

APPLIED CONE RESEARCH

by

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ABSTRACT

Review is made of the development of a comprehensive research oriented in-situ testing vehicle. Details are provided concerning vehicle specifications, hydraulic controls, electronics and cone penetration equipment.

Detailed information is provided about a 5 channel cone that can continuously record point bearing, friction, pore pressure, temperature and verticality using a standard 10 conductor cable. The use of computer graphics to handle and present the data is discussed and illustrated.

A review is presented of potential misinterpretations that can result if various details concerning equipment and measurements are not considered. Important effects such as temperature and pore pressure corrections are discussed and illustrated.

A short discussion is provided into cone data interpretation that highlights the importance of continuous monitoring of pore pressures generated during cone penetration.

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INTRODUCTION

The purpose of the paper is to bring together experiences of the past 5 to 6 years relevant to equipment development, measurement of soil parameters and their interpretation in 'quasi-static' cone penetrometer testing. As a logging tool this technique is unequalled with respect to the delineation of stratigraphy and the continuous rapid measurement of parameters like bearing and friction. The recent addition of pore pressure measurements has added a new dimension to the interpretation of geotechnical parameters particularly in soils which are partly drained (neither drained nor undrained). Also, the real advantage of cone logging is particularly evident when used in saturated deltaic deposits of loose to soft fine sands, silts and clays, where it is essentially impossible to measure meaningful parameters in the laboratory. It is essential therefore that the best advantage be taken of this technique which requires continued applied research into improved equipment development, potential errors and corrections, and factors affecting the measurement of soil parameters in order to improve our level of confidence with respect to the interpretation of cone penetration results.

RESEARCH VEHICLE

A research oriented in-situ testing vehicle has been under development as part of the overall in-situ research program at the Civil Engineering Dept. of the University of British Columbia since 1976. The truck has been fully operational since 1979 and is being continuously modified and updated. Currently, the vehicle is capable of performing mechanical cone soundings, electric cone soundings of the Fugro friction cone and piezometer cone, and UBC's piezometer friction cone, screw plate testing, vane testing, dilatometer testing and 54 mm Swedish STI fixed piston sampling.

The truck shown in Fig. 1 was designed as a low cost, versatile vehicle for both research and teaching in the field. It has a Ford LN600 cab and reinforced chassis, a 330 cu.in. V8 gasoline engine, an



FIG.1 - UBC Field Research Vehicle, supported and leveled on large pads, raised mast houses penetration device.

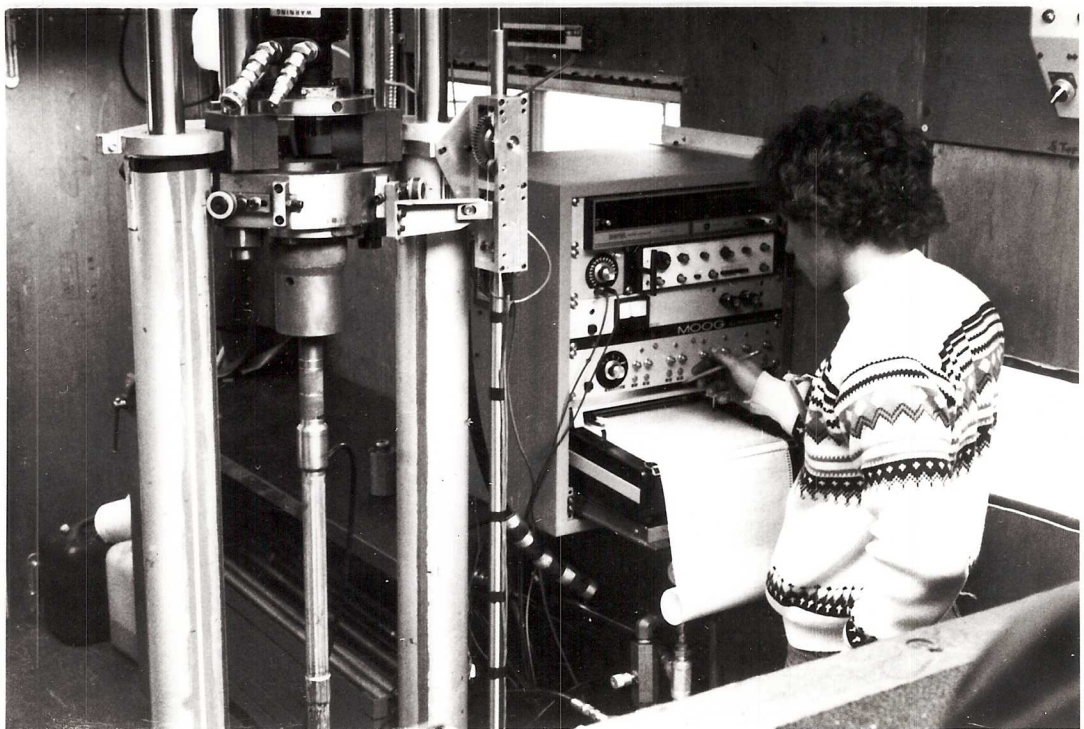


FIG.2 - Inside view facing rear, rods and working bench at rear, hydraulic controls under electronic console operated at front.

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automatic transmission with power take-off, a two speed single rear axle and a GVW of 24,000 lbs. The fully enclosed and insulated van is 8 ft wide by 14 ft floor length and 7 1/2 ft floor to ceiling height with a 4 ft deep by 3 ft high by 8 ft wide 'dog-house' over the cab. A 4.5 KVA gasoline engine AC generator provides the 60 Hz power for all electronics, recorders, lighting, heating, air conditioning and air circulation systems. A back-up 750 watt inverter running off two auxiliary batteries has yet to be needed. The twin piston hydraulic penetration device has a total pushing capacity of 40,000 lbs and a pulling capacity of 50,000 lbs and is located at the fore-aft center of gravity of the vehicle.

The space in the van (see Fig. 2) is carefully laid out to separate operations of electronics and hydraulics from rod handling, and provide storage of 100 one meter length high strength cone rods under the work bench. The truck also has a hand operated 7 ton calibration jack and reference load cell, precision regulated air pressure supply, storage cupboard, desk and file cabinet. An eight channel electronic signal conditioning unit with variable DC excitation is provided for sensors such as strain gauge load cells, pore pressure and hydraulic oil pressure transducers, 4 ft. DC displacement transducer on the penetrometer and the like. A 6 digit multimeter with 1 microvolt resolution is used as the primary reference electronic device for calibration and monitoring of all electronic signals. A 3-pen strip chart recorder is driven by a pulse drive - digital shaft encoder attached to the penetrometer so that depth is directly recorded instead of time. Also, any one of the transducer signal outputs can be used in the feedback loop of the servo-controller to provide a programmable load controlled or displacement controlled penetration system. A function generator allows dynamic or cyclic program loading.

A rotary hydraulic motor is also incorporated in the penetrometer head and facilitates installation of earth anchors. Outrigger reaction beams allow earth anchors to be secured to the vehicle to achieve increased pushing capacity to the limit of the hydraulics.

The safe pushing capacity without anchors is about 18,000 lbs. It has rarely been necessary to use anchors or ballast weights to obtain required depths of penetration especially since the cyclic loading feature of the servo-system has shown itself to be effective in penetrating dense layers and concretion zones of about one meter thickness or less. To date the deepest penetration in a saturated delta deposit has been to a depth of 80 meters without the use of anchors or ballast weights.

The rotary head is also used for in-situ vane testing as well as for screw plate testing to depths in excess of 20 meters.

Stabilizing jacks, located immediately behind the cab and behind the rear axle, are attached to full width pads (8 ft long by 2 ft wide) which are used to take the truck load off its springs and level the bed to provide a rigid and stable working platform.

Hydraulic controls

The hydraulic controls provide the versatility inherent in the vehicle. It was found essential to have a variable volume pressure compensated hydraulic pump to supply the multiple hydraulic systems in the vehicle. The function of this pump is to supply oil at a constant pressure for a range of volume capacities on demand. The pump has been set to operate at two pressure levels; its maximum rating at 2000 psi (13,800 kPa) and a lower setting at 1000 psi (6,900 kPa). The lower setting of 1000 psi corresponds approximately to the pressure required to push at the safe "dead weight" reaction of the vehicle of 18,000 lbs. It has been found that it is usually adequate to perform all hydraulic functions at the low pressure except where a higher response or capacity is required. The maximum capacity of the pump is 29 gpm at 1800 rpm on the power take-off (PTO) which requires about 20 HP at 1000 psi and 35 HP at 2000 psi. It is interesting to note that this type of pump is very efficient and only requires 2 1/2 HP when idling at 1000 psi and zero flow.

Fig. 3 shows the hydraulic circuit diagram. Both the high-low pressure control and emergency dump are solenoid operated from inside the van. The hydraulic circuits include four systems: the leveling jacks, the penetration head, the rotary head and an auxiliary system. After raising and leveling the truck the leveling jacks system is automatically locked and shut off.

The auxiliary system is used primarily to activate a rod clamp which is required for initial set-up and when rods tend to penetrate or slip back down under their own weight. The auxiliary system is also used in mechanical cone testing to activate a small 2 inch piston mounted in the pushing head which independently pushes the inner rods of the mechanical Dutch friction cone (Begemann) the required 7.5 cm.

