Instrumentation and Data Acquisition for Field Suction Measurement

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An instrumentation scheme for a study on tropical residual soil in Malaysia is described. This instrumentation enables automatic continuous measurements of soil suction, soil moisture, rainfall, and other related parameters. Descriptions of the selection, fabrication, protection, and installation of the instrumentation are provided.

The purpose of this paper is to describe the instrumentation used on a cut slope in Malaysia to monitor soil suction, soil moisture and temperature, antecedent rainfall, and water table fluctuations. The site for this work was a cut slope along the Kuala Lumpur–Karak Highway. The weathering profile is developed over a porphyritic biotite granite bedrock. A major objective of the instrumentation was to measure changes in suction and soil moisture caused by the rainfall.

INSTRUMENTATION

Before the instrumentation scheme was designed, a review of the equipment used to monitor soil water pressures conducted by the Geotechnical Control Office of Hong Kong (*1*) showed that there is practically no automatic equipment capable of measuring both positive and negative pore pressures. One exception is a tensiometer system, which has the capability of measuring pore pressures in both the positive and the negative ranges. In the tensiometer the upper limit of the range for measuring matric suction is 1 bar because water cavitates in this system. The actual measurable suction would depend on the depth of installation, which is less than 1 bar. Table 1 summarizes the operational ranges of various types of equipment.

Automation solves the problems of reliability, access, and safety, which are difficulties associated with manual data recording, and allows continuous monitoring. The peak and transient pore pressures and piezometric levels during and after rainstorms are therefore not missed.

The automated data acquisition system was designed to record outputs from tensiometers, soil moisture cells, piezometers, and a depth transducer. The system has 40 channels, of which 12 channels each are allocated for tensiometers for measuring suction, soil moisture cells for measuring soil moisture, and soil moisture cells for measuring soil temperature; 2 channels are allocated for piezometers; 1 channel is allocated for a depth transducer; and 1 channel is allocated for measuring atmospheric pressure. Table 2 provides the major technical specifications. A separate automated rainfall data acquisition system was also installed at the same site.

The system has three major components: instrument sensors, a multiplexer and data logger, and field interrogator and data communication devices. The system is specifically designed for low power consumption. It runs on 12-Volt direct current power. Automation eliminated many of the problems that arise with manual reading systems and facilitated continuous data logging at prescribed intervals. The logging intervals were achieved by prescribing the appropriate interval during the setup process. The interrogator, a sophisticated microprocessor-controlled unit, was used for data logger communication, computer communication, and simple data processing. It acts as a user interface with the data logger and allows the introduction of logging strategies, retrieval of data, scanning and checking of stored data, setting of alarm levels, and collection of manual readings. The data were set to be logged at 30-min intervals for a maximum duration of 8 days. The duration would be longer if fewer sensors were used. The recorded data were downloaded from the data logger into the interrogator. The data interrogator was transferred into a personal computer for processing via an RS232 interface and the instrumentation software supplied. The data can be analyzed by using the supplied software or imported into available spreadsheet software for a more rigorous analysis. Each tensiometer was deaired after every downloading or as frequently as possible to achieve reliable results. This was done by vigorously pressing the reservoir button up and down.

The solar-powered rain gauge records rainfall events on a real-time basis. The clocks in the tensiometer logger and the rainfall gauge recorder are always synchronized. Figure 1 shows a schematic arrangement of instruments at the site.

INSTRUMENT SENSORS

A combination of a tensiometer and a transducer was used to take suction measurements. The piezometric reading and depth were measured by using a vibrating-wire transducer and depth transducers, respectively. Rainfall was measured by using a tipping bucket. All sensors were connected to the designated calibrated terminals of the data logger through cables to record all responses.

Soil Suction

A jet-fill tensiometer (Soil Moisture Corporation, U.S.A.) was used for making soil suction measurements, with some modifications. It consists of a sealed tube with a porous ceramic cup at one end and a pressure-measuring device and a jet-fill water res-

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TABLE 1 Operational Ranges of Various Types of Equipment

DEVICE TYPE	OPERATIONAL RANGE
Psychrometer (including Peltier)	-1 bar to 100 bar(*,+)
Osmotic Tensiometer	-1 bar to 100 bar(*,+)
Tensiometer	-1 bar to +ve pressure
Porous Block	-0.5 bar to 10 bar(*)
Centrifuge	above 10 bar
Vacuum Desiccator	above 100 bar
Pressure Membrane	-1 bar to 100 bar(*,+)
Consolidation	0.1 bar to 10 bar(*)
Thermal Conductivity Sensor	0 to 175 bar(+)
Cassagrande open hydraulic piezometer	atmospheric
Closed Hydraulic : (low air entry) : (high air entry)	any positive pressure -1 bar to +ve pressure(*)
Pneumatic piezometer	any positive pressure
Electrical vibrating wire piezometer	any positive pressure
Electrical resistance type	any positive pressure

Note:
(*) - Denotes slow response time
(+) - Denotes sensitive to temperature changes

