). Any one of the seven sensor-parameters can be visually monitored through the display unit (item 16); the information is transmitted to the display controller as a standard 5-V signal and displayed (item 16) directly in the appropriate units — the bevameter force in newtons, the plate displacement in millimetres, the soil shear torque in newton metres, and the shear rotation in radians. These units have been selected for ease of conversion and analysis of data.

One of the features of our system is that it can collect, convert, and record continuously the output of all seven transducers. The data buffer, recorder, and controller (item 17) has the built-in capacity of recording the output of the system at a rate from 10 to 140 readings per

[9] B.H. McGregor, Engineered Instrument Sales and Service, Toronto, Ontario.

[10] Lebow Inc., Troy, Michigan.

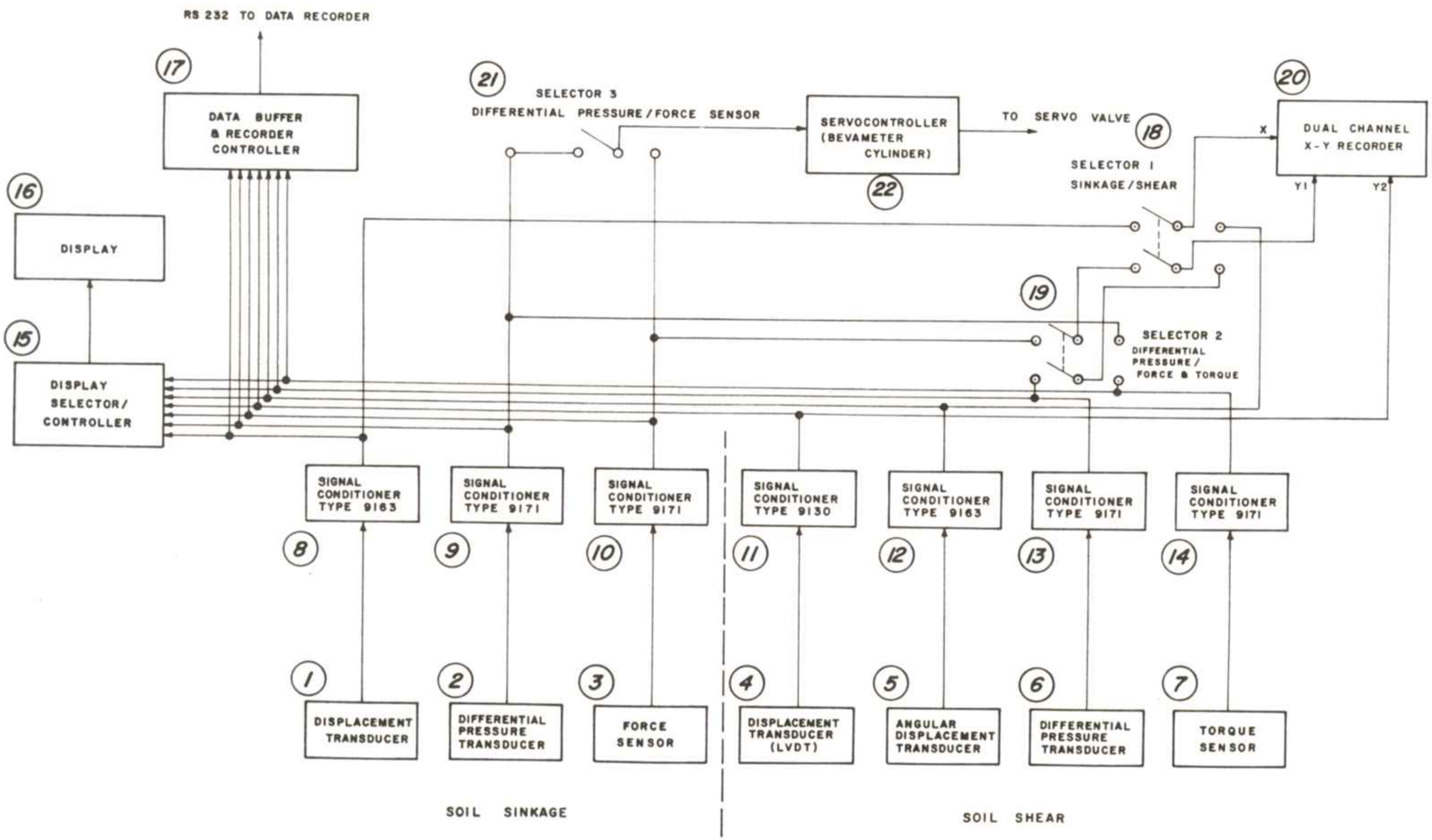

Figure 5. Bevameter data acquisition system. See Appendix B for list of electronic components.

minute. The rate is preselected and can be varied, depending on the amount of information and the ability of the buffer/controller to send the converted information to a magnetic tape or floppy disc. The buffer has a capacity of 1024 words of information, which are immediately converted from analog signals to ASC11 digital form and then transmitted to the recorder at a rate of 300 baud (1 baud = 1 pulse/s).