The penetration head and rotary head are so arranged so that either one or both simultaneously may be hand operated with control valves under independent flow control and adjustable relief pressures from 75 to 2000 psi. The penetrometer can have a different flow rate down than up with different relief pressure settings to protect against accidentally exceeding the dead weight and lifting the truck when pushing at high pressure or overstressing and bending the frame when pulling rods in high bearing soil. If pulling pressures in excess of 500 psi are required then reaction screw jacks are set immediately under the penetrometer reaction beam to transmit the pulling force directly to the ground.

The penetration head uses two 48 inch stroke welded hydraulic cylinders which have 4 inch diameter pistons with 2 inch diameter rods and rated at 3000 psi. The rotary head uses a hydraulic motor rated at 1500 psi maximum, intermittent to 2000 psi, 58 cubic inches per revolution, theoretical torque of 926 in-lbs per 100 psi and a maximum RPM of 100.

In addition to flow control operation, a MOOG servo valve may be used to program the control of either the penetration head or rotary head using the selector valves. It is possible to operate the penetrom-

**LEVELING JACKS
(ONE OF FOUR)**

PENETRATION HEAD

ROTARY HEAD

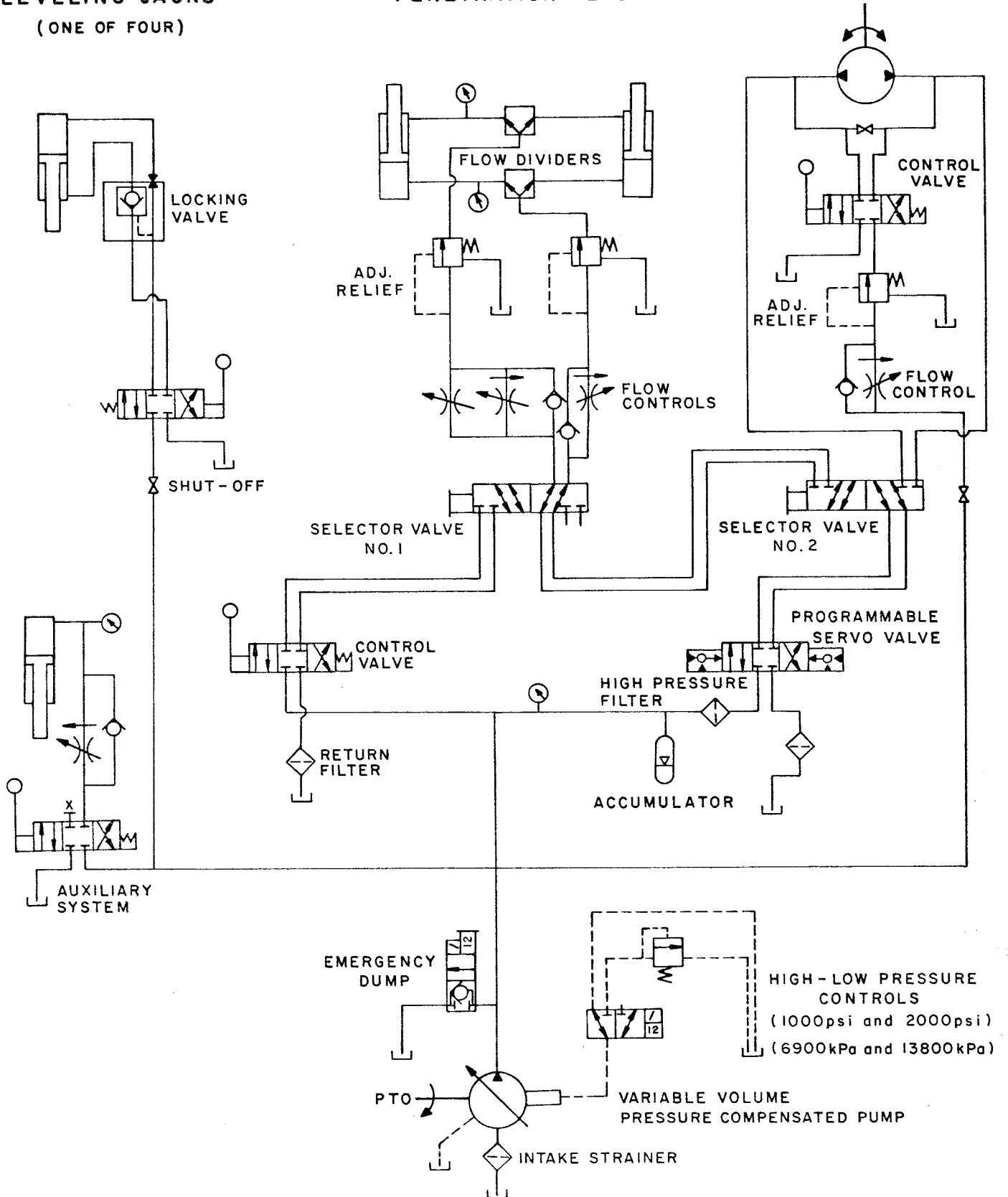


FIG. 3 HYDRAULIC CONTROL CIRCUITS FOR UBC RESEARCH ORIENTED FIELD VEHICLE .

meter head and rotary head simultaneously with either one under servo valve control at any one time. Also, depending upon the feed-back electronic transducer used, it is possible to operate the servo valve under either load control or displacement control. For example, if the control signal were from the cone bearing load cell or hydraulic oil pressure transducer or torque load cell the servo loading system could program the load, pressure or torque as a function of time. If the displacement transducer on the penetrometer were used for a feed back signal then the actual movement of the penetration head could be controlled and programmed with time. The program signal is provided by the wide range low frequency generator for ramps, sine wave and square wave (impulse) functions.

CONE PENETRATION EQUIPMENT

Friction Reducer

A friction reducer or expanded coupling is used at distances from 30 cm to 100 cm behind the cone tip. The purpose of the friction reducer is to expand the diameter of the hole to reduce soil contact against the cone rods and thus reduce rod friction behind the friction reducer at the expense of increased bearing and friction forces locally around the reducer. Also, experience suggests that the further back the friction reducer is from the tip the better are chances of maintaining a vertically aligned hole but this is at the expense of increased friction force in front of the friction reducer.

It has been found that a 2-inch long tube slipped over the cone rod with ends welded and machined to a 30° chamfer works well in most soils. Furthermore, there appears to be an optimum outside diameter depending upon the stiffness of the soil. During a recent cone logging investigation at a large tailings dam in British Columbia, four different sizes of friction reducer were used in the uniform clean, angular, fine sand that comprised the dam. These sizes represented a 100%, 50%, 25% and 12.5% increase in cross-sectional area of the cone rod. For example, since the rod is 10 sq. cm. in area, a 100%

reducer has a cross-sectional area of 20 sq. cm. In order to evaluate the effectiveness of a particular reducer the total pushing force was monitored at refusal, total pulling forces at initial withdrawal and after the rods were withdrawn more than a meter. The refusal depths were between 40 and 70 meters at a thrust of 35,000 lbs. It was found that the 25% reducer was the most efficient since it was the smallest size which was equally effective in reducing rod friction, thus increasing penetration force at the tip. The larger size reducers appear to be more effective in soft to very soft clays and silts.

Multi-Channel Cone

Most commercially available electric cones measure end bearing and friction and more recently bearing and porewater pressure. Sometimes an inclinometer is available. However, it is often most desirable to continuously measure bearing, friction and pore pressure. It is also important to monitor inclination or verticality of the sounding. And, following experiences with soundings in northern climates it would also be useful to monitor temperature especially if there is any possibility that frozen ground might be encountered.

The 5-channel cone shown in Fig. 4 has been under development for more than a year. The primary functions of measuring bearing, friction and pore pressure are well established, the temperature is a recent addition and the slope sensor is still under development. The dimensions conform to the European standard and the tentative ASTM standard for electric cones.

The one piece bearing and friction load cell is machined from Stressproof Steel (100,000 psi yield minimum and 125,000 psi ultimate). The working capacity of the load cells is designed for 60,000 psi. Thus, a 6 ton rated cone could withstand the full pushing capacity of the truck without anchors (9 ton) without damaging the load cell and exceeding the yield stress, and 12 ton cone could withstand the maximum pushing force of the hydraulic system when using

