Innovations in Hydraulic-Conductivity Measurements

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Innovations in laboratory methods for hydraulic-conductivity measurements have been developed by using a flow pump to generate a constant rate of flow through a test specimen and monitoring the hydraulic gradient induced thereby with a differential-pressure transducer. In most applications of this constant-flow method to date, hydraulic-conductivity tests have been conducted on stress-controlled specimens following conventional loading increments in one-dimensional consolidometers and also after increments of three-dimensional consolidation in triaxial cells. Similarly, a constant rate of flow through one end of a test specimen has been generated with a flow pump while flow through the opposite end of the specimen is driven to or from a pressure-controlled reservoir. More recent innovations include a new flow-pump actuator that enables identical flow rates to be infused and withdrawn from opposite ends of a test specimen and the use of additional flow pumps to control the effective stress and volume of a specimen. These innovations provide a convenient approach for obtaining hydraulic conductivity versus effective stress data in triaxial cells on a wide variety of materials, including sandstones and shales that cannot be trimmed and mounted in fixed-ring permeameters or one-dimensional consolidometers. These innovations also provide a means to integrate constant-flow hydraulic conductivity measurements with continuous-loading consolidation tests on fully saturated specimens in both back-pressured consolidometers and in triaxial cells.

Presented in this paper is an overview of the innovations in laboratory methods for hydraulic-conductivity measurements that have been developed using a flow pump to generate a constant rate of flow through a test specimen and monitoring the hydraulic gradient induced thereby with a differential pressure transducer. Experimental data are presented to illustrate how various applications of this constant-flow method can be used to provide more detailed and higher-quality technical information in less time than conventional methods.

The innovations involve applications of the constant-flow method in one-dimensional consolidometers and in conventional triaxial cells. The advantages of these innovations arise because the generation of low flow rates and the measurement of pressures and forces with transducers in the constant-flow method can be accomplished more easily and accurately than the measurement of low flow rates and the control of pressures and forces involved in conventional constant-head and falling-head methods. For example, flow rates as low as 10^{-7} cm^3/sec can easily be generated with commercially available flow pumps.

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However, the measurement of such flow rates requires long periods of time because the practical resolution of volume-measurement techniques used in geotechnical laboratories is about 10^{-3} cm^3 (*1*). Also, fluid pressures are easily measured to 10^{-3} psi with transducers; however, they can only be controlled to about 10^{-1} psi with air-pressure regulators commonly used in geotechnical laboratories.

FLOW PUMPS

The flow pumps that were used are the commercially available pumps shown in Figure 1 from The Harvard Apparatus Co., South Natick, Massachusetts. (Use of trade names in this report is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey.) These pumps are about 70 cm long, 20 cm wide, and 20 cm tall. One pump has a single carriage in which a cross member, known as a "saddle," moves in either direction by means of a worm gear that is driven by a variable-speed direct-current motor through a transmission box with 12 combinations of gears between the worm gear(s) and the motor. The other pump has two carriages whose worm gears are driven by the same motor and transmission box. In the dual-carriage pump, the saddles move at the same rate in either the same direction or in opposite directions. In both pumps, a speed controller on the direct-current motor governs rotation of the worm gears at speeds between those determined by the gear selector. These features enable the saddles to be advanced or withdrawn at any constant rate ranging from about 10^{-1} to 10^{-6} cm/sec.

These pumps are often called "syringe" pumps because they were initially designed to move the piston of a syringe with the saddle while the syringe barrel was held stationary within the carriage. A syringe of any size can be used, provided that it is not too large for the carriage. Hamilton gas-tight syringes that consist of precision-bore glass barrels and pistons with Teflon seals and stainless-steel syringes fabricated by a local machinist were used. Actuators that have advantages over syringes also were used (Figure 2). The top design (*A*), introduced by Olsen et al. (*2*), features a stepped shaft that has two diameters so that the flow rate is proportional to the difference between the cross-sectional areas where the diameter changes. With this design, the differential area that generates flow can be much smaller than the area of a piston in a conventional syringe. The middle design (*B*), introduced by Aiban and Znidarcic (*3*), has a shaft that is sealed in a piston guide block instead of in the cylinder barrel. This design is more rugged and easier to deair than a conventional syringe.

