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Publisher's version / Version de l'éditeur:

ASTM Special Technical Publication, 361, pp. 390-397, 1965-06-01

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A TRANSDUCER TO MEASURE PORE WATER PRESSURES
IN SOIL TESTS

BY

K. N. BURN

REPRINTED FROM
AMERICAN SOCIETY FOR TESTING AND MATERIALS
SPECIAL TECHNICAL PUBLICATION NO. 361,
1963, P. 390 - 397

RESEARCH PAPER NO. 252
OF THE
DIVISION OF BUILDING RESEARCH

FEB 23 1966

NATIONAL RESEARCH COUNCIL

OTTAWA

JUNE 1965

PRICE 25 CENTS

NRC 8512

UN TRANSDUCTEUR DESTINE A MESURER LA PRESSIE
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SOMMAIRE

Un transducteur de pressions convenant pour de très petits volumes a été conçu de manière à mesurer et à enregistrer les pressions interstitielles de l'eau qui se manifestent durant les essais de charge effectués en laboratoire sur des spécimens de sol saturé. Pour appliquer cette technique, on se sert d'un transducteur de pressions du type "jauge de contrainte". Des indications sont fournies en ce qui concerne les montages électriques auxiliaires, la méthode d'installation et le calibrage du système.

CISTI / ICIST

3 1809 00211 1489

Authorized Reprint from the Copyrighted
Laboratory Shear Testing of Soils
Special Technical Publication No. 361
Published by the
American Society for Testing and Materials
1963

A TRANSDUCER TO MEASURE PORE WATER PRESSURES IN SOIL TESTS

By K. N. BURN¹

SYNOPSIS

A pressure transducer with very small volume compliance has been adapted to measure and record the pore water pressures which develop during loading tests on saturated soil specimens in the laboratory. The technique described uses an unbonded strain gage type of pressure transducer. Details are given of the ancillary electrical circuitry, the method of mounting, and the calibration of the system.

Pore pressures which are generated in soil specimens during laboratory triaxial tests are usually measured by balancing them against pressures applied from hand pumps. Accurate measurements of pressure are obtained only if the flow of water into or out of the specimen is negligible. This is generally attained by controlling, within certain visual limits, a slug of mercury trapped inside a tube of small diameter between the internal and external fluid systems. Because this is a manual operation it requires continuous attention.

Electronically controlled devices which generate pressure as required to balance the pore pressures developed in the soil specimen are available.² Such instruments require a good deal of maintenance, and they respond too slowly for some tests. These disadvantages led to the search for a closed system device which would be sufficiently sensitive to measure small pressure changes with

negligible changes in volume. Such a device has been used at the Bureau of Reclamation for some years.³

Within recent years a variety of electro-mechanical devices, known as transducers, have been developed. One of these, designed to measure fluid pressures against a small diaphragm, was found to be suitable for measuring pore water pressures in the laboratory. The resulting system requires little attention and makes it possible to record pressures—a great advantage when conducting long-term tests.

This paper describes an automatic recording system of this kind installed in the Soil Mechanics Laboratory, Division of Building Research, National Research Council, and includes brief descriptions of the pressure transducer, the pressure block in which it is housed, the circuitry connecting the transducer to the recorder, and the calibration of the equipment.

¹ Research officer, Soil Mechanics Section, Division of Building Research, National Research Council, Ottawa, Canada.

² A. D. M. Penman, "Shear Characteristics of a Saturated Silt Measured in Triaxial Compression," *Geotechnique*, Vol. 3, No. 8, p. 312.

³ H. J. Gibbs, J. W. Hilf, W. G. Holtz, and F. C. Walker, "Shear Strength of Cohesive Soils," *Am. Soc. Civil Engrs., Research Conference on Shear Strength of Cohesive Soils*, Boulder, Colo., June, 1960, pp. 33-162.

FIG. 1—Pressure Transducer.

pressure is applied to the diaphragm. The four strain gages are connected in the form of a Wheatstone bridge so that any change in length, and consequently in the resistances in these gages, alters the electrical balance of the bridge. This produces a change in electrical signal in the output circuit which can be calibrated against applied pressure.

This pressure transducer was selected

FIG. 2—Section Through Pressure Block.