The input into the two-channel X-Y_1, Y_2 recorder is controlled by two selector switches (items 18 and 19), which control and direct preselected signals to the X and the Y axes of the plotter. Selector 1 (item 18) connects signals from transducers and conditioners used in one of the two soil strength tests — pressure-sinkage or soil shear test. During the pressure-sinkage test the downward displacement of the bevameter pressure plate is measured by the displacement transducer (item 1), filtered and amplified by the conditioner (item 8), then sent to the recorder and plotted on the X axis. The bevameter force is measured simultaneously by the 5000-kPa differential transducer (item 2) and the sensor/transducer (item 3). These two signals are filtered and amplified by their respective signal conditioners (items 9 and 10) and then transmitted to the selector switch (item 19), which sends the selected signal to the recorder (item 20), where it is plotted on the Y axis. This feature will make it possible to analyse the difference between the hydraulic pressure measurements and the direct sensor/transducer data.

The soil shear test requires a constant simulated ground pressure, which can be maintained by either the differential pressure transducer (item 2) or the force sensor/transducer (item 3). To activate the servo system, either one of the two transducers is connected through selector 3 (item 21) to the servocontroller (item 22), which in turn controls the hydraulic servo valve by means of a built-in feedback system designed to maintain a chosen transducer signal by activating the valve and increasing or decreasing the flow of oil to the bevameter cylinder. Before the soil shear test is performed, the ground pressure is set by preselecting and setting a desired transducer output voltage into the servocontroller.

The information obtained and recorded during the soil shear test is measured by the four transducers shown in Figure 5 under the heading Soil Shear. The torque required to shear soil is measured by the differential transducer (item 6) and by the torque sensor/transducer (item 7). The signals from these two transducers are filtered and amplified by their respective signal conditioners (items 13 and 14), and the selected one is transmitted through selector 2 (item 19) to the recorder (item 20), where it is plotted on the Y_1 axis. The two different modes will give us the opportunity to study the values measured by the hydraulic pressure transducer as compared to those measured by the direct torque sensor device.

The angular displacement of the soil shear ring is measured by the displacement transducer attached to the shaft connecting the oscillator motor to the bevameter cylinder rod (Figure 2; Figure 4, item 23; Figure 5, item 5). Its signal is filtered and amplified (item 12), then plotted on the X axis of the recorder. In addition to the usual measurements outlined above, we have introduced the measurement of sinkage during the shear by sensing displacement of the soil shear ring caused by the shear action under a constant ground pressure maintained through the transducer-controlled servo system. The signal is transmitted from the linear displacement transducer (item 4) through its signal conditioner (item 11) to the recorder, where it is plotted on the Y_2 axis for a comparative record parallel to the shearing torque and as a function of the angular displacement.

METHODOLOGY OF MEASUREMENTS

The soil strength measuring method chosen by the PNFI is the technique developed by Bekker (1969) and the one most widely used in the analysis of terrain-vehicle systems when parametric analysis is preferred to the comparative technique. The theories behind the bevameter method are well documented (Bekker, 1969;

Sohne, 1969; Reece, 1965; Wong, 1978), but these theories have not as yet been developed to the point that will permit an accurate field definition of terrain-vehicle relationships, and the existing methods for the analysis of experimental data require considerable refinement and improvement (Wong, 1978; Wong, 1979).

In addition to the terrain-vehicle relationships, the PNFI investigations will apply bevameter soil parameters to the relationships between soil-working tools and forest soils. This additional research requires a set of scaled-down test plates, illustrated in Figure 3, *b* and *c*; also, probes other than the bevameter test plates will be used, and the results will be correlated with soil parameters obtained by the bevameter technique. The copies of components used in forest operations, such as different tree-planting containers, will be tested directly by the bevameter and correlated to bevameter parameters. The soil parameters that will be used in our analysis of soil strength are based on the equations developed by Bekker (1960) and Reece (1965) and expanded by Wong (1979). These parameters are computed from the soil test results, based on interpretation of curves obtained in the pressure-sinkage and soil shear tests.

Pressure-sinkage relationship

The expression proposed by Bekker (1960) is most commonly used in the pressure-sinkage analysis and will also serve as the basis for the PNFI experiments:

$$p = (k_c/b + k_\phi)z^n$$

where p = ground pressure under the test plate

b = pressure plate diameter (Because each test requires at least two plates of different diameters, we have b_1 and b_2 plates in all tests.)

k_c = cohesion modulus of deformation

k_ϕ = friction modulus of deformation

z= depth of penetration under the ground pressure, p

n = exponent of deformation

The moduli, k_c and k_ϕ, are computed from the following equations:

$$a_1 = (k_c/b_1 + k_\phi)$$

$$a_2 = (k_c/b_2 + k_\phi)$$

The values a_1 and a_2 are obtained in the graph illustrated in Figure 6, in which pressure-sinkage relationship is plotted on a logarithmic scale; the exponent of deformation, n, is taken as tan of the angle α in the graph.