TABLE 2 Specifications of Field Instrumentation for Slope Stability Study in Residual Soil

A. MULTIPLEXER	
a. Number of channels	32 channels (modified)
B. DATA LOGGER	
a. Power supply	12V + 1.5V
b. Input	2V maximum
c. Consumption	Warm up & reac 500 μA
d. Memory solid state	176 k bytes RAM
e. Maximum number of readings	80,000 readings
f. Reading interval	minimum 30 seconds
C. INTERROGATOR	
a. Power	Internal 6V lead acid battery(rechargeable)
b. Memory	System RAM 128 k bytes User RAM 256 k bytes
c. Maximum number of readings	118,000 readings
d. Communications	RS232
D. TRANSDUCERS	
Range	Tensiometers 2 bar abs.
Supply	10 V
Temperature error band	0 -50 C + 0.5 %
Full sensitivity	100 mV
Non-linearity	+ 1 % BSL
E. RAIN GAUGE	
a. Each tip equals 0.5 mm precipitation. Mercury switch (Manual gauge with monthly chart is also installed as a check)	
F. PIEZOMETER	
a. Vibrating wire type - capable of measuring up to 35 meters	

ervoir on the other. The measuring device consists of a vacuum gauge and a pressure transducer gauge attached via an adapted threaded Y-piece to the port at the side of the body tube of the tensiometer. Figure 2 shows the details of the tensiometer and the Y-piece.

Soil Moisture and Temperature

Both soil moisture and temperature were measured by using commercially available soil cells. The one used in the study described here has an electric sandwich wrapping and thermistors with three wire leads (Figure 3). The resistance of the thermistor in the soil is accurate to 1 percent. Each soil cell was calibrated to establish the soil moisture–soil cell resistance and temperature–soil cell resistance relationships.

The relationships were determined in the laboratory by using undisturbed core samples obtained as close as possible to the zone where the soil moisture cell was to be installed. This ensures that the calibration curve is applicable to the soil under investigation. A typical calibration curve for the soil cell in one of the zones is shown in Figure 4. The cell was also individually calibrated against temperature.

Piezometric Water Levels

A high-precision vibrating-wire piezometer was used to monitor water levels. The external diameter of the piezometer was such that it could be lowered into a 19-mm-diameter standpipe with ease. The change in water level was recorded by converting wire vibrations into an electrical output related to the tension of the vibrating wire.

Rain Gauge

The antecedent rainfall was recorded by using a tipping-bucket rain gauge that automatically logs the measurements. The system is powered by a small solar-powered system on the roof with a rechargeable battery for nighttime use. The data are logged onto a data card with 32 kilo-bytes of memory. This rain gauge is self-contained and facilitates easy data collection and setting of strategy. The arrangement is shown in Figure 5. The rain gauge system was developed by the instrumentation section of the Department of Irrigation and Drainage. To compare its performance, an additional tipping-bucket rain gauge with a chart recorder was also installed. The total rainfalls measured by both rain gauges were very similar. The rain gauge with the data logging system gave readings at closer intervals, however.

Vee-Notch Depth Measurement

Surface runoff measurements were carried out with a vee notch fixed with a depth transducer in the infiltration studies. The precipitation is controlled artificially by using calibrated agricultural sprinklers.