PRESSURE TRANSDUCER

A pressure transducer is an electro-mechanical device that can convert minute displacements to proportional changes in electrical potential. In this case the physical displacements are those of the center of a small diaphragm that take place when pressures are applied to one side of it. The center of the diaphragm is linked to a group of four unbonded strain gages of equal length; two increase and two decrease in length as

because of its small size and extra sensitivity. It is model No. PA 208 TC-100f 350 from Satham Instrument, Inc. of Calif. (Fig. 1). Some important design features are:

1. Barrel diameter, $\frac{1}{2}$ in.—active diameter, 0.300 in.
2. Pressure range is 0 to 100 psi with a permissible 100 per cent overload.
3. It is temperature compensated over a range of -65 to $+250$ F.
4. The Wheatstone bridge has a

NOTE

PRESSURE TRANSDUCER-PA.208 TC (STATHAM INST. INC.)

 S_1 - SWITCH, DOUBLE POLE, SINGLE THROW S_2 - SELECTOR SWITCH R_1 - WIRE-WOUND POTENTIOMETER - 10,000 OHMS
(GAIN ADJUSTMENT) R_2 - WIRE-WOUND POTENTIOMETER - 20,000 OHMS
(ZERO ADJUSTMENT) R_3 - WIRE-WOUND RESISTOR - 33,000 OHMS (PADDER) R_4 - WIRE-WOUND RESISTOR - 16,395 OHMS ± 10 OHMS R_5 - WIRE-WOUND RESISTOR - 5,552 OHMS ± 10 OHMS R_6 - WIRE-WOUND RESISTOR - 11,130 OHMS ± 10 OHMS R_7 - WIRE-WOUND RESISTOR - 33,320 OHMS ± 10 OHMS

FIG. 3—Electrical Circuit for Pressure Transducer Used in Recording Pore Water Pressures.

nominal resistance of 350 ohm with an output of 4 mv/v input.

5. Because strain gages are used, the resolution is infinite and limited only by the nature of the reading instrument or recorder.
6. The nonlinearity and hystereses are less than ± 0.75 per cent of full scale.
7. One of the most important features in this particular application is the very small volume change required to activate the instrument. Full-scale pressure produces a volume change at the diaphragm of only 0.2×10^{-6} in.³ or 0.0033 mm³.

PRESSURE BLOCK

A pressure block, shown in Fig. 2, was designed to provide a small volume of water continuous with the pore water of the test specimen and in contact with the diaphragm of the transducer. Two holes penetrate a small chamber in the block, one of which is used as a connection to the test cell and the other as a vent for flushing air bubbles from the water system. O rings are used to make the connections watertight.

A shut-off valve for the chamber is provided in the form of a screw, which tightens down on a miniature O ring to a fixed position when the head of the screw comes in contact with the outer surface of the pressure block. The transducer is held in a fixed position in the block by a clamping system over a shoulder on the transducer. Watertightness is achieved by incorporating an O ring in this positive position clamping arrangement.

To eliminate corrections to the final readings caused by positive or negative heads of water between the pressure block and the specimen under test, the pressure block is mounted on a stand which permits vertical adjustments from $2\frac{1}{2}$ to $14\frac{1}{2}$ in. above base level.

ELECTRICAL CIRCUIT

The electro-mechanical properties of the pressure transducer required for the design of the electrical circuit are listed on the data sheet supplied by the manufacturer. A drawing of the circuit is shown in Fig. 3. The main circuitry follows the arrangement outlined by the manufacturer. As the output voltage to the recorder is directly proportional to the input voltage, the gain can be controlled by a rheostat. Zero settings are adjusted by means of a high-shunt resistance across the input terminals to which a wiper and a buffer resistance are connected in series through one of the output terminals.

Although the transducer itself is temperature compensated, the external circuitry is slightly but noticeably affected by temperature changes particularly during the warm-up period. It is also affected by slight variations in power supply. It is therefore necessary periodically to check the gain against a given pressure increment. This, of course, cannot be accomplished by applying pressure to the diaphragm of the transducer without also applying it to the test specimen. A check calibration is accomplished by keying a shunt resistor across one arm of the bridge, thus causing an imbalance in the circuit and producing an output signal which can then be adjusted by the gain rheostat. The actual magnitude of this signal depends upon the value of resistance and can be calculated to simulate any given pressure interval. A calibration factor supplied by the manufacturer is used to calculate the magnitude of the shunt resistor.