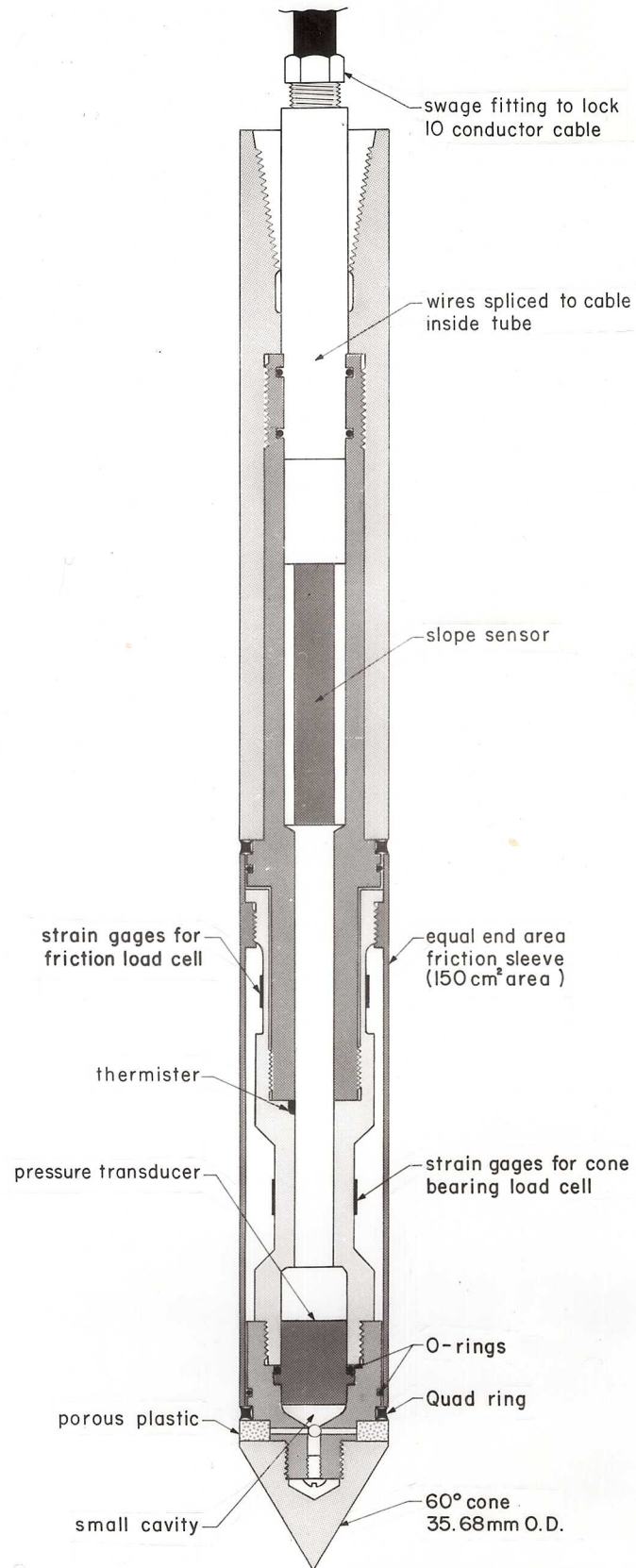


FIG.4 5-CHANNEL CONE PENETROMETER.

anchors. This assumes the cone may get stopped by a very hard stratum which could cause all the applied load to be transmitted to the tip. The friction load cell is usually designed to have about 0.25 to 0.33 the capacity of the bearing load cell. The friction sleeve has been recently redesigned to have 'equal end areas' which eliminate the requirement of zero shift correction due to an all around pore water pressure developed in soft saturated soils. Many cones in use today generate an apparent friction load due to pore pressures acting on unequal end areas. The magnitude and importance of friction corrections due to pore pressure effects are demonstrated and discussed in a later section. Encapsulated 0.125 inch foil strain gauges are used with four compression and four 'Poisson' gages in a fully active four arm Wheatstone bridge. Repeatability and linearity have been excellent and the sensitivity is usually between 2 and 3 mv/v at the working capacity of the load cell.

The pressure transducer is a hermetically sealed all welded flush diaphragm absolute pressure type. The miniature CEC 4-313 pressure transducer chosen has a 4 pin socket electrical connector and can be changed in the field for one of a different capacity. A very small cavity is used and surrounded by a porous plastic element. The cavity is easily saturated with glycerin (to be discussed later) with a hypodermic tube when the cone is inverted with the cone tip and filter removed. The hypodermic entrance is then sealed with a screw. The use of porous plastic such as polyethylene and polypropylene has proved to be particularly effective and long lasting. The plastic has withstood many penetrations in very dense and very angular or abrasive sand (cone bearing over 500 bar or 50,000 kPa). Previously used ceramic porous elements always broke-up after one penetration through even a rounded medium dense sand.

A precision ($\pm 0.1^\circ\text{C}$) miniature thermister is embedded in the cone load cell as shown in Fig. 4. A single axis sub-miniature DC accelerometer with active axis along the axis of the cone is used as an inclinometer or slope sensor. An accelerometer type of slope sensor has the advantage that it indicates an output when the cone starts to

move as well as when it slopes in the ground. If one is penetrating a high bearing layer below a very soft layer, rod buckling would be indicated if the accelerometer showed no initial acceleration at the start of a push. Unfortunately, sub-miniature accelerometers that read gravity are usually designed for dynamic applications and so their stability characteristics, especially due to temperature changes, are quite poor. However, if most of the instability is due to temperature effects, the thermister output could provide the basis for a zero drift correction. This aspect is currently being studied and it is hoped that a suitable accelerometer with good stability characteristics may soon be commercially available.

Also, the thermister output can be used to correct the zero drift due to temperature of load cells and pressure transducer when the cone penetrates the ground and rapidly changes from its air temperature to ground temperature. Although this drift is usually small it can sometimes be significant in soft soils and where one is trying to determine if a small equilibrium excess pore pressure exists in the ground. For example, a water pressure measurement of one meter might be very significant but obscured by thermal zero drift.

Fig. 5 shows the electronics used for signal conditioning a 5-channel cone with common excitation and a 10 conductor cable. Many electric cone users have 10 conductor cable but are skeptical of using common excitation. If isolated excitation and output were used, it would only be possible to have two continuously reading channels. The electronic circuit shown in Fig. 5 has proved to be perfectly adequate with excellent stability and essentially free of electrical noise. The 15 volt regulated power supply is used to provide a fixed 10 volt excitation. The balance resistors are needed to obtain zero output at the reference setting for each transducer in order to be able to change ranges on the chart recorders without an offset voltage. The scaling resistors are used to attenuate the signals in order to directly plot in engineering units on the recorders. Only half the sensitivity is currently being used for the DC accelerometer output as shown. It is proposed to use the full bridge sensitivity

TEMPERATURE SENSOR

Precision Thermistor
YSI No. 44030

SLOPE SENSOR

DC Accelerometer
(under development)

FRICTION SLEEVE

700Ω Load Cell
M-M CEA-06-I25UT-350
Strain Gauges

TIP BEARING

700Ω Load Cell
M-M CEA-06-I25UT-350
Strain Gauges

WATER PRESSURE

350Ω Transducer
CEC 4-313
0-150 psia

10 CONDUCTOR CABLE

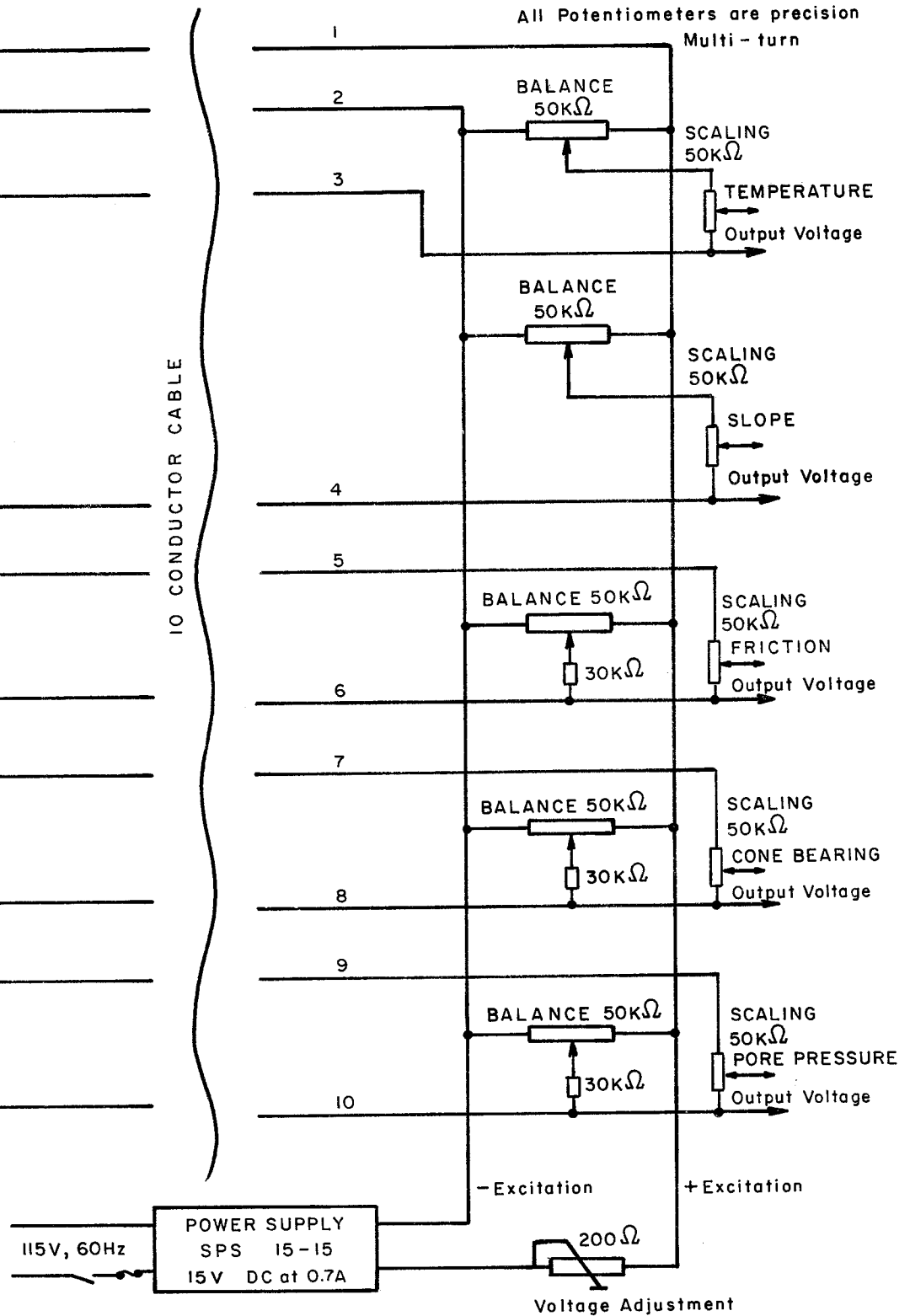


FIG.5 ELECTRONICS FOR 5-CHANNEL CONE

and add a miniature differential amplifier in the cone to transmit the output signal on one wire.