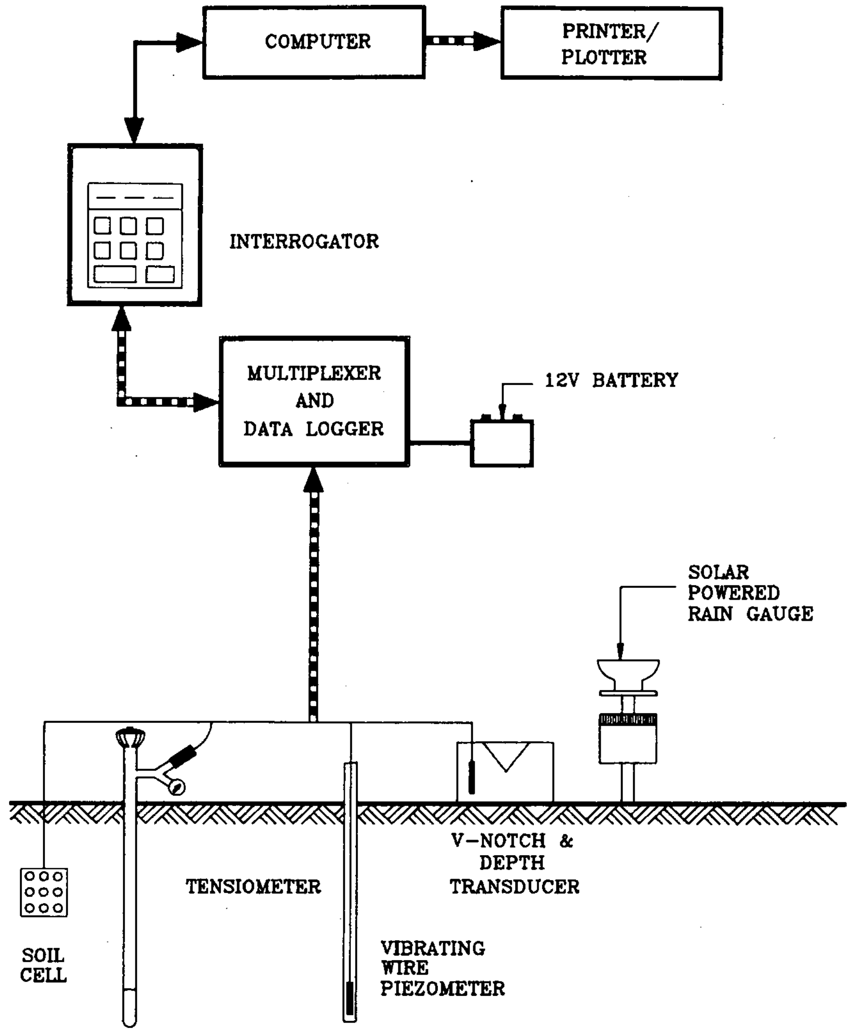


FIGURE 1 Schematic arrangement of the instrumentation at the site.

INSTALLATION

A specially fabricated coring tool was used to core the holes in which tensiometers or soil moisture cells were installed. The diameter of the coring tool was chosen to create a snug fit between the ceramic sensing tip and the soil, which is necessary for the functioning of the tensiometer. The tensiometer installation procedure is shown in Figure 6.

The soil moisture cells were also installed with the same coring tool used to install the tensiometers. The soil moisture cell was inserted by using a simple tool fabricated in the form of a long rod with a modified tip. Another, larger-diameter rod with a modified tip was fabricated for tamping the soil surrounding the moisture cell. This was necessary to ensure that the soil surrounding the soil moisture cell was tamped tightly to prevent the augered hole from becoming a water passage. Other sealing methods such as the use of grout and bentonite were not used in order to maintain the status quo of the soil material. A typical arrangement of the tensiometer system and the soil moisture cell for a single location is shown in Figure 7. This arrangement is installed at four berms with different weathering grade profiles.

The vibrating-wire piezometers were installed in the usual manner, as prescribed in the procedure for their installation (*2*). The depth transducer was attached to the base of the trough with a vee-notch arrangement for flow depth measurement.

All of the wire leads from the sensors were inserted into a polypipe and were buried in a shallow trench in the ground. The wires were directed to the data logger-multiplexer situated midway between the berms. The wires were fixed in the appropriate sockets.

The adverse tropical climate and vandalism were major concerns in the installation. The tensiometer and soil moisture cell installation were protected by lockable steel security cages grouted to the slope. The data logger was contained in a lockable steel cabinet.

The transducers for the tensiometers were protected from direct sunlight by wrapping them with a double layer of foam rubber on the inside and aluminum foil on the outside.