Rather than use only one resistor to check the gain over a limited range, a series of resistors were installed in the circuit to check the gain over pressure ranges of 1, 2, 3, and 4 kg/cm² or approximately 15, 30, 45, and 60 per cent of the full-scale range of the transducer.

CALIBRATION

The calibration factor which the manufacturer supplies relates output voltage change to a given pressure increment at any input voltage. As it was anticipated that pore water pressures no higher than 4 kg/cm^2 might be generated in most of the testing, it was deemed adequate to check the calibration against a single mercury column available in the laboratory which could register pressures slightly in excess of 3 kg/cm^2 . Measurements were made at pressure intervals up to 3 kg/cm^2 and calibration factors calculated. They varied by slightly more than 1 per cent but differed from that of the manufacturer by as much as 5 per cent.

This led to a little unexpected difficulty in determining the shunt resistances for that part of the circuit designated Calibrate. The values of the resistors had to be determined by trial and error rather than from the calibration factor.

PROCEDURE FOR OPERATION IN
TRIAXIAL SHEAR TESTS

The pressure block should be inverted (with the valve on the bottom) and connected by the copper tube to the bottom plate of the triaxial cell. Deaired water should be run from the cell until both copper tube lines are filled. The valve should then be closed and the pressure chamber allowed to fill with water. This can be accomplished by lowering the block below the level of the lower bearing plate of the triaxial cell. At this stage the pressure transducer should be inserted, displacing both water and air, and secured in place by the O ring, washer, and retaining nut which should be turned until a positive pressure is encountered.

Taking care not to loosen the connection to the test cell, the pressure block should be returned to its upright position, that is, pressure transducer below.

If there are any air bubbles in the system they will rise to the tip of the conically shaped pressure chamber. The valve should then be released and the system flushed again from the triaxial cell end. When there are no bubbles flowing through, the valve should be tightened down until it meets a positive resistance. The hexagonal head should be in contact with the upper surface of the pressure block.

The triaxial cell is then ready to receive the test specimen, which should be mounted in the usual manner. When this is done the height of the pressure block should be adjusted so that the diaphragm of the pressure transducer will be at the same level as the base of the test specimen. A mark on the side of the pressure block shows the position of the diaphragm.

Finally, the connection to the electrical circuit can be made by fitting the disconnect assembly to the end of the pressure transducer. The positions are clearly marked 1, 2, 3, and 4. The switch and the recorder chart should then be turned on. (The recorder should be started some time in advance to give it time to warm up. Two hr is considered a minimum, and it is best left overnight.) The pore water pressure should be adjusted to zero using the mercury manometer and the position of the appropriate recorder points adjusted by means of the knob on the variable resistor marked Zero.

The scale selected can be adjusted by shunting into the circuit 1, 2, 3, or 4 kg/cm^2 by turning the knob marked Calibrate to the appropriate position and adjusting the knob marked Gain until the recorder prints the point in the correct position on the chart.

As large a pressure difference as possible should be chosen commensurate with the selected scale. It will be necessary to check these adjustments two or three times since the Gain adjustment has a

noticeable but small effect on the Zero setting.

EXPERIENCE WITH OPERATION

The system has performed satisfactorily in undrained triaxial shear testing. Actual response time appeared to be limited only by that of the recorder. Any time lag in the system was undetectable by visual observation and of little consequence in testing at ordinary or prolonged rates of strain.

The transducer and a pen recorder were then used in a series of consolidation tests in which an attempt to measure pore water pressures with time was made. In the original design an attempt was made to reduce the volume of the pore water line and increase its rigidity as much as possible, but the effects of flexibility of the system as described by Whitman et al⁴ became obvious when the pen trace failed to record pressures greater than 75 to 80 per cent of the applied pressure increment and only reached the peak about 3 to 4 sec after the application of the load. Some improvements have since been made, but further work is necessary for the successful application of this system to measuring pore water pressures in drained compression tests.

A six-volt wet cell battery was first

used when recording pore water pressures in triaxial specimens, and it operated reasonably well. However, it was necessary to make minor gain adjustments several times during a test. This arrangement had one great disadvantage when the equipment was subsequently used in special consolidation tests. Without a full power supply of 7v it was not possible to use a chart scale of 1 kg/cm² equal to 10 mv output, which seemed the most suitable scale for the study.