Computer Graphics

The continuous records of bearing, friction, and pore pressure represent a substantial volume of data reduction especially since there are corrections to be made and friction ratios and pore pressure ratios to be calculated from the 3-pen strip chart recordings. The records can be digitized using a computer, digitizing tablet and cursor. Data reduction routines can then correct each reading as necessary and calculate and plot results. Friction ratios can be calculated for different offset depths between simultaneous cone and friction values. Pore pressure ratios can be in terms of excess dynamic pore pressure after inputting an equilibrium pore pressure profile and subtracting it from the total dynamic pore pressure profile. The results can then be filed and stored on tape or discs. The logs shown later in this paper are direct computer outputs from a Printronics printer. This amount of data reduction and plotting for a 30 meter sounding can be done in less than an hour even with 300 to 500 points per profile. This type of data processing may even be more efficient than automatic digital data logging at the time of penetration. During the digitizing process it is convenient to eliminate all extraneous data such as unloading, reloading, random noise, and the like. This is not so simply done if the unwanted data is automatically digitized at the time of penetration and stored on tape. There is also the added problem of maintenance, training and cost of automatic data logging and the fact that one still requires a visual record at the time of penetration.

RESEARCH SITE

A research site for in-situ testing is located on an abandoned farm (McDonalds Farm) near the Vancouver International Airport. The site is located on the north side of Sea Island on MOT Canada land in the Municipality of Richmond. Sea Island is located between the North

Arm and Middle Arm of the Fraser River on the north side of the main Fraser River Delta. The site is approximately level with the natural ground at elevation +1.6m. Sea Island is contained by a system of dykes to protect against flooding from the Fraser River.

A summary of the soil profile based on sampling, laboratory testing and cone penetration is shown on Fig. 6.

The upper 2m of soil consists of soft, compressible clays and silts. The sand from 2m to 13m was deposited in a turbulent environment and is therefore relatively non-uniform in density. However, in general the sand increases in density with depth. The sand generally has a medium to coarse grain size with thin layers of medium to fine sand. A thin deposit of fine sand with some silt exists from 13m to 15m.

The sand is underlain by a thick deposit of soft, normally consolidated clayey silt. The clayey silt is estimated to extend to a depth of more than 300m.

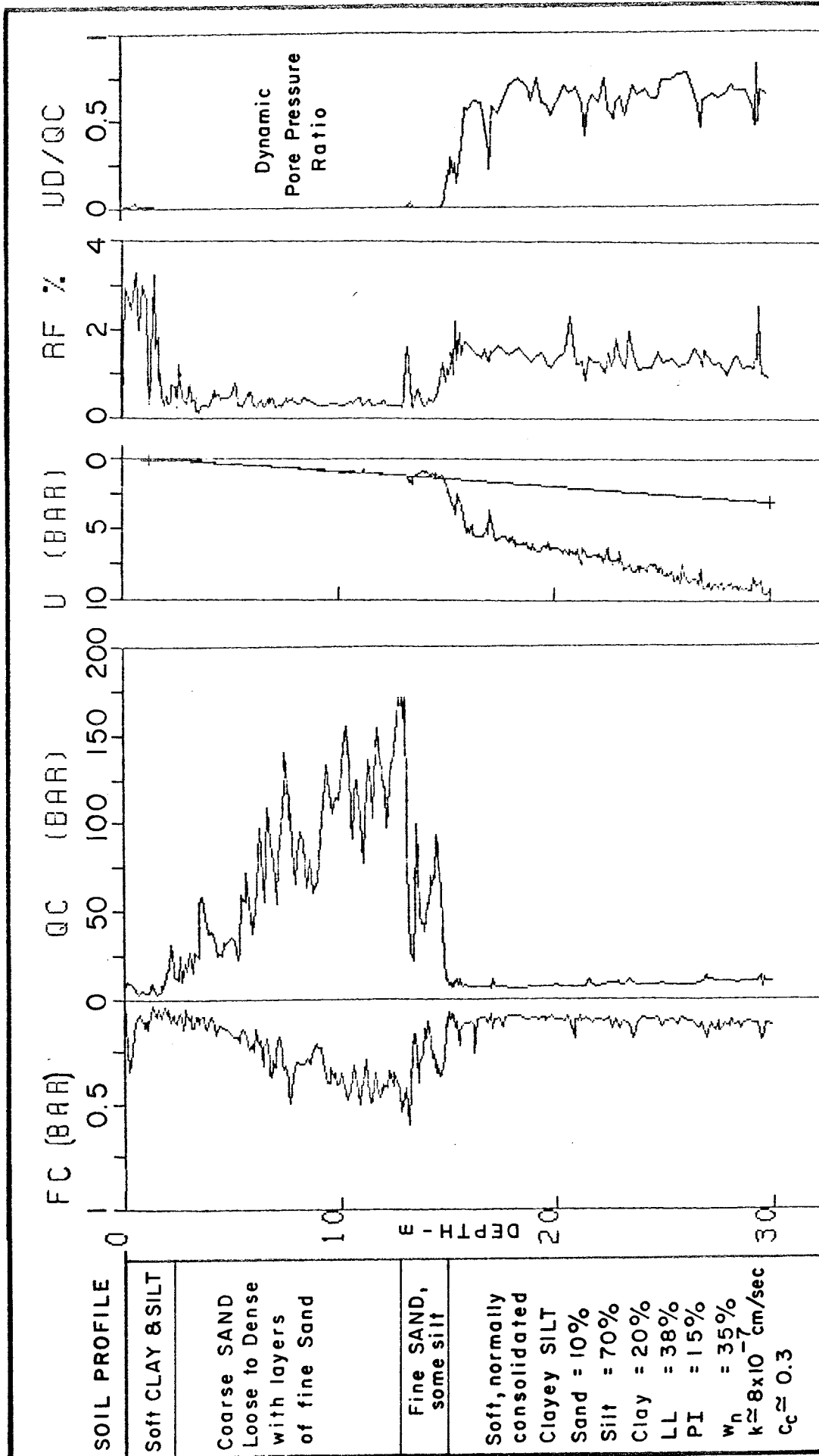
Groundwater is approximately 1m below existing ground surface and groundwater pressures are approximately hydrostatic. Tidal fluctuations are of the order of 5m.

POTENTIAL MISTINTERPRETATIONS

Before analysis of any friction cone data it is important to realize and account for the potential errors that each element of data may contain. During development of our equipment several significant aspects concerning the data collection and interpretation have come to our attention. Some of these points are summarized here.

Bearing and Friction

The tolerance in machining the standard Fugro type friction cone is such that the difference in diameter between the tip and the sleeve can be up to 0.010 inches (0.25mm). This combined with wear during



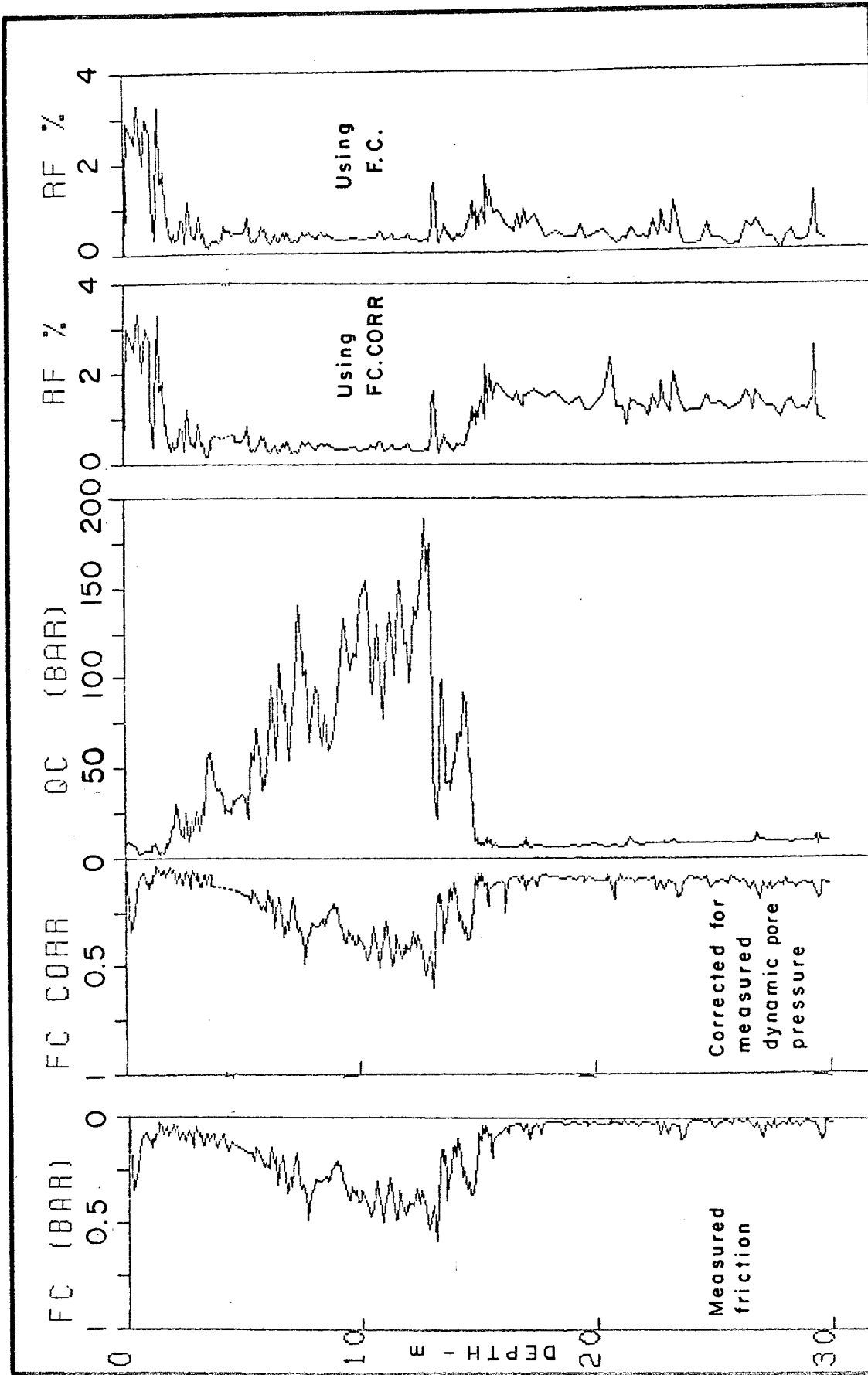
1 BAR = 100kPa \approx 1 kgf/cm² \approx 1 ton/ft²

