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COMPUTER-AIDED PRESSUREMETER TESTS

by K.T. Law

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RÉSUMÉ

Il s'agit d'un servo-mécanisme commandé par ordinateur, entièrement portatif et conçu pour être utilisé avec un pénétromètre autoforeur Cambridge. L'appareil comprend un calculateur, un système d'entrée de données (DAS) et un transducteur électro-pneumatique (E/P). L'ordinateur enregistre des données au cours de l'essai grâce au DAS et agit en fonction de celles-ci en ajustant la différence de potentiel appliquée au transducteur E/P, ce qui a pour effet d'augmenter proportionnellement la pression qu'exerce le pénétromètre. À présent, il existe quatre programmes d'essais: augmentation de la contrainte par incréments, contrôle de la vitesse de déformation, contrôle de la déformation et essai cyclique. Les expériences effectuées dans différents sols indiquent que le mécanisme se comporte conformément aux spécifications de conception.

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Computer-Aided Pressuremeter Tests

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ABSTRACT: A completely portable computer-controlled servo-mechanism designed for use with the Cambridge self-boring pressuremeter consists of a computer, a data acquisition system (DAS), and an electric-to-pneumatic (E/P) transducer. The computer obtains information on the current state of a test through the DAS and determines the next step in accordance with prescribed test conditions. An appropriate voltage is then sent to the E/P transducer, which regulates in proportion to the voltage received the pressure for expanding the pressuremeter. At present, four test conditions are programmed: a controlled stress increment test, a controlled strain rate test, a controlled strain test, and a cyclic test. Experience with different soils shows that the mechanism operates to design specifications.

KEYWORDS: computers, drill holes, transducers, pressuremeter, servo-mechanism, computerized soil testing, in situ tests

Use of the pressuremeter for in situ testing is increasing. The instrument has the potential to measure the stress-strain relation of soil and in situ horizontal stress, both essential quantities for design and analysis; the Menard pressuremeter has been used extensively in France for the past 20 years [1]. As a pre-drilled borehole is required for this test, some soil disturbance is inevitable. The last decade has however seen the successful development and application of a self-boring pressuremeter designed to reduce soil disturbance [2-5], although experience has revealed some remaining difficulties; minor changes in procedure may affect the results significantly [6,7]. The reduced disturbance may still underestimate the soil modulus and in situ horizontal stress but overestimate soil strength [8]. Different methods of interpreting the same set of data yield different results [9,10]. As yet the possible effect of loading rate has not been resolved. It is therefore desirable to test the various types of self-boring pressuremeters with repeatable and consistent procedures. For this purpose a computer-controlled servo-mechanism has been designed by the Geotechnical Section of the Division of Building Research, National Research Council Canada (DBR/NRCC), for use with a Cambridge self-boring pressuremeter. This paper describes the mechanism and the various types of tests it can perform.

Self-Boring Pressuremeter

The self-boring pressuremeter used in this study is similar in principle to that described by Wroth and Hughes [3]. The probe is 80

mm in diameter and 0.9 m long, with a cutting shoe and inside rotating cutter at the bottom. Water is pumped down the shaft of the cutter to flush to the surface the soil that enters the bottom end of the probe. Above the shoe is an adiprene membrane section about 0.61 m long, protected by an outer flexible stainless steel sheath. Located near the center of the membrane are sensors for measuring the total radial pressure applied to the soil, pore pressure, and the radial displacement of the membrane. Dry nitrogen gas is used to expand the membrane. The amount and rate of expansion are controlled by the servo-mechanism.

The only correction required for this instrument is necessitated by the resistance of the membrane and the sheath. The pressure P_{mr} in overcoming resistance at any given strain ϵ , defined as the ratio of the radial displacement to the original diameter of the membrane, can be described with a fourth degree polynomial

$$P_{mr} = \sum_{n=0}^4 a_n (\log \epsilon)^n \quad (1)$$

where a_n is the coefficient of the polynomial. Several methods are available for interpreting the test data giving soil characteristics. Some are based on the assumption of a certain stress-strain model [11-13]; others yield the stress-strain relation by assuming soil homogeneity [2,14,15]. The latter method has been used in the DBR/NRCC study because of its simplicity and general application. It should be noted that the test procedures are generally independent of the method of interpretation, which can be carried out after the test has been completed.