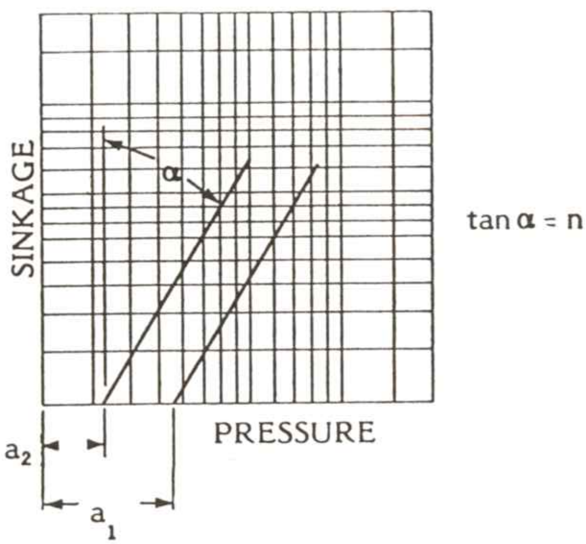

Figure 6. Explanation of a_1, a_2, and n values in pressure-sinkage relationship. See text above, under subhead "Pressure-Sinkage Relationship."

Reece (1965) proposed a revised expression because "it has been shown to fit experimental and computed results for sand and clay more closely than the Bekker equation and to have the great advantage that the three soil constants are all dimensionless." However, after extensive field tests, Wong (1979) determined that given the same set of data, the same degree of good fit is achieved with both the Bekker and the Reece equations, and the curves calculated from each fall into a single curve. The expression by

Reece is as follows:

$$p = (ck_c' + \gamma bk_\phi')(\frac{z}{n})^n$$

where c = cohesion and γ = soil density.

The obvious value of soil parameters obtained in pressure-sinkage tests is in the possibility of predicting how much a soil will give, deform, under certain ground pressure; this can then be applied to a multitude of forest and agricultural operations. Soil tests are necessary to provide the information needed to compute these soil strength parameters.

Our equipment has been designed to accept the full range of pressure plate sizes illustrated in Figure 3, from a large plate 30 cm in diameter to one 2 cm in diameter, intended to be used in hard forest soils because of the limited weight/force capacity of the test vehicle.

Local nonhomogeneities and irregularities in soil may affect the test results obtained with very small pressure plates (Wong, 1979), therefore we shall try to correlate the results obtained with these small plates and those obtained with the regular, larger plates. The 3-cm plate is shown in the test position in the left section of Figure 2; because of its small diameter the plate is attached to a test rod of small diameter, which is screwed into the lower end of the test tool coupler, which in turn is bolted to the torque/thrust sensor device. The reference structure is extended to provide the additional height required for the test clearance for the two undersized tool rods.

Once the reference pads are in positive contact with the ground and the reference structure is resting free, the steel cable from the displacement potentiometer/transducer is attached to the hook on the cylinder rod coupler just below the reference structure, shown in the illustration on the right in Figure 2. When the bevameter is activated, the rod coupler extends downwards with the cylinder rod, and the displacement transducer measures the relative distance between the reference structure and the point of attachment to the rod coupler, which is the same as the displacement of the test plate from the zero point at the beginning of the test. The amplified signal is plotted on the X axis of the recorder mounted at the back of the test vehicle (Figure 1), and it is also recorded and stored on the tape.

The down force is measured by the load cell in the torque/thrust sensor shown in Figure 2 as well as by the differential pressure transducer (Figure 4, item 22) installed between hydraulic lines going to the rod end and the piston end of the bevameter cylinder. The signals from both force transducers are recorded on the tape for future comparison and analysis; also, either one of the two signals is plotted on the Y axis of the recorder.

Other test and forest tools, shown in Figure 3*d*, can be installed and tested in a manner similar to that of the 3-cm test plate illustrated on the left in Figure 2. Pressure plates larger than 10 cm in diameter are attached directly to the test tool coupler (Figure 2), the reference structure extensions are removed, and the reference pads are screwed directly into the reference structure. If required, a counterweight can be placed on the platform, attached to the bevameter cylinder just above the reference structure, to compensate for possible high forces.

Soil shear test

The horizontal stress-strain relationship in soils is determined through the soil shear test, which is done, in the case of the PNFI bevameter, by rotating a ring equipped with shear plates (Figure 3, *a* and *c*) for horizontal shearing of soil. The ring shear plate tool was first introduced because of its simplicity compared to the linear apparatus described by Reece (1965) in his paper on principles of soil-vehicle mechanics.

The soil ring shear test results are comparable to the results obtained by the rectangular plate, although it is commonly agreed that the optimum size of the ring plate has yet to be determined, and the design detail should be improved (Bekker, 1969). The ratio of the diameter of the outer ring to that of the inner varies from 1.3 (Wong, 1979) to 1.6 (M.G. Bekker[11]).

[11] See note 2 above.