FIG. 6 SOIL PROFILE FOR RESEARCH SITE AT McDONALDS FARM, SEA ISLAND.

usage often results in significant differences in diameter between the tip and sleeve. It has been found that variations in diameters between the tip and sleeve can result in significant differences in measured friction values. This variation can be reduced by careful machining during construction and regular tolerance checks during the life of the cone. The O.D. of the cone should be identical or less than O.D. of friction sleeve by about 0.010 inches (0.25mm).

The load cells within the cone are often temperature dependent and are almost always calibrated at room or air temperature. However, soil and groundwater are often considerably cooler than the calibration temperature and a shift in the zero can occur for both load cells during penetration. This usually has little consequence to the tip measurement which is usually a large value. However, the zero shift can have a significant effect on the friction measurement, particularly for soft soils. Temperature shifts should therefore be accounted for when penetrating in soft soils.

It has been observed by us and others that when the standard electric cone is exposed to an all round water pressure there is a shift in the zeros for both the friction and tip measurements. High water pressures exist in both deep profiles below the water table and in low permeability saturated soils where very large positive dynamic pore pressures are generated. Again this shift in the zeros is less critical for the tip measurement but can be significant for the sleeve friction. Fig. 7 illustrates a friction cone profile through a clayey silt where the initial evaluation indicated a zero, or in places, even negative friction values. However, with careful attention applied to the zero shifts, due to temperature and water pressure effects, a small positive friction value was obtained. The friction cone used here did not have equal end area friction sleeve. These factors affecting the measured friction value can become important when using the friction for detailed soil classification or evaluation of the undrained shear strength for design of piles (Nottingham 1975). Furthermore, total pore pressures must be measured during penetration to apply the zero correction;



1 BAR = 100kPa \approx 1kgf/cm² \approx 1 ton/ff²

FIG.7 EXAMPLE OF FRICTION CORRECTION ON CONE INTERPRETATION (MCDONALDS FARM, SEA ISLAND).

hydrostatic pressures are not applicable for this correction.

It is usually accepted that when measuring friction with the Begemann mechanical cone, these values are always higher than those measured with the electric cone, especially in soft soils. Our experience has shown that when the friction force on the mechanical cone is corrected for weight of inner rods and for end bearing on the sleeve (assume full closure of hole with bearing same as tip), and the electric cone friction is corrected for measured dynamic pore pressure then the friction ratio by each device is comparable in soft and loose saturated soil.

Pore Pressures

The inclusion of the pore pressure element has greatly improved our understanding of the cone data. However, it is important to ensure that the pore pressure element is measuring the correct dynamic or static pressure. It is therefore essential that the element is completely saturated and maintains its saturation throughout the profile. We have found that saturation can best be achieved and maintained by using glycerin and designing the sensing cavity to be as small as practical and to avoid unnecessary corners that may entrap air. The glycerin has been found to work admirably even during deep profiles with a low water table. The effectiveness of this method was illustrated during a recent study at a large tailings dam in B.C. where the piezometer friction cone was pushed for over 50m through unsaturated fine sands before encountering the water table and measured by the piezometer. Confirmation of the reading was obtained from a nearby standpipe piezometer installed during the previous drilling program.

Response to the dynamic pore pressure appears to be significantly affected by entrapped air within the sensing element. This is particularly true for soft low permeability soils such as normally consolidated clays. An illustration of the effect of an unsaturated piezometer cone is shown on Fig. 8. An earlier model piezometer cone that

BURNABY SITE - VERY SOFT SILTY CLAY

$$q_c = 4 \text{ kPa}, k = 10^{-7} \text{ cm/sec}$$

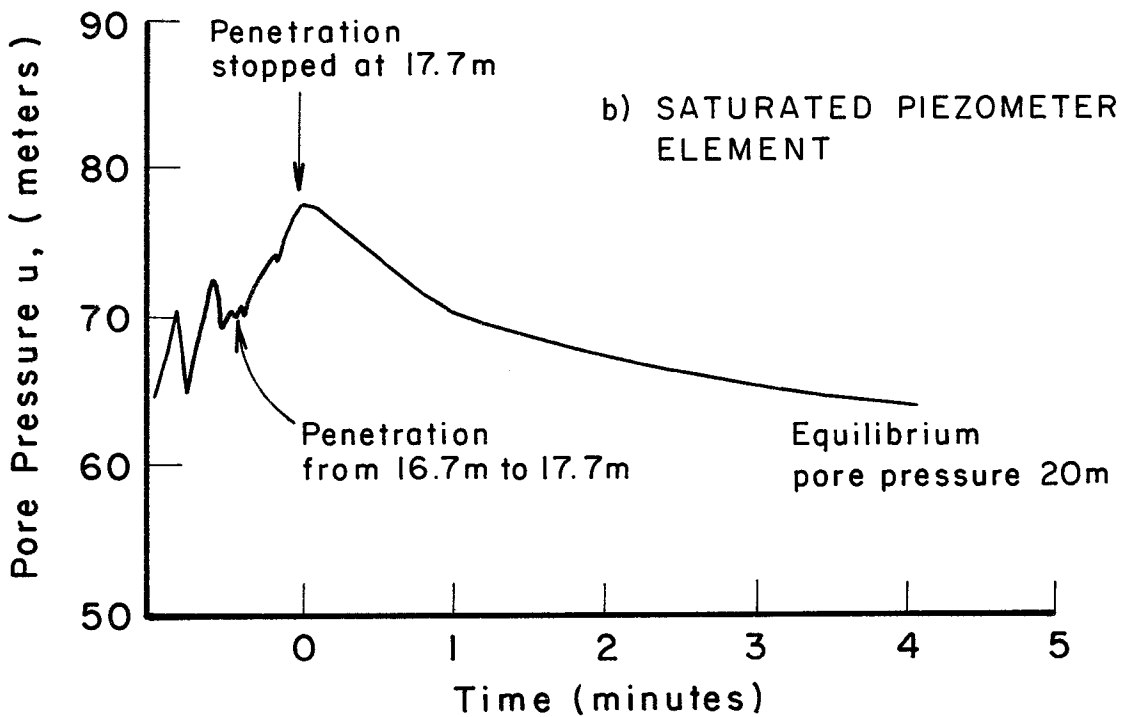
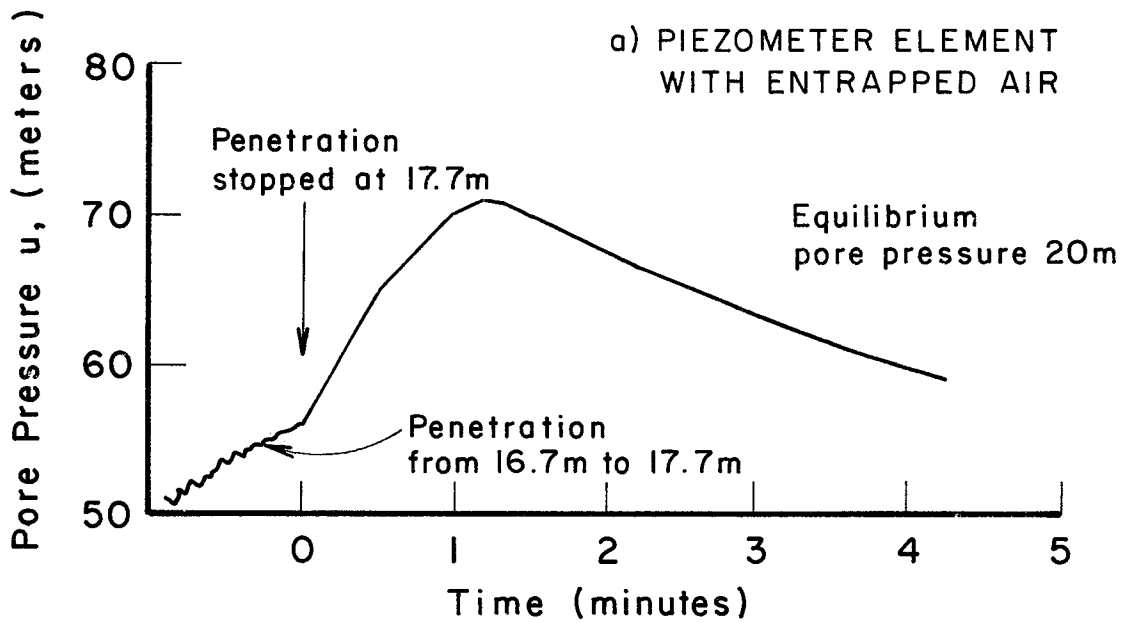


FIG. 8 INFLUENCE OF SATURATION ON PORE PRESSURE RESPONSE OF PIEZOMETER CONE.