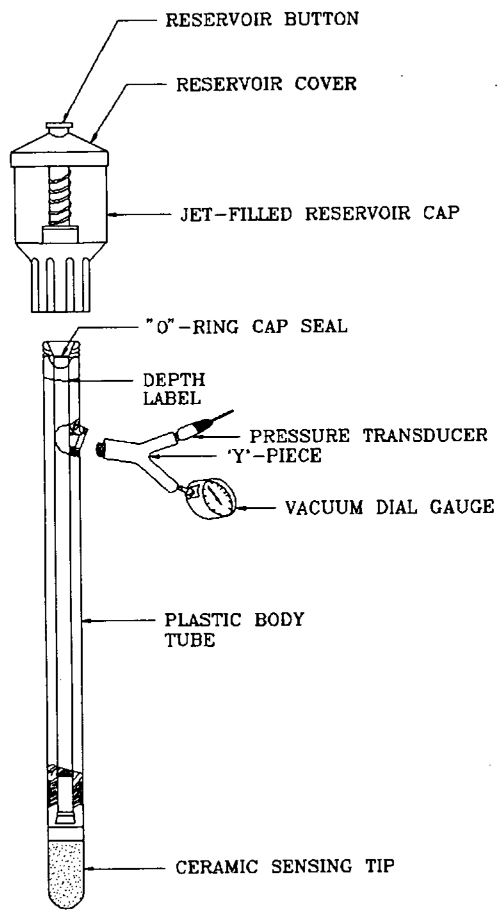


FIGURE 2 **Details of the tensiometer-transducer arrangement.**

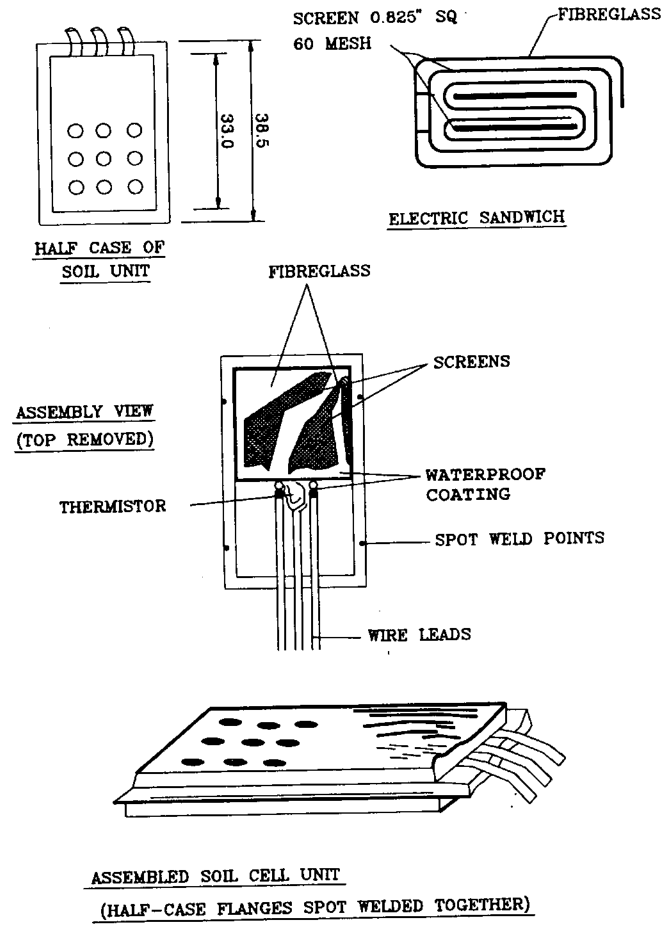


FIGURE 3 **Details of the soil moisture cell.**

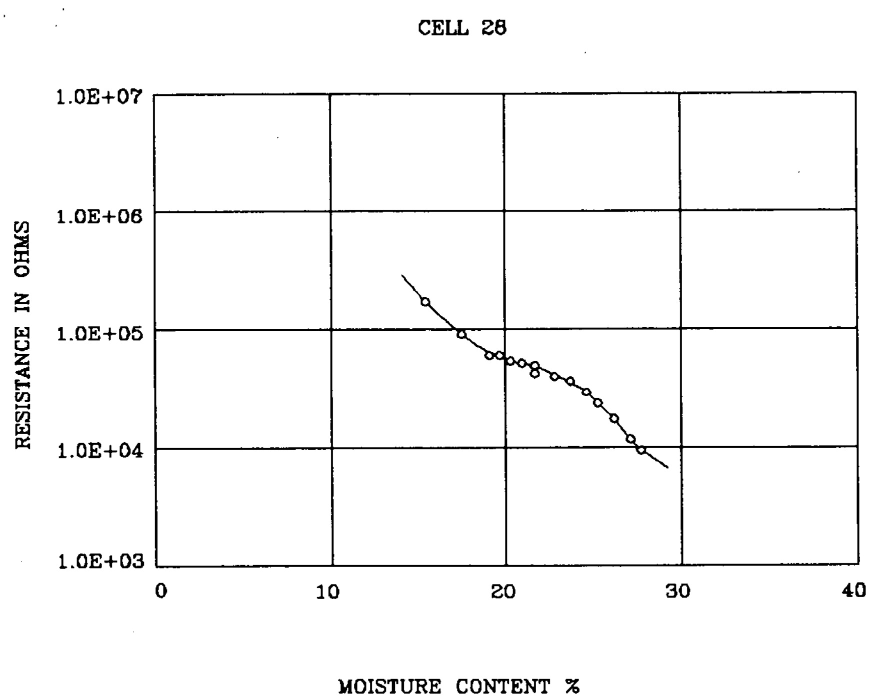


FIGURE 4 **Sample calibration curve for the soil moisture cell.**

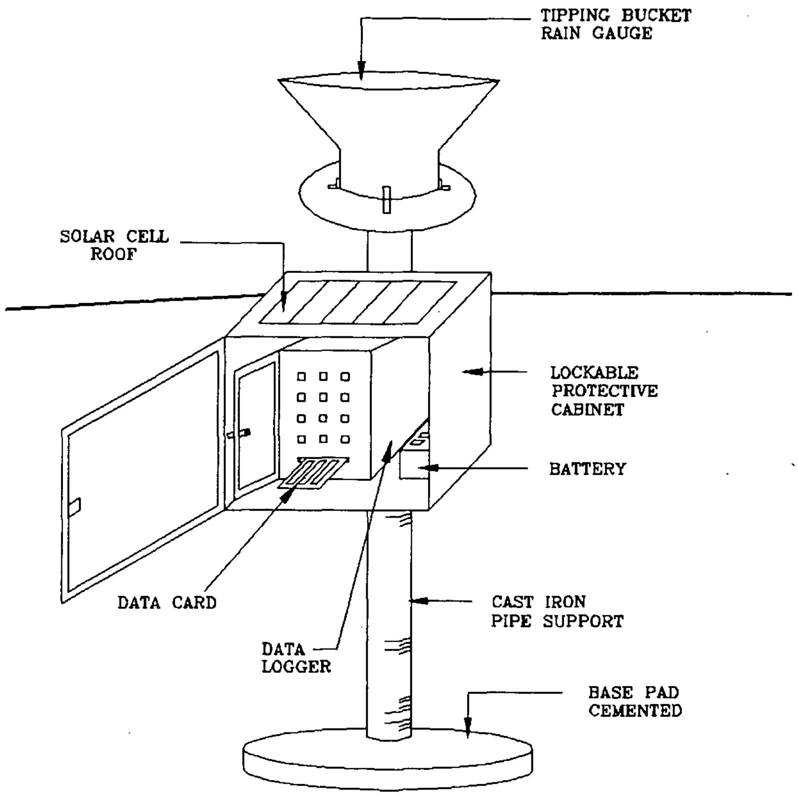


FIGURE 5 Solar-powered automatic rain gauge.

INSTRUMENTATION PERFORMANCE

Matric suction is obtained by subtracting the atmospheric pressure from the individual absolute pressure reading of the transducer attached to the Y-piece in the tensiometer system. The calculated matric suction is checked with the vacuum gauge reading at every data downloading. The suction reading obtained from the transducer was plotted against the vacuum gauge reading and was found to be satisfactory. The vacuum gauge gives the suction reading directly in centibars. A typical suction variation plot is shown in Figure 8.