The PNFI shear ring ratio is approximately 1.6, which will be varied to study the effect of the ratio on the quality of the information. Both shear ring assemblies have replaceable shear ring plates, so that different shear plates and shear plate spacing can be evaluated; five different small shear rings will provide information on the effect of the number of shear plates on the shearing torque. The expression representing the shear deformation curve, first proposed by Bekker (1969), is based on Mohr-Coulomb failure criterion. Bekker's expression is fairly complex, because it involves two empirical constants, k_1 and K_2:

$$\tau = (c + p \tan\phi)/Y_{max} \left[e^{(-K_2 + \sqrt{K_2^2 - 1})K_1 d} - e^{(-K_2 - \sqrt{K_2^2 - 1})K_1 d} \right]$$

where: τ = soil shear stress

c = cohesion

p = unit ground pressure

ϕ = angle of soil friction

K_1 = shear slip parameter

K_2 = shear slip parameter

e = 2.7182

d = shear displacement

The maximum shear stress, τ_{max}, is computed from the following expression:

$$\tau_{max} = c + \tau \tan\phi$$

The equation for the soil shear stress can then be simplified to

$$\tau = (\tau_{max}/Y_{max})\, Y$$

which represents the soil shear stress in brittle soils, where

$$Y_{max} = Y$$

when displacement, d, is maximum and

$$Y = e^{(-K_2 + \sqrt{K_2^2 - 1})K_1 d} - e^{(-K_2 - \sqrt{K_2^2 - 1})K_1 d}$$

For plastic soils the expression was simplified by Z. Janosi and B. Hanamoto (Bekker, 1969) to

$$\tau = \tau_{max}(1 - e^{-d/K})$$

A third expression, representing the shear-stress–displacement relationship for muskeg, was recently proposed by Wong (1979):

$$\tau = \tau_{max}(ed/K_w)\, e^{-d/Kw}$$

where K_w is an empirical constant.

The general rule for obtaining the τ_{max} is illustrated in Figure 7, where in section *a* are plotted three curves representing shear force and displacement for three different ground pressures. The maximum forces for all three curves are then plotted in section *b* against their corresponding ground pressures, and the line is drawn through the three points, forming an angle, ϕ, with the line that is projected from the intersect of the plotted line with the Y axis, parallel to the X axis. The point of intersect on the Y axis is the value, c, of soil cohesion. The values K and K_w can be obtained from the experimental data; however, the procedures for obtaining the empirical values, K_1 and K_2, are usually quite involved. An explanation of the empirical constants (K_1, K_2, and K) is shown in Figure 8 along with the general rule for obtaining the value, K, for plastic soils.

To initiate the soil shear test, the shear head with the shear ring is lowered to the test position by manual hoist control. Following this, the desired ground pressure is first applied by manually setting the pressure control valve, and then the system is switched to the servo-controlled valve, activated by the signal from either the differential pressure transducer or the force load cell in

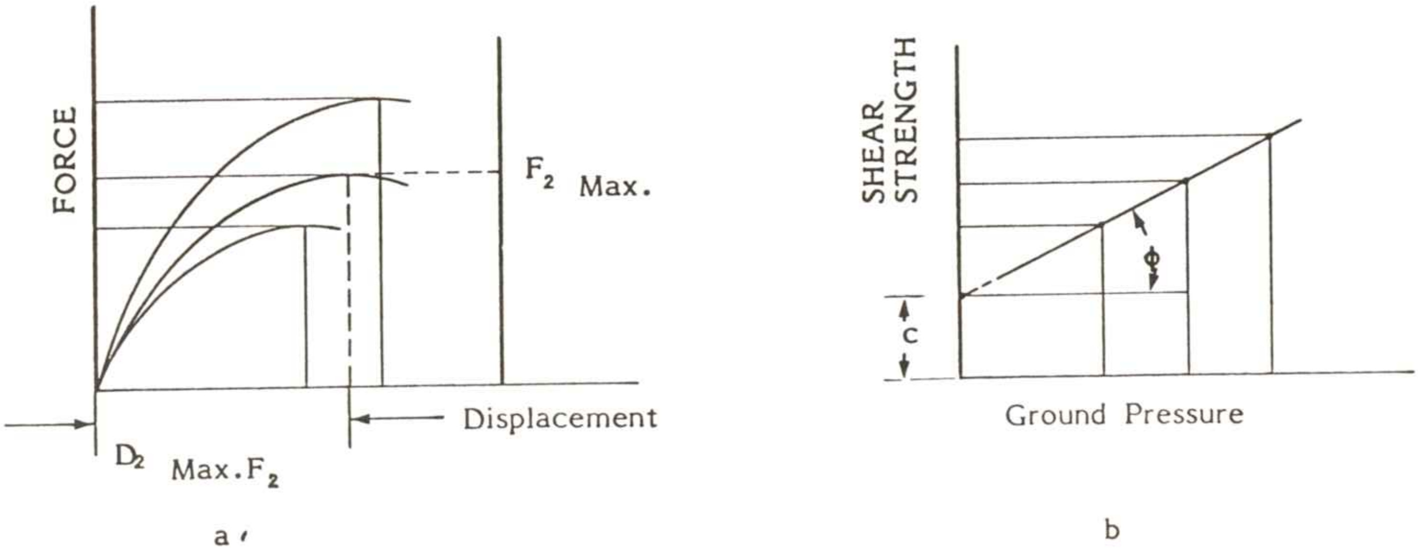

Figure 7. Illustration of how the soil cohesion, c, and friction, ϕ, are obtained. See text, p. 15.