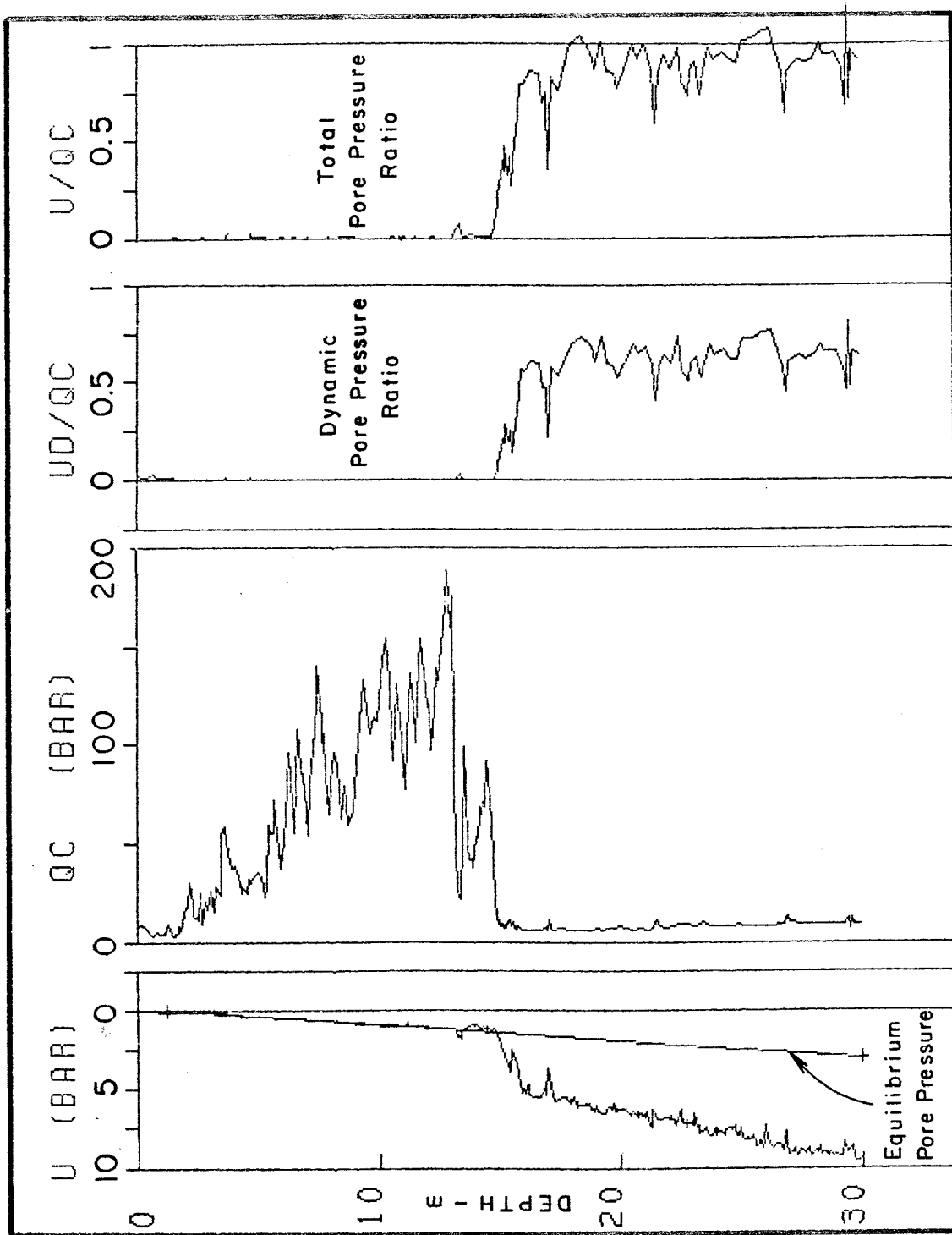
had a large sensing element cavity that could not satisfactorily be saturated showed that when pushing was stopped during penetration through a soft clay the measured pore pressure continued to rise for a short period followed by the expected decrease due to pore pressure dissipation. However, when using the more recently designed piezometer cone in the same deposit the continued increase in measured pore pressure following a stop in penetration was not observed. It was concluded that the continued increase in measured pore pressure observed in the early model was due to time effects due to water flow caused by some entrapped air within the element. It should also be noted that the dynamic pore pressure measured with the unsaturated piezometer is significantly less than the pore pressure measured by the saturated piezometer.

The importance of pore pressures in the interpretation of cone data has been discussed by others (Wissa et al. 1975, Schmertmann 1974 and Senneset 1974) and shall not be repeated here except to caution that care is required to ensure correct pore pressure measurement.

EXAMPLES OF CONE INTERPRETATION

Pore pressures

It has been recently suggested that the measured pore pressures during cone penetration could be used to indicate consolidation history of clays (Baligh et al. 1980). The proposed method involves the use of the pore pressure ratio (U/QC) and it appears the proposed pore pressure ratio uses total pore pressures measured during penetration. However, it may be more realistic to use dynamic pore pressures for the pore pressure ratio. The dynamic pore pressures are defined as the pore pressures generated during penetration which are above or below the static equilibrium pore pressures. Fig. 9 illustrates the same profile as shown on Fig. 7 but includes the measured pore pressures and the two forms of pore pressure ratio. It is interesting to note how well the pore pressure and pore pressure ratio's define the boundary between the sand and the underlying



1 BAR = 100kPa \approx 1kgf/cm² \approx 1 ton/ft²

FIG.9 EXAMPLES OF PORE PRESSURE INTERPRETATION DURING CONE PENETRATION (McDONALDS FARM, SEA ISLAND).

clayey silt. This is one case where the inclusion of a pore pressure element in the cone can be of extreme value.

It appears that for normally consolidated soils the dynamic pore pressure generated is linear with depth similar to the cone resistance. The dynamic pore pressure ratio, (UD/QC) , also appears to be constant at approximately 0.7. This value agrees quite well with that predicted from the theory of the expansion of a spherical cavity (Vesic 1972). The total pore pressure ratio will only be constant with depth for normally consolidated soils if the equilibrium water pressure is hydrostatic, i.e. linear with depth.

The use of dynamic pore pressures highlight the importance of evaluation of equilibrium static pore pressures. This can easily be achieved by one or more pore pressure dissipations during a stop in penetration. The pore pressure dissipation data can also be used to infer consolidation characteristics of the soil.

The pore pressure element for our piezometer friction cone is located immediately behind the tip. This position has been found by us and others (Roy et. al. 1980) to record dynamic pore pressures that are very close to the maximum in soft soils.

It is well recognized that the maximum pore pressure developed during penetration in soft soils is near the cone tip. However, for standard penetration rates of 2 cm/sec the area behind the tip is in the previous location of the tip within several seconds. During this very short time period there has usually been very little time for dissipation of the maximum pore pressures.

The area behind the tip is also better protected for penetration through denser soil where damage can occur to porous elements located on the tip. The piezometer element located behind the tip appears to be a reasonable compromise for evaluation of both dynamic and dissipation pore pressures. However, it does appear that in stiffer soils this location may produce a more dilatent dynamic pore pressure res-

ponse. Further research is required into these affects. The optimum position of the pore pressure element may depend on the results desired and the type of soil to be investigated.

Tailings and ice

Fig. 10 shows a piezometer friction cone profile carried out over a mine tailings disposal area. The profile was located on the beach area of a large tailings pond a short distance behind the main tailings dam. The equilibrium pore pressure profile obtained from a total of eight dissipation stops shows an almost downward flow of water from the pond with a hydraulic gradient of unity. This was an extremely important piece of information for the stability of the dam, as pore pressures at depth were considerably less than the, often assumed, hydrostatic condition. This increase in effective stress and thus increase in strength of the tailings is also illustrated by the surprisingly large cone bearing values recorded. The cone bearing increases with depth as the tailings consolidate under the weight of the overlying tailings.

The tailings pond is located in the central area of British Columbia where winters are quite severe and considerable snow and ice is formed on the pond during the winter months. Some of this ice becomes entrapped within the tailings and remains permanently frozen. The existence of the ice lenses was determined from the large sudden changes in cone bearing. The pore pressures during penetration also provide a very clear indication of the existence of these ice rich lenses. Perhaps the friction ratio is the best indicator of ice and ice rich soil when the friction ratio dropped below 0.5%. It appears that almost pure ice gives friction ratios close to zero with very sharp increased in bearing and dynamic pore pressures. The complete profile using the piezometer friction cone provided an extremely extensive amount of data about the ground and groundwater conditions at the tailings dam.