Principle of Operation

A number of test procedures are possible with the servo-mechanism. The controlled strain rate test is used here for illustration. It involves pressurizing the probe at a constant rate of membrane expansion with time and is divided into three stages. In the first, the probe is pressurized in increments until the lift-off pressure is reached. This pressure corresponds to the point at which the applied pressure just balances the in situ total horizontal stress and the membrane starts to expand. The rate of pressure increments depends on soil stiffness. Experience shows that typical values are: 5 and 10 kPa/10 s for soft and stiff soils, respectively. It is clear that no measurable strain is recorded at this stage.

In the second stage, the membrane is expanded at a constant strain rate by applying a pressure increment to the probe and checking the induced strain. Depending on the difference between the strain increase and the prescribed constant rate, one of the following options is taken: (1) if the strain increase is less than the prescribed rate, another pressure increment is applied; (2) if strain increase is

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within an acceptable range of the prescribed rate, no change in pressure is necessary; and (3) if the strain increase exceeds the prescribed rate, the pressure is decreased. This second stage is illustrated in an exaggerated manner in Fig. 1. The smoothness of the curve depends on the size of the pressure increment, the magnitude of the acceptable range, and the frequency of pressure application. All these quantities are adjustable before and during a test to accommodate different soil response at different pressures.

The third stage is for unloading. As soon as the strain reaches a given value, usually 7.5%, the pressure in the probe is decreased at a standard rate of 50 kPa/½ min.

Servo-Mechanism

Figure 2 is a schematic diagram of the servo-mechanism for inflating the pressuremeter probe, showing the three main components of the system: computer, data acquisition system (DAS), and electric-to-pneumatic (E/P) transducer. All use a 110-V power source supplied by a portable Honda® power generator.

FIG. 1—Prescribed and actual strain-time plot in controlled strain rate test.

FIG. 2—Schematic diagram of servo-system for pressuremeter tests.

Figure 3 shows the actual servo-mechanism mounted in a service truck. In addition, a backup manual pressure control unit is installed below the E/P transducer in case of power failure or problems in the servo-mechanism. It was seldom used after the initial trial period.

Computer

The computer controls the experiment and processes the experimental data. As the probe is pressurized, total pressure, strain, and pore pressure are monitored by its transducers. Signals are transmitted via the DAS to the computer where they are processed to give engineering quantities. These are examined with respect to the conditions prescribed for the test. A decision is then made within the computer for the next step. The basic requirements for the computer are therefore the ability to interface with a DAS and the E/P transducer, an internal clock or timer, sufficient storage capacity to run the software for the experiment, and portability for use in the field.

Optional features considered desirable include the following: a screen display for interactive operation during the experiment, a printer for hard copies of experimental data, tape or disk storage of data for future analysis, and a plotter for displaying the result in graphical form. A number of systems are available on the market that satisfy both basic and optional requirements. The system chosen for the present setup is the Hewlett Packard HP85S.

Data Acquisition System

The Hewlett-Packard HP3497A equipped with a 5½ digit-resolution voltmeter and a 20-channel scanner was used to obtain measurements from the pressuremeter. Only three channels are required for ordinary tests, but six channels are needed if the three displacement transducers and the two pore-pressure cells are to be read separately, as described by Dalton and Hawkins [16].

Besides taking readings, the DAS transmits an electrical signal (voltage) to the E/P transducer to bring a change of pressure to the probe. After the readings have been processed, a decision is made in

FIG. 3—Resistance arrangement for stepping down voltage from D/A converter to E/P transducer.

the computer, and a corresponding number is sent to the DAS. This number is turned into voltage through the digital-to-analogue (D/A) converter installed on the DAS. Ranging between 0 and 10 V, this voltage is stepped down by a voltage divider and then transmitted to the E/P transducer, which has an operating range of 0 to 0.1 V. The voltage divider can be replaced by a permanent resistor arrangement connecting the D/A converter and the E/P transducer, as shown in Fig. 4. The ratio of resistance values, R_1 and R_2 , is given by

$$R_1/R_2 = (V_1/V_2) - 1 \quad (2)$$

where

V_1 = voltage from D/A converter and
 V_2 = voltage to E/P transducer.