FIGURE 1 Single-carriage (top) and dual-carriage (bottom) flow pumps.

The bottom design (*C*), introduced here, provides a means to simultaneously infuse and withdraw at identical rates. This design is also rugged and easy to deair. In addition, it provides a means to minimize the force imposed on the saddle from the piston of a conventional syringe when the fluid pressure is elevated. In the bottom design (*C*) in Figure 2, the force on the saddle is proportional to the difference between the inflow and outflow pressures, which is generally small, on the order of a few psi or less. In contrast, for design *B* and for conventional syringes, the force on the saddle is proportional to the pore pressure, which is commonly elevated to 50 psi or greater.

Figure 3 illustrates that flow rates ranging from about 10^{-7} to greater than 10^{-1} cm^3/sec can be obtained with the flow pumps in Figure 1 when equipped with syringes having inside diameters of 0.05 in. (0.127 cm) to 2 in. (5.08 cm). The corresponding range of cross-sectional areas can also be obtained with the actuator designs in Figure 2. The horizontal axis shows transmission gear settings ranging from 1 to 12 and the resulting velocities of the saddle that pushes or pulls a syringe piston. The curves extend to the left of gear setting 12 to the velocity obtained with a gear setting of 12 while the speed controller on the variable speed motor is set at 10 percent of its full range. For each gear setting, the saddle velocity varies directly with the speed controller setting. According to the manufacturer's specifications, the system delivers flow rates accurate to within 2 percent and with a reproducibility of 0.5 percent.

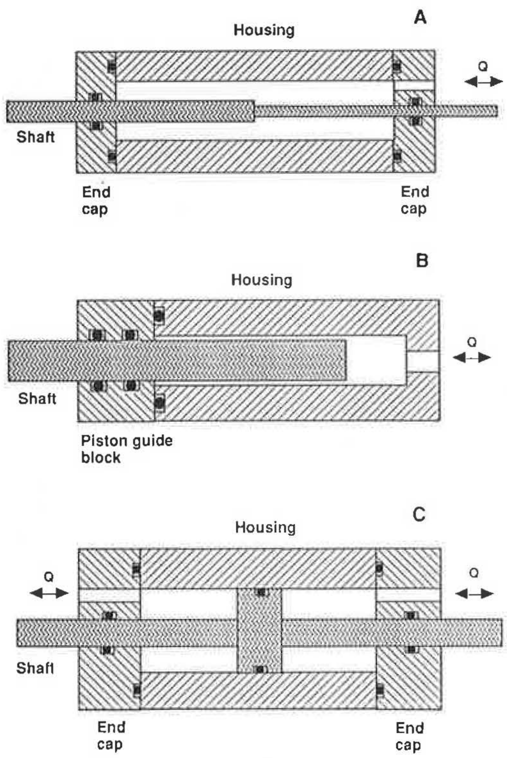

FIGURE 2 Flow pump actuator designs with advantages over conventional syringes: (*A*) the stepped shaft, (*B*) the piston guide block, and (*C*) the symmetry of the shaft and housing on either side of the central part of the shaft that is sealed to the housing with an O-ring.

STRESS-CONTROLLED SPECIMENS IN CONSOLIDOMETER AND TRIAXIAL SYSTEMS

The constant-flow method was introduced during the mid-1960s (*4–6*) in fundamental studies of the laws and mechanisms governing pore-fluid movement in kaolinite. The test cell was a one-dimensional consolidometer wherein the specimen was rigidly confined in a cylindrical sleeve and between two hydraulically controlled pistons.

Beginning in the late 1970s, applications of the constant-flow method for stress-controlled specimens in one-dimensional consolidometers and triaxial cells expanded in both research and practice (*2,3,7–14*). In most of these applications, a constant rate of flow through one end of a test specimen has been generated with a flow pump while flow through the opposite end of the specimen moved to or from a pressure-controlled reservoir, as illustrated in Figure 4. In both systems a flow pump (*P*) infuses or withdraws fluid across one end of the specimen (*S*) while flow across the opposite end moves to or from a pressure-controlled reservoir (*R*). A differential pressure transducer (*M*) monitors the induced pressure difference across the specimen. In the consolidometer (top), a linear variable differential transformer (LVDT) (*K*) monitors the