The suction values obtained from these measurements were used to assess the stability of the slope. The shear strength equation incorporating suction (*3*) is as follows:

$$\tau = c' + (\sigma - u_a)\tan \phi' + (u_a - u_w)\tan \phi^b \qquad (1)$$

where

c' = effective cohesion,
σ = total stress,
u_a = pore air pressure,
ϕ' = effective angle of friction,
u_w = pore water pressure,
$(u_a - u_w)$ = matric suction, and
ϕ^b = friction angle with respect to changes in $(u_a - u_w)$ when $(\sigma - u_a)$ is held constant.

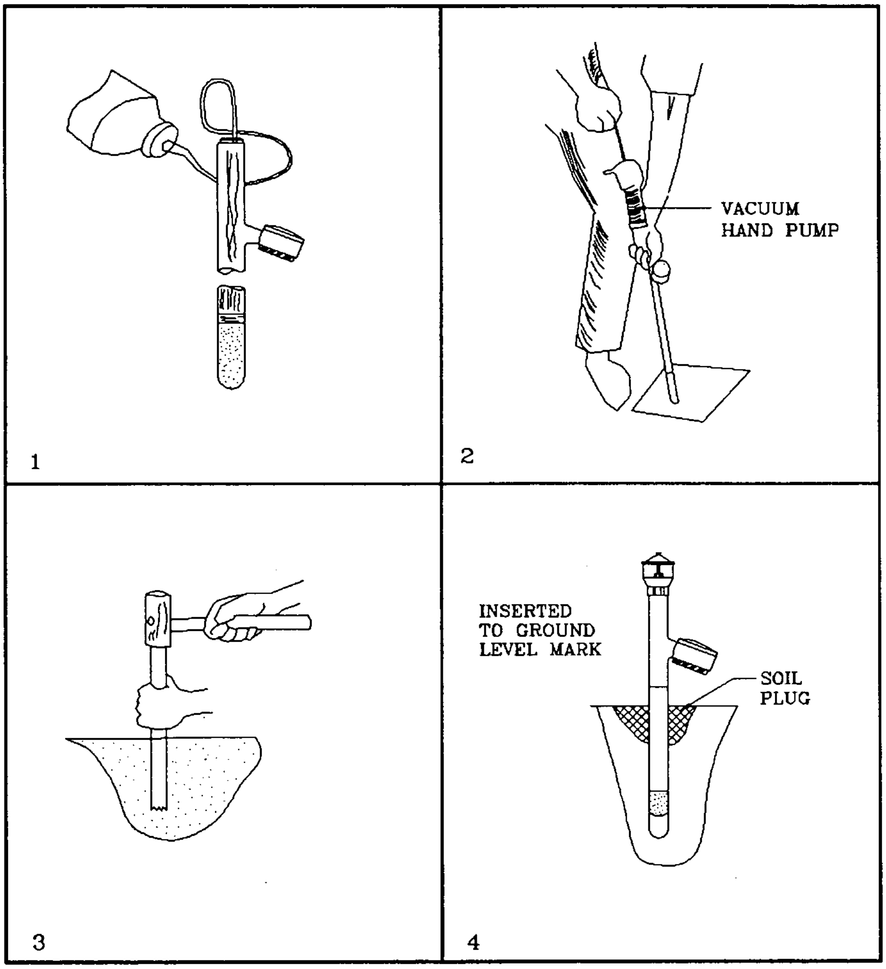
An initial assessment of the slope indicated that the factor of safety decreases with the decrease in suction. At this time it is not possible to suggest any threshold values of suction that would warrant remedial measures; this will not be possible until more data become available.