Electric-to-Pneumatic Transducer

This transducer is an instrument (Moore's Model 77) for regulating a pressure output proportional to a DC voltage input. The basic unit delivers a pressure range of 20 to 100 kPa, and for the present study a 6:1 pressure-amplifying relay was used to boost the pressure range from 120 to 600 kPa. Higher amplification is possible if two relays are connected in series. The transducer and the relay are each supplied with a constant pressure (from a nitrogen tank) 30 kPa higher than the respective maximum output pressures.

System Performance

The HP855 with DAS uses an averaging technique to reduce signal noise. Readings of a certain channel are taken repeatedly, and a mean value is calculated. Trials show that there is hardly any difference in the mean values, whether for 2 or for 100 readings. The times required for 3 channels, however, vary from less than 1 s to about 16 s for mean values of 2 to 100 readings. The present setup adopted a mean of 5 readings, taking 1.5 s to read 3 channels.

The E/P transducer also has a response time for operation, caused mainly by the compliance of the nitrogen in the pressure hose and probe. The length of response time varies slightly with the size of the pressure increment. At a 10-kPa increment, for instance, the average time to reach 90% of the given increment is 7.7 s and to reach 100% is 22 s. This response causes no difficulty in the controlled strain rate test since the computer constantly checks and adjusts the pressure input to the probe. It does however set an upper frequency limit on a cyclic test at 0.067 Hz or 15 s per cycle. A higher frequency is possible, but the pressure amplitude may not be so easily controlled because there is insufficient time for the pressure increment and decrement to develop substantially within the cycle.

The E/P transducer with its 6:1 pressure amplifying relay has a pressure range of 120 to 600 kPa, as suggested by the manufacturer. The model used here is a reverse acting version that yields a decreasing pressure with increasing voltage input. With a small overloading (about 25% of rated maximum voltage input) the linear range of the

FIG. 4—Servo-system mounted on service truck.

transducer is extended to 14 kPa (Fig. 5). The extension of the lower pressure range is very useful for measuring the in situ total horizontal stress in shallow, soft deposits. Any pressure output below 20 kPa will be taken up by the rigidity of the membrane and the sheath, and therefore nonlinearity below 14 kPa, the lower limit, may be disregarded. The E/P transducer has been used at the low pressure range for more than a year without causing problems.

Test Types

At present four test types of practical interest in geotechnical engineering have been programmed into the system: controlled stress test, controlled strain rate test, controlled strain test, and cyclic test.

The controlled stress increment test is the simplest, applying pressure increments at regular intervals throughout the loading stage. The value of the pressure increment and the length of the interval are fed into the computer at the beginning of each test, allowing an almost infinite range of loading rates. In addition, after the test begins the computer takes continuous care of it, thus freeing the operator. When strain reaches a specified value, the pressure will be decreased at a standard rate of 50 kPa/ $\frac{1}{2}$ min.

The controlled strain rate test was described earlier. Again, the strain rate is provided at the beginning of a test and an infinite range of rates within practical limits is possible. To obtain a smooth linear relation between strain and time, it was found that typical rates of pressure adjustment for soft and medium clays are at 3- and 7-kPa/5 s intervals.

The controlled strain test consists of inflating the membrane at a constant strain rate until it reaches a certain value, at which it is maintained. The first part of the constant strain rate test is identical to that of the controlled strain rate test. To maintain a constant strain, the control system monitors strain about every 5 s to see whether there is significant deviation (0.01%) from the constant value. If deviation is detected, the pressure is adjusted, as for the controlled strain rate test. For most soils the total pressure tends to decrease with time at constant strain because of consolidation or relaxation. By noting the change in total and effective stresses, the coefficient of consolidation can be obtained [17].

Figure 6 shows a plot of total pressure and strain versus time for a constant strain test in a sensitive medium clay with the detailed soil characteristics given by Eden and Law [18]. This plot was obtained by means of a chart recorder added to the system. The recorder is not normally required because all test data and results are available

FIG. 5—Characteristics of electric to pneumatic transducer.

FIG. 6—Result of constant strain test.

through the computer, but it was used here to illustrate the system performance. Stage I is the incremental pressurization below the lift-off pressure, with no observable strain. Stage II is the constant strain rate loading. The linear strain-time relation indicates that constant strain rate is achieved. The pressure-time curve is not linear because of nonlinear soil behavior. The pressure generally increases with strain in spite of some "wiggles" involving small temporary pressure decreases to maintain constant strain rate. At the end of this stage there was a small strain overshoot into Stage III of constant strain. The result shows that the control system can maintain constant strain with remarkable steadiness by varying total pressure. Stage IV is the standard procedure for unloading the pressuremeter at 50 kPa/½ min.