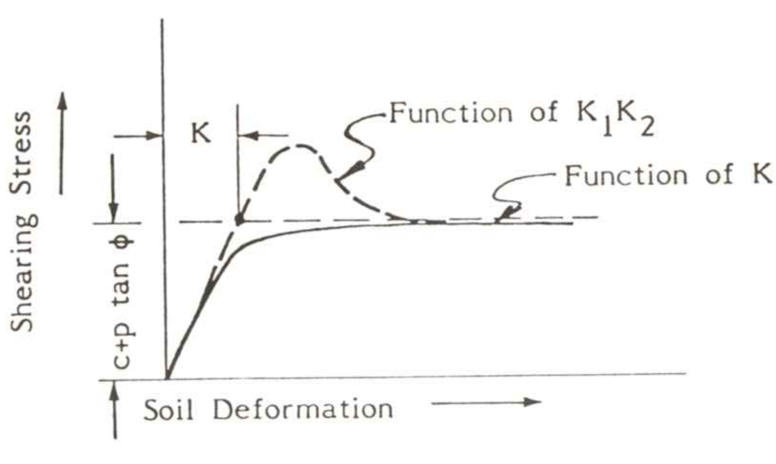

Figure 8. Explanation of the empirical constants—K_1, K_2, and K. See text, p. 15.

the torque/thrust sensor transducer. The ground pressure for soft soils can vary from that for a very soft muskeg type having a support strength of 10 kPa to that for a fairly firm soil capable of withstanding pressure of 100 kPa. The force required to apply these pressures to the large 46-cm shear ring ranges from 1000 to 10 000 N, generated by the hydraulic pressure in the bevameter cylinder, which ranges from 240 to 2300 kPa. The small ring plate (14 cm outside diameter) requires cylinder force from 100 to 1000 N for bevameter cylinder pressures from 22 to 220 kPa. The soil shear tests for harder forest soils, needed to study soil scarifying and planting operations, will require ground pressures of up to 450 kPa under the small shear ring, produced by a force of 4400 N generated by a bevameter cylinder pressure of 970 kPa.

The desired speed of shear rotation is obtained by manually setting the flow control valve for the required flow, determined by computing the rate of flow from the proposed shearing speed in centimetres per second. Typical off-road locomotion shear rates are in the range of 2.5 cm/s to 25 cm/s; when translated to the rotation of the small PNFI shear ring, which has an average shear plate diameter of 11.2 cm, this makes 35 cm for one full revolution, 27 cm for 280, and 17.5 cm for 180. The displacement of the PNFI oscillator motor is 62 cm^3 per radian of revolution, or 304 cm^3 for the total shaft travel of 4.89 rad (280). At a speed of 2.5 cm/s, it would take 7 s to rotate it 3.14 rad (180), requiring a total flow of 196 cm^3 at a rate of 28 cm^3/s, or 0.028 dm^3/s. For the shearing speed of 25 cm/s, the required rate of flow would be 289 cm^3/s, and it would take 0.7 s to rotate the shear 3.14 rad.

The installation of the large shear ring is shown in Figure 2, in phantom lines on the left and in full lines on the right, where displacement transducers are fully visible. The displacement transducer used for the pressure-sinkage test must be disconnected before the soil shear test is activated.

The soil-shearing force is determined by measuring torque needed to rotate the shear head; this is then divided by the moment arm, the distance to the center of the shear plate (grouser). The torque is obtained either by direct signal from the torque/thrust sensor, located at the lower end of the cylinder rod, or by measuring hydraulic pressure with the help of a differential transducer connected to the two lines leading to the bevameter oscillator motor. Signals from both transducers are recorded on the tape, and the selected signal is also plotted on the Y_1 axis of the recorder.

Angular displacement is measured by the transducer shown in Figure 2, mounted just under the motor; the fine steel cable from the transducer is hooked, through the hole in the housing, to the coupler shaft between the motor and the rod. Displacement of the cable, when wound on the shaft, is calibrated to the rotation of the shear ring, it is displaced and recorded in radians for ease of conversion to the linear displacement of shear plates, and it is plotted on the X axis of the recorder.

During the soil shear tests, the shear head is also displaced downwards, as a result of slip sinkage caused by the lateral flow of the soil. This sinkage is measured by the linear displacement transducer shown in Figure 2, the free end resting on the top flange of the rod coupler and the body secured to the reference structure. The output of the transducer is plotted on the Y_2 axis of the recorder.

CONCLUSION

Terramechanics is a relatively new field of research, and so most of its theories, definitions, and methodology of measurements are still in the initial stages of development. Almost no work has been done in the area of forest soils and their interaction with soil-working tools, regeneration equipment, and forest-based vehicles.

The PNFI is committed to research in new and improved methods of preparing soil bed and planting trees. The present plans call for an extensive computer software system that will process all field data and compile a nationwide forest soil information system. Together with other forest terrain information, the forest soil strength data will be recorded in the form of computerized maps, available to planners of forest operations, researchers, and equipment developers.