A curve was produced by using the available data collected from the instrumented site to predict the suction reduction after a rainstorm. All soil suction changes caused by storm rainfall events were relocated on an arbitrarily established rainfall axis. Upon repositioning of the rainfall events and the corresponding suction changes, a curve defining the soil suction changes caused by an antecedent rainfall event was established, as shown in Figure 9.

The suction values before the rainfall event and the total amount of rainfall can be used to predict the minimum suction resulting from such a rainfall event. The curves can be established for various weathering zones and are shown in Figure 10. Generally, the gradient of the curve is steeper for shallower depths.

This method, however, does not allow for positive pressures to be established. Furthermore, this method is not particularly satisfactory with regard to the physical processes of soil moisture distribution in the unsaturated zone and the continuity between the unsaturated zone and the saturated phase. The predicted data fit reasonably well with the actual values (Figure 11).

An initial analysis was undertaken to predict the resulting suction values (S_r) for different periods (T) after the cessation of rainfall. In establishing the relationship between S_r and T, all observations of the lowest suction after a storm and the recovery suctions over a period of no rainfall were used. The suction recovery equations obtained for one of the berms (Berm 4) at approximately 30-, 92-, and 124-cm depths, respectively, are as follows:



1. FILLING TENSIOMETER WITH DEAIRED WATER
2. DEAIRING THE TENSIOMETER USING VACUUM HAND PUMP
3. CORING SOIL TO ACCEPT THE TENSIOMETER
4. TENSIOMETER PUSHED INTO GROUND UNTIL GROUND LEVEL MARK

FIGURE 6 Tensiometer installation procedure.

$$S_r = 0.183 + 0.97S_l + 0.134T \quad (2)$$

$$S_r = 0.230 + 0.91S_l + 0.079T \quad (3)$$

$$S_r = 0.423 + 0.98S_l + 0.053T \quad (4)$$

where

S_r = resulting suction (kPa),
S_l = lowest suction attained during rainstorm (kPa), and
T = period after rainfall (hr).

A plot of the actual suction against the predicted suction for different periods after the cessation of rainfall is shown in Figure 12.

With the restricted amount of data available, an attempt has been made to carry out a multiple regression estimation of suction recovery.

SUGGESTIONS FOR FURTHER DEVELOPMENTS

The present system records the data at a prescribed interval, regardless of the intensity of the rain that is falling. The data are logged at the prescribed interval even when there is no rain. The datalogging interval should be more frequent when there is rainfall and should be changed to a longer interval after a threshold level is reached. Rapid changes in moisture and suction occur only in the event of rainfall. These changes would be possible if the recording of rainfall and other parameters were carried out with one logging system. It would be useful to accommodate these conditions in future designs of the system. There would be great savings of memory space in the data logger if the data recording interval depended on the frequency of rain.

CONCLUDING REMARKS

Reasonable success in the system designed to automatically log data can be achieved if one strictly adheres to the installation and calibration procedures. The automatic data logging system for monitoring suction and other related parameters has been described, and the objectives of the system have been reasonably

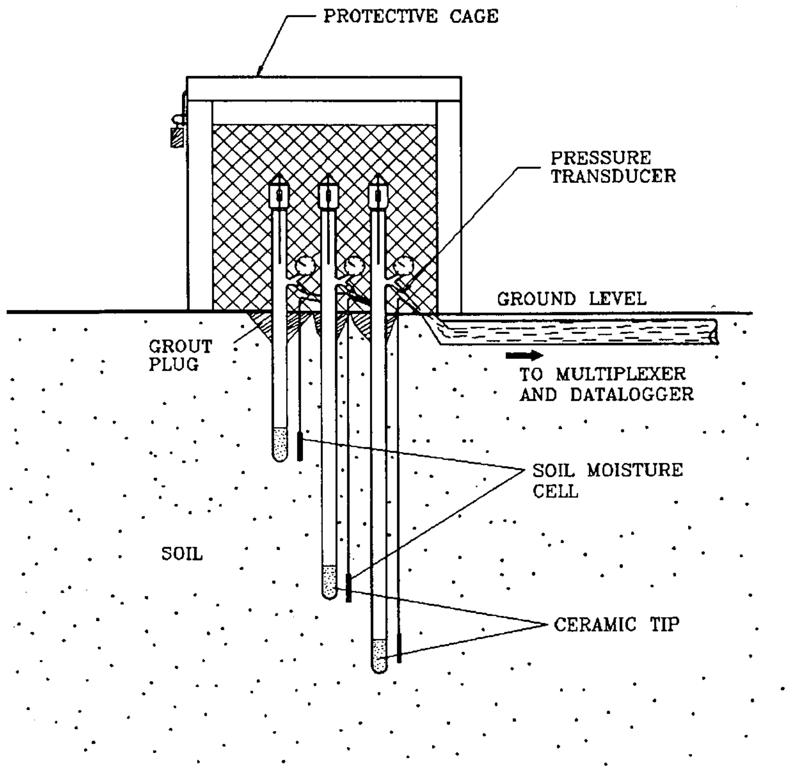


FIGURE 7 Typical instrumentation details for a single location.