Banks of dry and mercury cell batteries were tried and used but these did not provide a sufficiently constant power supply. A 12-v wet cell with a guarded 7-v take-off was then used and found to be much better but was finally replaced by a regulated d-c power module, the output of which varied by not more than ± 0.05 per cent of 7 v. The installation of this unit has practically eliminated all need for periodic adjustments of zero and gain.

Acknowledgments:

The author wishes to acknowledge with appreciation the assistance of D. C. MacMillan in the installation of this equipment and M. Bozozuk for general observations on the performance of the equipment in consolidation testing. This paper is a contribution of the Division of Building Research, National Research Council, Canada, and is published with the approval of the Director of the Division.

⁴R. V. Whitman, A. M. Richardson, and K. A. Healy, "Time Lags in Pore Pressure Measurements," *Proceedings*, Fifth International Conference on Soil Mechanics and Foundation Engineering, Paris, Vol. 1, 1961, pp. 407-411.

DISCUSSION

L. BARDEN¹—The use of pressure transducers is a most promising method of measuring pore pressures, whether in short term undrained triaxial tests or in more prolonged tests where automatic recording is obviously a great advantage. I have used transducers similar to the type described in the paper, and also a much smaller and more sensitive type, for measuring pore pressures in the triaxial test.

A stabilized d-c supply is essential and will give a constant gain and an almost negligible zero drift over periods of many days. There is, therefore, no need for the ancillary circuit and the adjustments during test described by the author, which were only necessary because batteries were used as the d-c supply.

The very small sensitive transducer referred to above is based on the piezo-resistance characteristics of quartz crystals. The entire transducer is about the size of a pea and so has a very small volume change under pressure. It has a full scale, 100 psi, output of 500 mv, compared with 40 mv for most transducers, and when used with a small driver unit which supplies constant current as well as constant voltage, it is extremely stable.

The null method of pore pressure measurement requires some flexibility in the system for it to be efficient. A completely rigid system would hunt too much. However the closed transducer

circuit should be as rigid as possible, and the transducer should preferably be connected directly to the cell base. The volume of the connecting water should be a minimum and no air bubbles should be present.

The author's method of connecting his transducer housing to the cell base by a length of flexible copper tube does not seem advisable. Also, from my own experience, the suggested method of deairing is not always reliable and there is no method of checking for air bubbles. To ensure complete deairing it is best to leave the water under a pressure of about 100 psi overnight and then to flush through to prevent the air from coming out of the solution again when the pressure drops. It is highly desirable to incorporate some device for checking the compliance of the deaired system; I use the system illustrated in Fig 4. One null indicator can be used to check a whole bank of transducers.

The author uses a chart recorder as his output device. This is an excellent device for long term tests when automatic recording is really necessary. However for short-term tests a digital voltmeter is very accurate and easy to use, and for automatic recording it can print out tabulated results on an electric typewriter.

I agree that, provided the system is correctly deaired, the response time is excellent, but it is unlikely to be so quick as to be limited only by that of the recorder for all types of soil. The system always possesses some compliance (often

¹ Lecturer in engineering, Manchester University, Manchester, England.

of the order of 1×10^{-6} in.³/psi), and with a clay of low compressibility and permeability the response time must be appreciable.

The value of the compliance of the transducer described in the paper is given as 0.2×10^{-6} in.³ for full scale pressure (100 psi). Should this value not be 0.2×10^{-6} in.³/psi?

Barden pointed out, virtually eliminates the need for an ancillary circuit to check amplification. This circuitry is, however, still extremely convenient in selecting the correct amplification for visual recording of pressures on a chart.

The manufacturer's calibration chart, giving the compliance of the transducer, was not interpreted correctly. The

FIG. 4—Device for Checking Compliance of Desired System.

In conclusion, I would like to express my support for the author's advocacy of the use of transducers for pore pressure measurement.

K. N. BURN (*author's closure*)—Mr. Barden's comments on my equipment and the description of the pore pressure measuring apparatus he has developed are very useful and sincerely appreciated.

Shortly after writing this paper and before the conference, I procured a 7-v stabilized d-c supply which, as Mr.

figure given in the paper is not for full-scale load, but for each psi change in pressure. Although this is still a very small volume, it is considerably larger than that required to activate a solid state transducer.

I am also indebted to Mr. Barden for his observations on difficulties of de-airing the pressure system. I thank him for sharing these thoughts and for describing the technique he uses to reduce this problem.