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APPENDICES

APPENDIX A

Calibration and Setup of Signal Conditioners

by
Digital Electronic Laboratories of Ottawa

9171 Conditioners

Four 9171 conditioners are present in the system. They are used in conjunction with the differential pressure sensors and the force and torque sensors. The conditioner is set up in accordance with the calibration data provided with the particular transducer. An example of such calibration data is shown for the model 503-750D differential pressure transducer in Figure A-1. This example will be used to describe the setup of the 9171 conditioner:

i) Determine the maximum percentage of full-scale deviation that the sensor will experience. If this is unknown, assume 100 per cent. The mV/V sensitivity of the conditioner is then set to the value that corresponds to this percentage. In this case it was known that the signal would never exceed 25 per cent of full-scale value and would always be negative. Hence the mV/V sensitivity was set to 1/4 x 3.089 = 0.7723. This is accomplished by depressing button 1 on the 9171 unit (Fig. A-2) and adjusting the coarse (C) and fine (F) mV/V controls to obtain 0.7723 on the display.

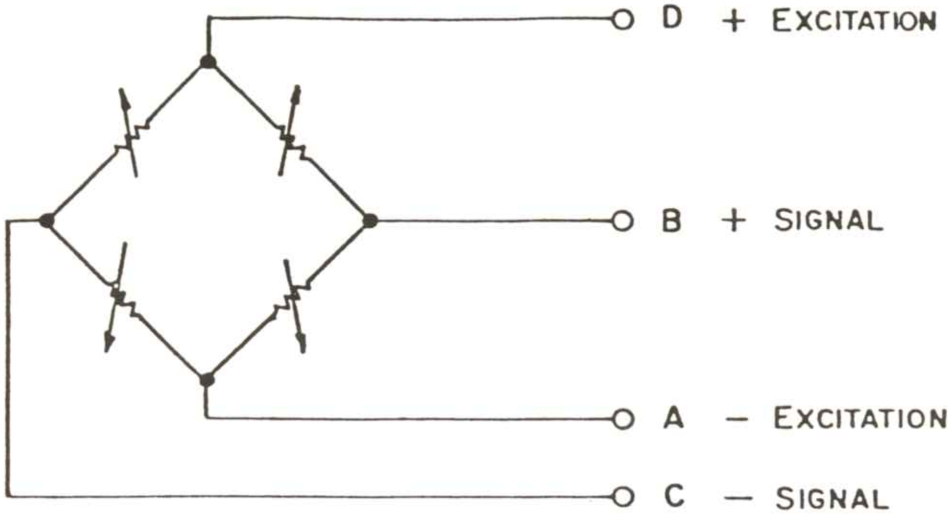
ii) With the transducer unloaded or disconnected, the coarse and fine balance controls are adjusted until zero is read on the display. This sets the zero point.

iii) Depress button 2 on the 9171 (Fig. A-2) and adjust the transducer C and F controls until the display indicates the maximum parameter value in the appropriate engineering units. If the display decimal point is in the wrong position or if the display overruns, then the appropriate DECIMAL and SCALE switches in the 9305 channel caller (Fig. 5, item 15) must be changed to provide the desired display.

In the example, the signal from the pressure transducer is actually used to measure force, hence the display should indicate newtons. The full-scale value is 25 per cent of 750 psi, which corresponds to 5895 newtons. Further, it was desired to have the display read in kilonewtons; hence the full-scale value should show 5.895 kilonewtons. Thus the 7500 scale was used in the channel caller and the decimal switch set to three. The transducer C and F controls (Fig. A-2) were subsequently adjusted, with button 2 depressed on the 9171 until 5.895 kN showed on the display.

DAYTRONIC MODEL 503-750D RANGE ±750 PSID SERIAL NUMBER 4.1

PIN CONNECTIONS



MATING CONNECTORS

500 SERIES
AMPHENOL
97-3106A-14S-6S
DAYTRONIC P/N 25007

400 SERIES
BENDIX
PT06A-10-6S
DAYTRONIC P/N 25073

NOTE: PIN CONNECTIONS SHOWN WHEN APPLIED TO SERIES 400 LOAD CELLS HAVE OUTPUT GOING UP-SCALE (POSITIVE) FOR COMPRESSION LOADS.

SHUNT CALIBRATION: INSTALLING A RESISTOR VALUE OF 30.1 K OHMS AS THE SHUNT CALIBRATION RESISTOR IN THE DAYTRONIC CONDITIONER MODULE WILL GIVE A CALIBRATION VALUE APPROXIMATELY

EQUIVALENT TO
- 701.0 PSID (500 SERIES)
- ______ Lbs. COMPRESSION (400 SERIES)
- ______ Lbs. TENSION (400 SERIES)

500 SERIES			400 SERIES
PRESSURE %FULL SCALE	OUTPUT mV/V	OUTPUT mV/V	OUTPUT
0	0.008	0.008	
20	0.624	−0.602	COMPRESSION + ______ mV/V FULL SCALE
40	1.243	−1.221	
60	1.865	−1.843	
80	2.488	−2.466	TENSION − ______ mV/V FULL SCALE
100	3.106	−3.089	

Figure A-1. Technical data for differential pressure transducer model 503-750D. (Reproduction of material supplied by the manufacturer, Daytronic Corporation.)