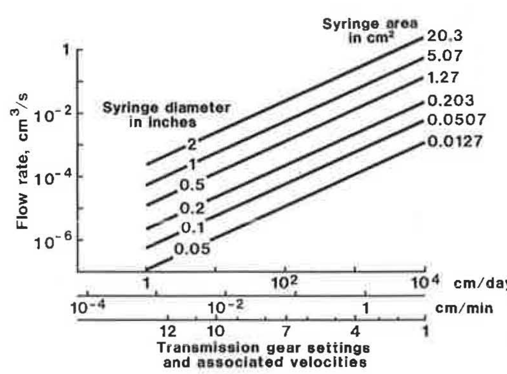

FIGURE 3 Flow rates that can be generated by the flow pumps in Figure 1.

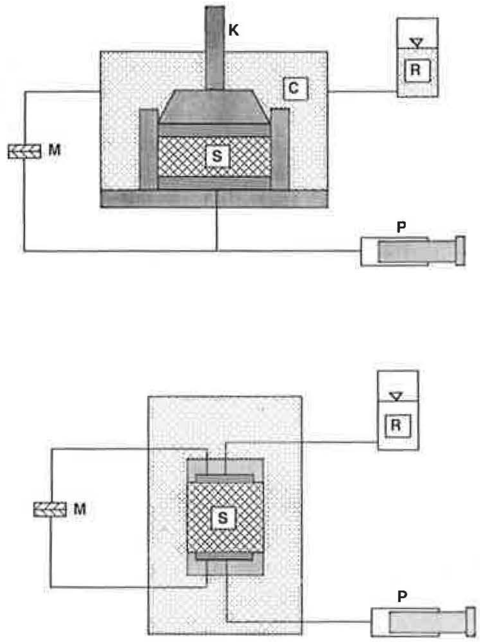

FIGURE 4 Diagrams of a back-pressured one-dimensional consolidometer (top) and a triaxial cell (bottom) equipped for constant-flow hydraulic-conductivity measurements on stress-controlled specimens.

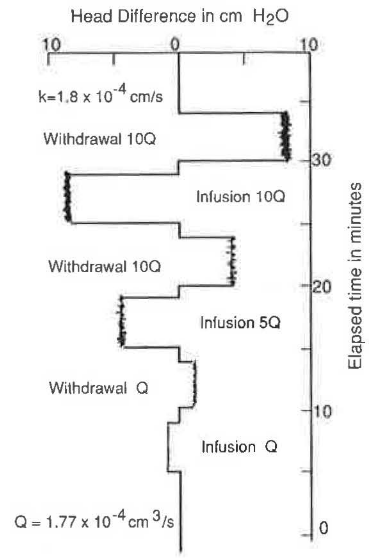

FIGURE 5 Constant-flow hydraulic-conductivity data on a sand specimen under stress control in a triaxial system like that illustrated in Figure 4.

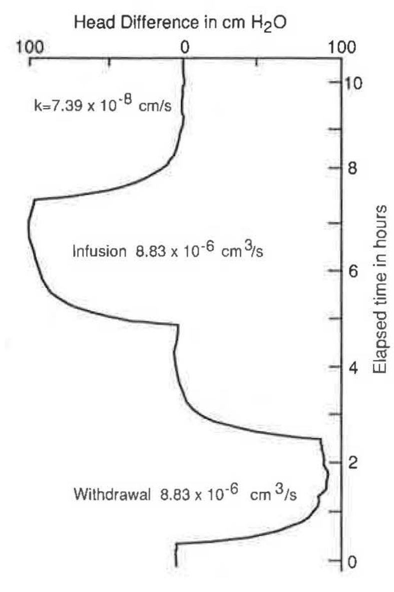

FIGURE 6 Constant-flow hydraulic-conductivity data on a clay specimen under stress control in a triaxial system like that illustrated in Figure 4.

specimen thickness, and flow between the sample (S) and the reservoir (R) passes through the back-pressure chamber (C).

Hydraulic-conductivity measurements have been conducted following increments of one-dimensional consolidation in consolidometers and three-dimensional consolidation in triaxial cells. For these systems, the demonstrated capabilities of the constant-flow method and its advantages over constant-head and falling-head methods are as follows.