The cyclic test can be carried out by varying the total pressure at a certain amplitude and frequency. The procedure adopted was to vary the pressure for one complete cycle in a number of steps after reaching a given pressure or strain. The total number of cycles is assigned by the operator.

Figure 7 shows the record of a cyclic test registered on the chart recorder. After pressurizing the probe to 3.5% in constant increments, the system switched to the cyclic mode. Ten cycles were carried out, each consisting of six pressure steps, three for loading and three for unloading. After the cyclic stage the probe was inflated to 7.5% and then unloaded in the standard way.

FIG. 7—Result of cyclic strain test.

Other test procedures are also possible. The drained test, for instance, can be conducted by slowly pressurizing the probe while watching the excess pore pressure. If there is no excess pore pressure, the pressurization can be continued; if there is significant excess pressure, the pressurization may be slowed down or even stopped. While such a process is tedious if manually operated for clays, it is well suited to the servo-system.

Input and Output

Preparing the system for a test involves connecting the leads from the pressuremeter through the electronics box supplied by the manufacturer to the data acquisition system. The program, written in BASIC language, is then loaded into the computer from the cassette tape. The operator interacts with the computer in a conversational mode to specify the test parameters (Fig. 8). When all the parameters have been supplied, the computer instructs the operator to start testing by turning on the pressure supply.

There are three types of output for the tests results. First, the raw data in engineering units are printed out; second, the data are stored on the cassette tape for possible future analyses; and third, the data are plotted on the machine (Figs. 9 and 10). These plots are limited in size and quality. Better plots may be obtained by attaching a compatible plotter to the computer.

Summary and Conclusion

A servo-system comprising a portable computer, a data acquisition system, and an electric-to-pneumatic transducer has been designed for use with the Cambridge self-boring pressuremeter. The computer serves as both controller and data processor. It instructs

CAMBRIDGE S.B. PRESSUREMETER TEST

KEEP PRESSURE VALVE OFF

ENTER DATE AND TIME
YYMMDDHHMMSS

?
Δ 820721132500
ENTER LOCATION
?

Δ OTTAWA M-24
ENTER TEST NO.
?

Δ 82-M2
ENTER COEF. FOR MEMBRANE RIGIDITY
?

Δ 19.6534, 4.06588, 4.18306, 2.30261,
Δ 0.17401

ENTER FACTORS FOR TP, STRAIN, EP I
N kPa, %, kPa PER VOLT
?

Δ 1316, 38.46, 1408
ENTER TEST CODE:
1 FOR CONTROLLED STRESS
2 FOR CONTROLLED STRAIN RATE
3 FOR CONSTANT STRAIN
4 FOR CYCLIC LOAD.
?

Δ 2
STRAIN RATE CONTROLLED TEST
ENTER STRAIN RATE IN %/MIN
?

Δ 0.16
NOW TURN ON PRESSURE VALVE

Δ INPUT BY OPERATOR

FIG. 8—Input data for interactive operation.

FIG. 9—Typical arithmetic plot of results from HP85S.

FIG. 10—Typical semilog plot of results from HP85S.

the data acquisition system when to take a reading and when to transmit a signal to the electric-to-pneumatic transducer to change the pressure to the pressuremeter in accordance with some prescribed condition. Different testing procedures can be carried out by feeding the computer appropriate information in a conversational mode. At present, four test types have been incorporated for testing various soils: controlled stress increment test, controlled strain rate test, controlled strain test, and cyclic test. The system performs well, actual test paths following closely the prescribed ones. A wide choice of rates of testing is possible, whether in terms of stress or of strain. For the cyclic test, there is a limitation in that adequate control is difficult with frequencies exceeding 0.067 Hz because of the compliance of nitrogen gas. This limitation is inherent if gas is used as the pressurizing fluid. All test results are stored on cassette tapes, printed, and displayed on the plotter of the computer. Thus, the use of computer technology enhances the capability of the pressuremeter, increases its reliability and accuracy, and reduces the time required for data processing and dependence on human limitations.

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