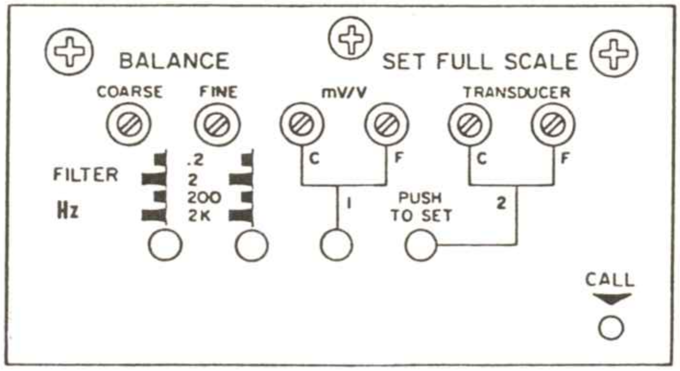


Figure A-2. Strain gauge conditioner model 9171. (Reproduction of illustration provided by the manufacturer, Daytronic Corporation.)

9163 Conditioners

Two 9163 conditioners are present in the system. One is used to measure vertical displacement, the other to measure angular displacement. In both cases, the displacement signal is derived from transducers that are effectively potentiometers connected to a small steel cable. As the cable is extended, the potentiometer setting varies directly with the amount of cable extended. For the angular displacement, this cable is wound around a shaft of known diameter. The conditioners are calibrated as follows:

i) With the transducer at its zero position, adjust the zero screw on the 9163 until 0.0 is read on the display. See Figure A-3.

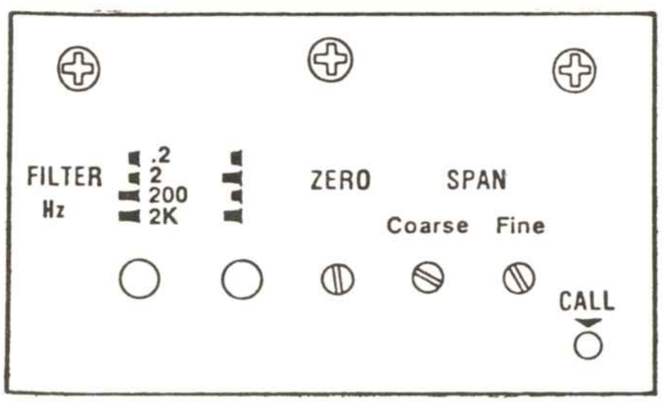


Figure A-3. Analog input module, conditioner model 9163. (Reproduction of illustration provided by the manufacturer, Daytronic Corporation.)

ii) Extend the steel cable from the transducer and measure the length extended with a steel rule. The extended length should be close to the maximum that will ever occur in operation. Adjust the span controls on the 9163 to obtain this value on the display. The appropriate SCALE and DECIMAL switches on the 9305 channel caller must be selected to ensure that the display has adequate range and the decimal point in the proper place.

For angular displacement, compute the amount of length that must be extended to obtain a rotation of 3.1416 rad (180°). Extend this amount of cable and set the span control to obtain a reading of 3.1416.

iii) The conditioner is now calibrated. As a precaution, it is advisable to extend the cable by various measured intermediate amounts and take readings of the display. A check is thus made of the transducer linearity. If the transducer is markedly nonlinear, its response can be plotted and the resulting curve used to correct measurements made during actual data-gathering experiments.

9130 Conditioner

The 9130 conditioner is used with an LVDT transducer (see Appendix B, Electronic Components, item 4) to provide vertical displacement data. The conditioner is designed to accept signals resulting from displacements of 150 mm of the LVDT. We required displacements of 250 mm, hence the following modifications were made to the 9130. This is also the calibration procedure:

The 12-k Ω resistor internal to the 9130, labelled R46 and connected to QA6, is replaced by a 20-k Ω trimpot. The null and zero controls are set to midrange (see Figure A-4). With the transducer in the zero position, the trimpot is adjusted until a zero of minimum reading is obtained. With the transducer extended 250 mm, the coarse- and fine-span controls are adjusted for a reading of 250 mm on the display. The transducer is then returned to the zero position. If the reading is not zero, the trimpot is readjusted to obtain zero or a minimum. The transducer is then extended 250 mm and the span controls adjusted again for a reading of 250 millimetres.

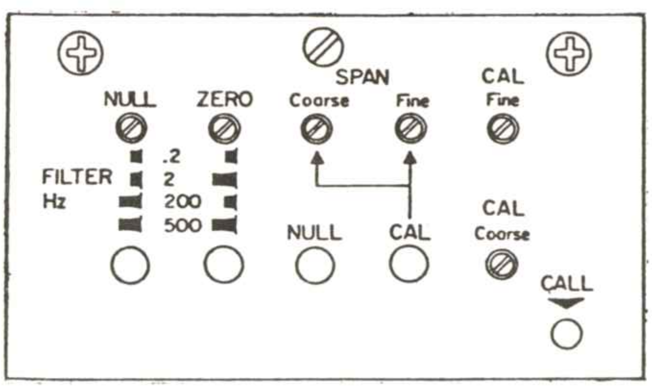


Figure A-4. LVDT conditioner model 9130. (Reproduction of illustration provided by the manufacturer, Daytronic Corporation.)