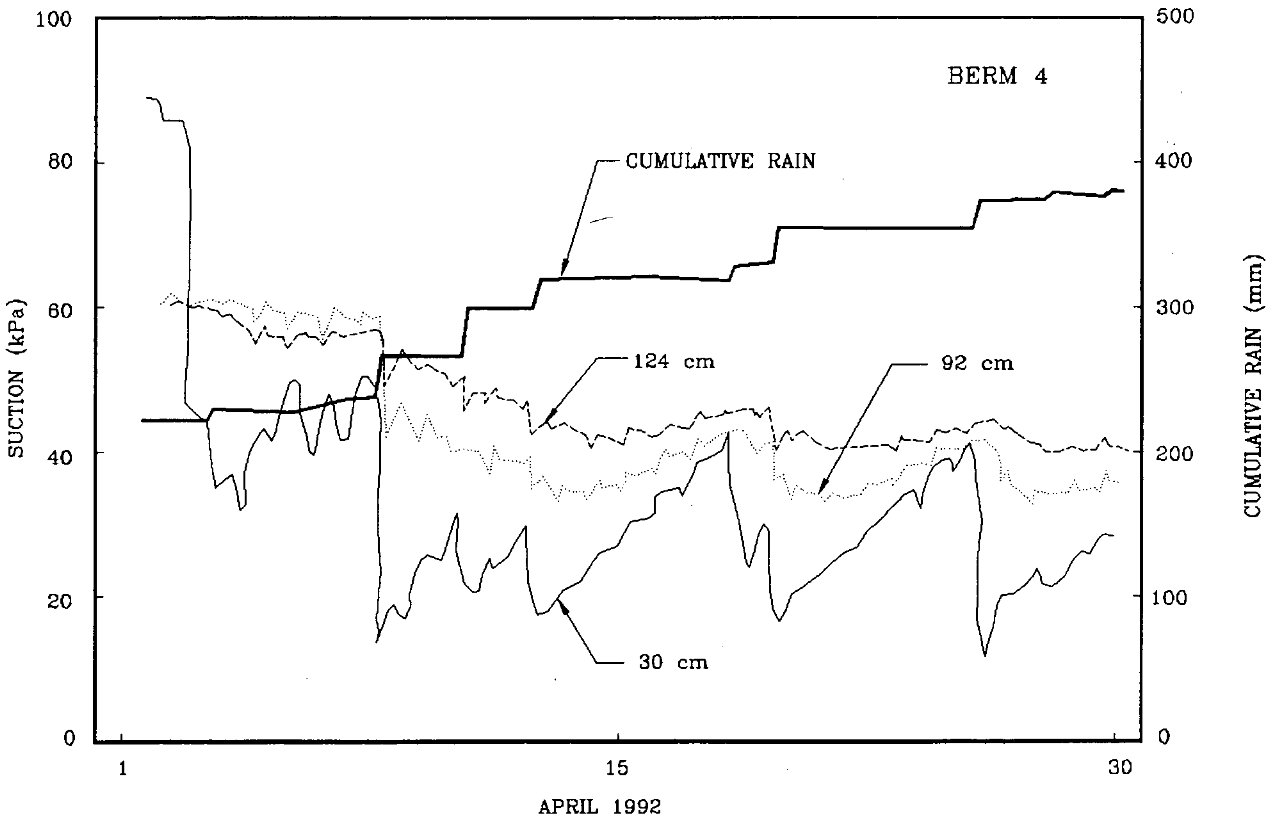


FIGURE 8 Typical suction variation curve for depths of 30, 92, and 124 cm.

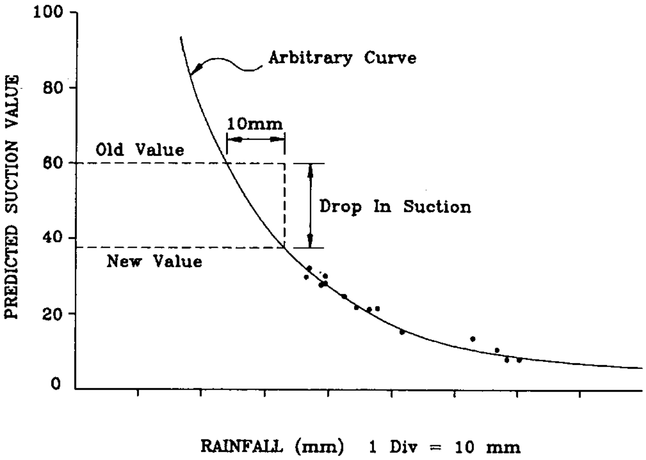


FIGURE 9 Typical suction reduction prediction curve.

achieved. The advantage of a fully automated system is its flexibility and the continuity of the data that are obtained. Rapid data acquisition and transfer to a suitable office-based computer are achieved by using a field interrogator. The solar-powered rain gauge allows rainfall measurements to be taken at closer intervals than can be done with the chart recorder type of rain gauge.