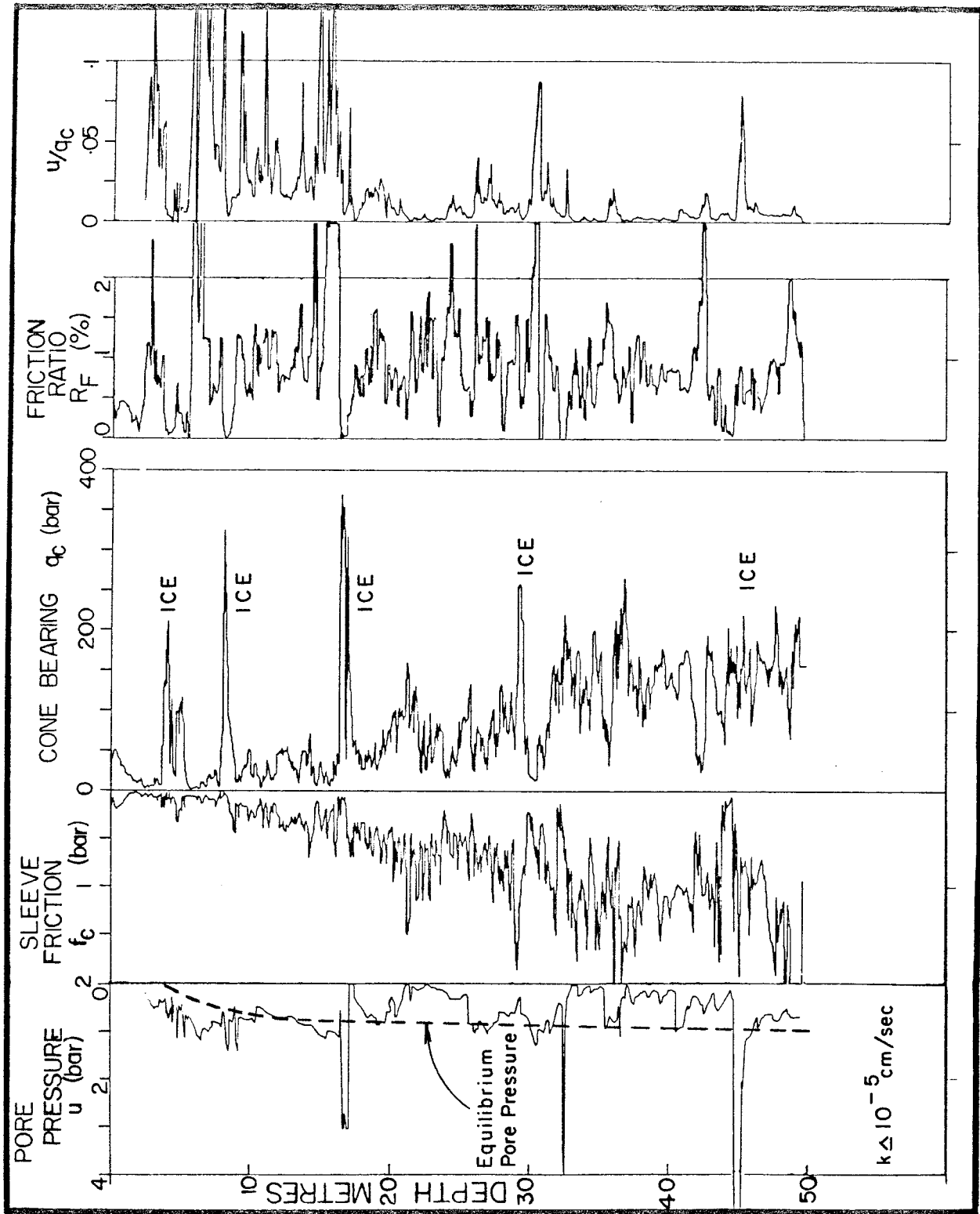


FIG.10 EXAMPLE OF PIEZOMETER, FRICTION CONE LOG THROUGH TAILINGS DEPOSIT.

Rate of penetration

The inclusion of pore pressure measurements during cone penetration considerably improves our understanding of the cone data. The pore pressure measurements enable an effective stress appraisal to be made of the cone data. However, further research is required in this direction, and the potential for future improvements in interpretation look promising.

Traditionally cone penetration in sands have been considered to be drained and penetration in clays undrained. However, for mixed soils such as silts and clayey silts it is less well defined if the penetration is in a drained or undrained condition. Fig. 11 shows the results of piezometer cone data at the same site as shown in Fig. 7, but for different penetration rates. The data is summarized for the results obtained as the cone passes the 20m depth. The soil is clayey silt with a permeability in the order of 8×10^{-7} cm/sec. The results show that the penetration is essentially undrained down to a penetration speed of about 0.1 cm/sec. As the penetration speed is progressively decreased below this speed the dynamic pore pressure decreases and a corresponding increase is observed for the cone bearing and friction. The increase is particularly noticeable for the friction. The increase is less noticeable for the bearing in part because the bearing also records the water pressure. Thus as the water pressure decreases the bearing tends to decrease but this is offset by the increase in effective stress in the soil which increases the bearing. The use of the piezometer cone will considerably improve our understanding of the cone data particularly in mixed soils.

Friction along shaft

The friction measurement made with the standard friction cone is usually used for soil classification and pile design. However, a better understanding of the friction measurement is required. A study to this aim was carried out by progressively moving the

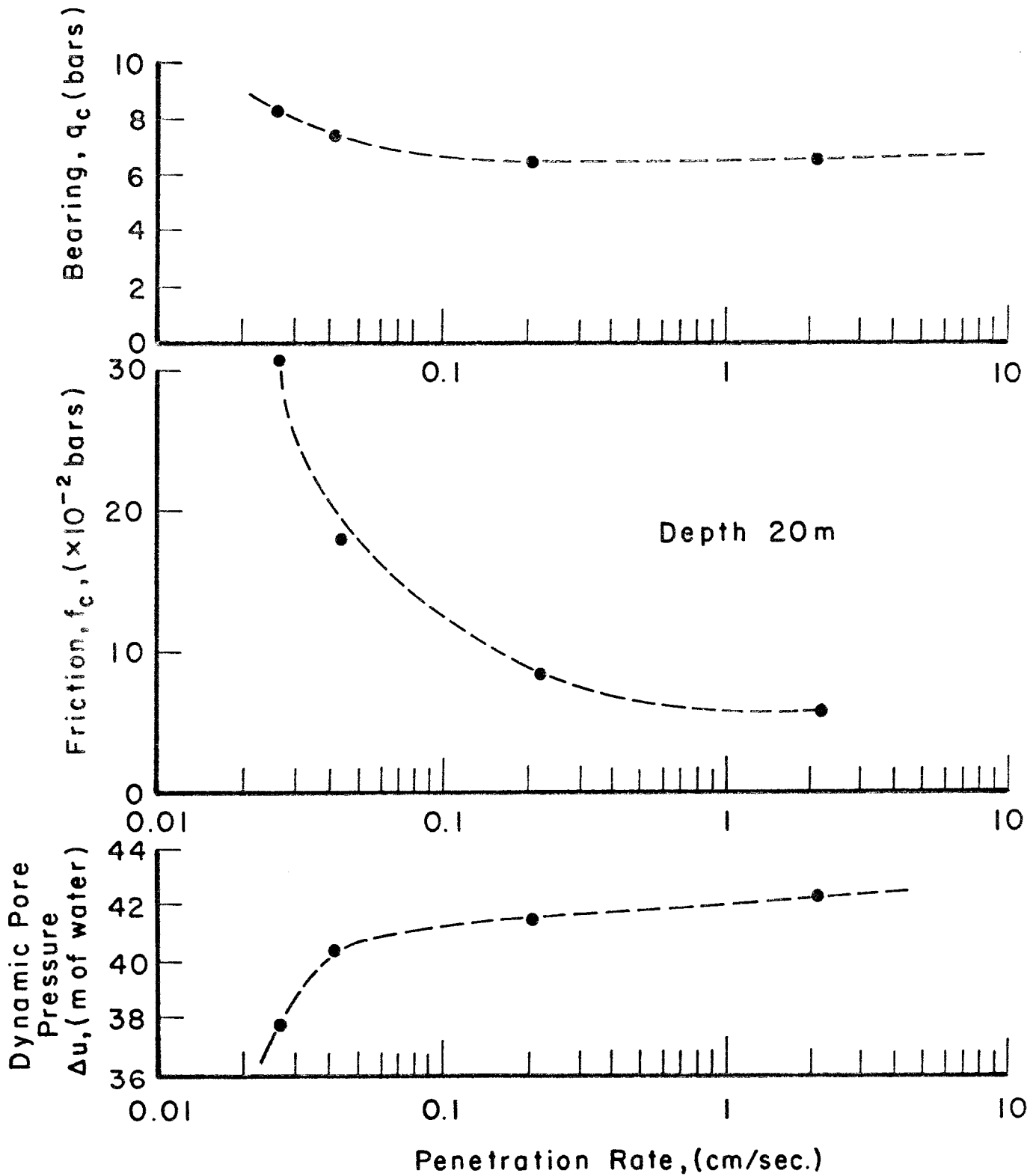


FIG. II PENETRATION RATE AFFECTS IN CLAYEY SILT DEPOSIT (McDONALDS FARM, SEA ISLAND).

friction sleeve further away from the tip. The measured friction versus distance from tip is shown on Fig. 12 for penetration through a loose and a dense sand. The results show that there is a marked increase in the friction measurement between 10 and 25cm behind the tip. This increase appears more pronounced in the dense sand. Beyond about 40cm behind the tip the friction appears reasonably constant.