By the use of this iterative process, the proper setting for the trimpot is found. It may also be necessary to adjust the zero setting slightly for a zero reading. The trimpot is then removed and measured. A resistor of equal value is installed in its place. The calibration is checked, and if there is any deviation, the null and zero controls can be used to reset it.

APPENDIX B

Hydraulic and Electronic Components

Hydraulic components shown in Figure 4

Item	Name	Model	Manufacturer
1	Rotary bevameter cylinder		Hyd-Mech Engineering Ltd., Woodstock, Ontario
2	Oscillator motor	SS-4-280	Bird-Johnson Company, Walpole, Massachusetts
3	Hoist cylinder		Hyd-Mech Engineering Ltd., Woodstock, Ontario
4	Two-Spool control valve	VDP11-DD-10	Parker Hannifin, Cleveland, Ohio
5	Single-spool control valve	VDP11-D-10	Parker Hannifin, Cleveland, Ohio
6	Hydraulic double pump	PR 142	Stone Hydraulic Industries, Rockford, Illinois
7	Return line filter	FS5-P10-10	Sperry Vickers, Rexdale, Ontario
8	Flow control valve	FCG-02-300-50	Sperry Vickers, Rexdale, Ontario
9	Pressure control valve	XGL-03-B-10	Sperry Vickers, Rexdale, Ontario
10	Counterbalance valve		
11	In-line flow meter	201 and 600	Hedland Products, Racine, Wisconsin
12	Precision pressure gauge	1403	Ametek, Sellersville, Pennsylvania
13	Push-button valve, gauge		
14	High-pressure filter		Can Flo Corporation, Royal Oak, Michigan
15	Strainer	OF 3-10-10	Cole Hydraulics Ltd., London, Ontario
16	High-pressure filter		Can Flo Corporation, Royal Oak, Michigan
17	Push-button valve, gauge		

Appendix B—Hydraulic components (cont.)

Item	Name	Model	Manufacturer
18	Precision pressure gauge	1403	Ametek, Sellersville, Pennsylvania
19	Press shift selector valve		
20	Push-button valve, gauge		
21	Precision pressure gauge	1403 (6-inch)	Ametek, Sellersville, Pennsylvania
22	Pressure transducer	503-750D	Daytronic Corporation, Dayton, Ohio
23	Pressure transducer	503-3000D	Daytronic Corporation, Dayton, Ohio
24	Torque/thrust transducer	6459-102	Lebow Associates, Inc., Troy, Michigan
25	Servovalve	A076-103	Moog Inc., East Aurora, New York
26	Solenoid-operated valve	D3W10BY	Parker Hannifin, Cleveland, Ohio
27	Solenoid-operated valve	D3W1EY	Parker Hannifin, Cleveland, Ohio
28	Accumulator	BR-20-60	Hydrodyne Industries Inc., Hauppauge, L.I., N.Y.
29	Manual relief valve	La31-R3-30S	Fluid Controls Inc., Mentor, Ohio

Electronic components shown in Figure 5

Item	Name	Model	Manufacturer
1	Displacement transducer	4004 (0–48 cm)	Research Inc., Minneapolis, Minnesota
2	Pressure transducer	503-750D	Daytronic Corporation, Miamisburg, Ohio
3	Torque/thrust transducer	64590102	Lebow Associates, Inc., Troy, Michigan
4	LVDT displacement transducer	LMA-742Q84	G.L. Collins Corp., Long Beach, California
5	Displacement transducer	4004 (0–15 cm)	Research Inc., Minneapolis, Minnesota
6	Pressure transducer	503-3000D	Daytronic Corporation, Miamisburg, Ohio
7	Torque/thrust transducer	64590102	Lebow Associates, Inc., Troy, Michigan
8	Analog input module	9163	Daytronic Corporation, Miamisburg, Ohio
9	Strain gauge conditioner	9171	Daytronic Corporation, Miamisburg, Ohio

Appendix B—Electronic components (cont.)

Item	Name	Model	Manufacturer
10	Strain gauge conditioner	9171	Daytronic Corporation, Miamisburg, Ohio
11	LVDT conditioner	9130	Daytronic Corporation, Miamisburg, Ohio
12	Analog input module	9163	Daytronic Corporation, Miamisburg, Ohio
13	Strain gauge conditioner	9171	Daytronic Corporation, Miamisburg, Ohio
14	Strain gauge conditioner	9171	Daytronic Corporation, Miamisburg, Ohio
15	Channel caller	9305A	Daytronic Corporation, Miamisburg, Ohio
16	Digital indicator	9530	Daytronic Corporation, Miamisburg, Ohio
17	Data buffer/controller	Custom	Farrell Development Corp. Ltd., Ottawa, Ontario
18	Selector switch		
19	Selector switch		
20	Two-channel recorder	D-72BP	Riken Denshi Co., Ltd., Tokyo, Japan
21	Selector switch		
22	Servocontroller	121-103	Moog Inc., East Aurora, New York