The system combines some important qualities; for example, it has a simple construction, it uses well-proven devices, and it is easy to install.

In Malaysia, which has a humid tropical climate, slope failures are more frequent and responsive to the intense, seasonal rainfall. This rainfall and the dry spells cause a fluctuating suction regime. The suction changes decrease with increasing soil depth. The rainfall intensity also influences the magnitude of decrease in suction.

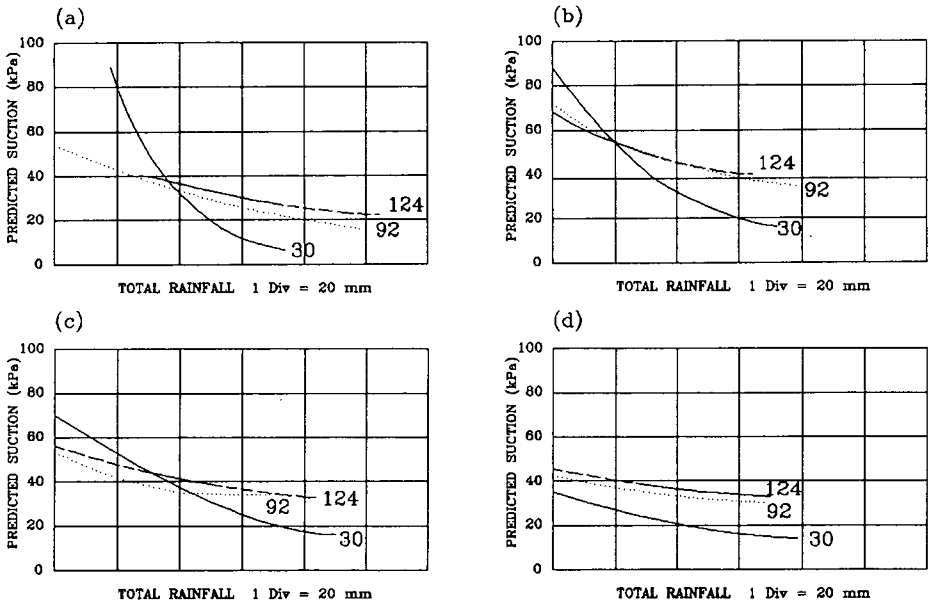


FIGURE 10 Suction reduction prediction curves for all berms: (*a*) Berm 1, (*b*) Berm 4, (*c*) Berm 3, and (*d*) Berm 2.

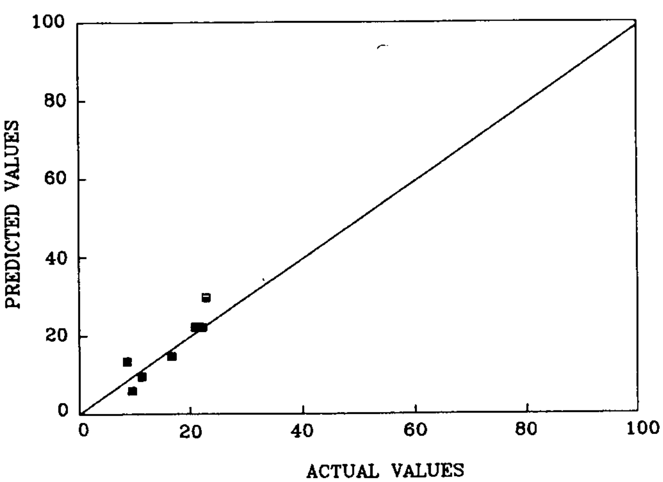


FIGURE 11 Suction reduction: actual versus predicted.

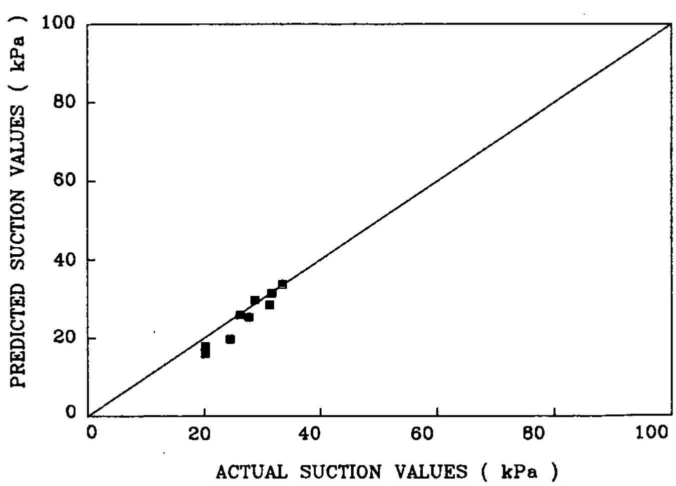


FIGURE 12 Suction recovery: actual versus predicted.

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