It is interesting that the average friction stress measured by the friction sleeve immediately behind the tip appears to give a good estimate of the actual friction away from the tip even though the friction sleeve is in a complex non-uniform strain field. This is important information for those using friction sleeve results for pile design.

If a constant frictional resistance between the cone steel and the sand is assumed the data indicates changes in the in-situ horizontal stresses around the probe. In loose to medium dense sand it appears little change occurs in the horizontal stress. However, for dense sand an approximate two fold increase in horizontal stress occurs. This is expected since loose sands tend to compress when sheared whereas dense sands dilate on shearing.

If the tip measurement is assumed to be a measure of density in sand the friction ratio should be constant for any density. The friction measurements shown in Fig. 12 were divided by the tip resistance to give friction ratio versus distance from tip, as shown on Fig. 13. A unique friction ratio relationship appears to exist for any density sand.

FURTHER RESEARCH

There are two areas of applied cone research that appear to be of highest priority. The first of these is applying an effective stress analysis to the cone bearing values using the direct measurements of pore water pressure during penetration. An effective stress analysis

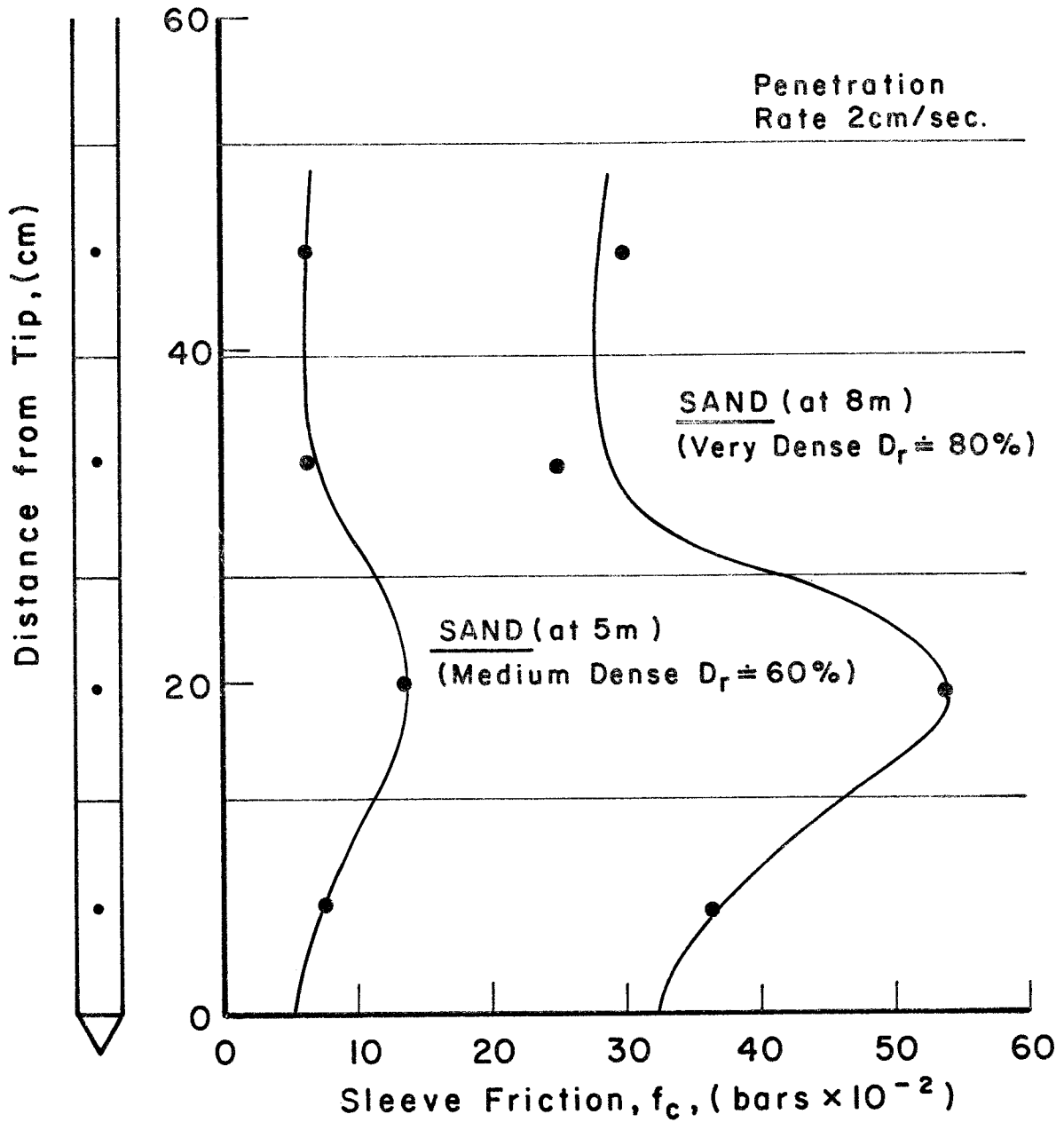


FIG.12 FRICTION ALONG SHAFT DURING CONE PENETRATION IN SAND.
(McDONALDS FARM, SEA ISLAND)

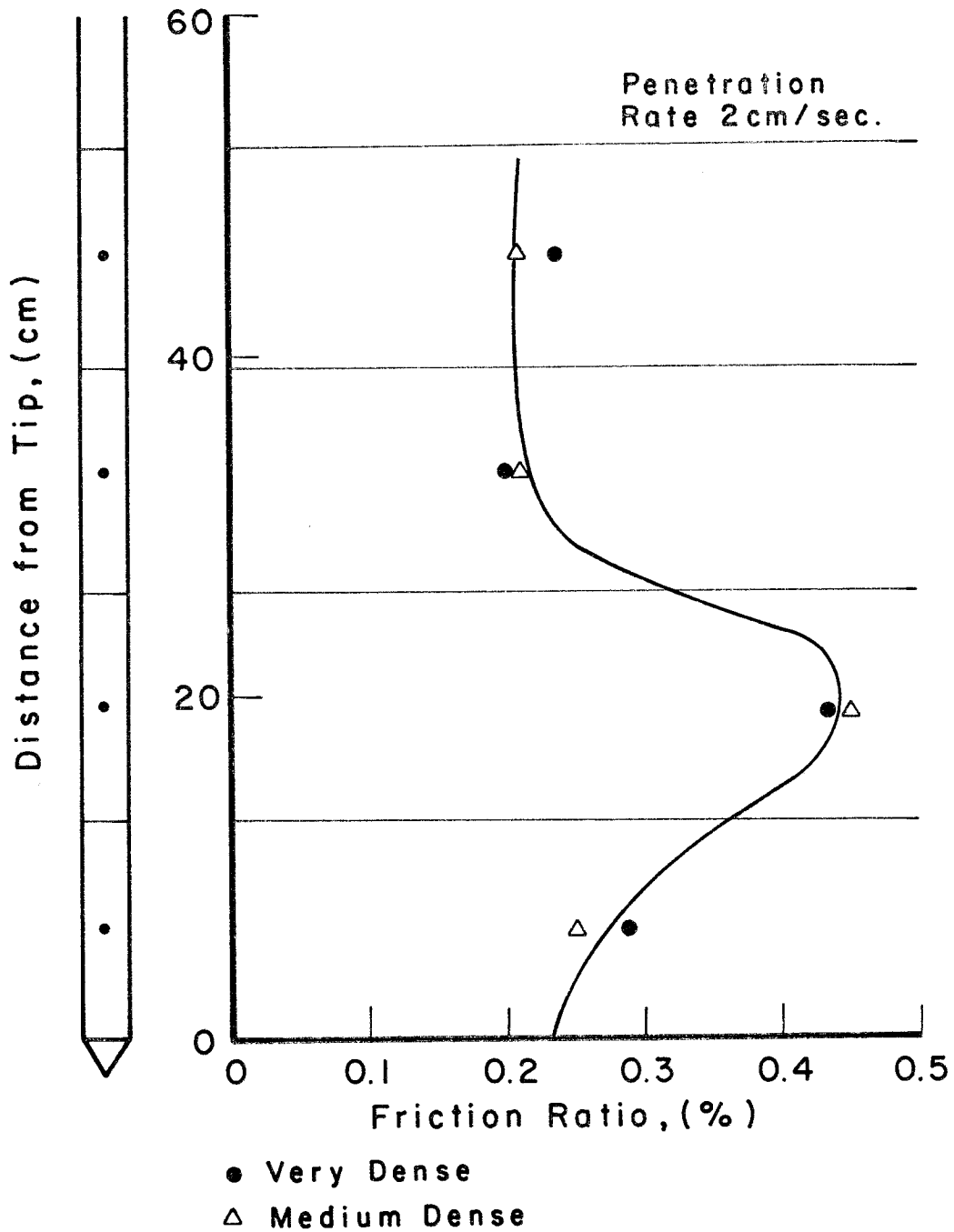


FIG.13 FRICTION RATIO ALONG SHAFT DURING CONE PENETRATION IN SAND (McDONALDS FARM, SEA I.)

would be particularly useful when interpreting cone data in undrained or partially drained soils. The other area of concern is in applying methods of statistical analyses to the continuous cone log data in order to develop a probabilistic basis for the evaluation of design parameters. This type of analysis seems particularly appropriate at this stage of developments since all of the data is being digitized and easily accessible by the computer. These statistical techniques would allow us to develop a measure of the variability of natural soil deposits, which is one of the strong points of cone logging in general.

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