Constant-flow test data for sand and silty-clay specimens in a triaxial system (like that illustrated in Figure 4) are shown in Figures 5 and 6. Figure 5 shows that the response time for sand is short and that small head differences across the specimen (on the order of a few centimeters of water or less) can be measured with both high resolution and accuracy, even though some noise appears in the measured head differences as a result of fluctuation in flow rates from mechanical sources within the flow pump. In contrast, Figure 6 shows that the response time for clays can be substantial. Moreover, the measured head difference across a clay specimen includes a small head difference (on the order of a few millimeters of water) which is present during the zero flow condition.

Experience shows that residual head differences are not uncommon and that they can vary somewhat with time. Their causes may include variations in room temperature with time, internal pressure gradients caused by variations in the degree of saturation, and geochemical sources of osmosis within a specimen (*15*). The practical significance of these small differences is that they can be a source of experimental error that limits the sensitivity of the constant-flow method for low-gradient hydraulic-conductivity measurements on clays. Nevertheless, the constant-flow method allows tests on clays to be run at much lower hydraulic gradients than can be accomplished with conventional constant-head and falling-head methods in a reasonable period of time.

Regarding the response time (the time required to reach steady state after beginning or ending a period of flow through a specimen), its cause was recognized to be seepage-induced consolidation in constant-head tests more than 20 years ago (*16–18*). For example, Al-Dhahir and Tan (*17*) showed how Terzaghi's (*19*) governing equation for one-dimensional consolidation can be used, with analogous heat conduction theory from Carslaw and Jaeger (*20*), to interpret the coefficient of

consolidation from the initial transient phase of a constant head test. For a constant-flow test, the response time can be similarly described with analytical solutions in work by Carslaw and Jaeger (*20*), and the coefficient of consolidation can be interpreted therewith on data from either the initial or the final transient phases of a constant-flow test (*12,13*). However, this approach for interpreting the coefficient of consolidation should be used with caution because undissolved air and other sources of compliance in the specimen and permeant system will be sources of error in the interpretation of the coefficient of consolidation.

The practical significance of the response time is that it is a measure of the time required to carry out a constant-flow hydraulic-conductivity test, and this time is much shorter than that required for conventional constant-head and falling-head tests because the latter depends on the time required for a measurable quantity of flow through the specimen. In addition, because the response time is governed by the consolidation process, it varies with the square of the drainage path and therefore can be shortened substantially by reducing the height of a specimen.

When large gradients are externally imposed or induced across compressible specimens under stress control in consolidometers or triaxial cells, seepage-induced volume changes can be of sufficient magnitude to cause substantial errors in hydraulic-conductivity measurements. Pane et al. (*9*) summarized the advantage of the constant-flow method for minimizing this error as follows: "In using conventional tests one is faced with a paradox. The use of high gradients reduces the time of testing but introduces substantial errors in the test results. However, the use of low gradients extends the testing time to unacceptable limits. The flow pump test [constant-flow method] solves both these problems."

It should be recognized that although errors from seepage-induced volume changes can be readily minimized with the constant-flow method, they cannot be avoided entirely. Pane et al. (*9*) concluded, "If the clay is very soft and normally consolidated, even the lowest gradients can cause significant seepage consolidation." They further suggest that to minimize induced errors, "The gradients must be such that the seepage-induced effective stresses are substantially less than the maximum past effective stress." In this regard, recent work by Aiban and Znidarcic (*3*) is of particular interest because it shows small discrepancies between hydraulic-conductivity values obtained with constant-flow and constant-head methods that are clearly attributable to seepage-induced volume changes even though the magnitudes of the discrepancies are negligible for most practical applications.

CONTROLLED INFLOW AND OUTFLOW RATES IN TRIAXIAL SPECIMENS

Recently the new infuse/withdraw actuator (Figure 2*C*) has been used in the triaxial systems illustrated in Figure 7. In both systems the infuse/withdraw actuator, which is mounted in a single-carriage flow pump, generates identical flow rates through opposite ends of the specimen while the pressure differences across the specimen and between the pore fluid and chamber fluid are monitored with differential transducers (*M* and *N*). Both systems also have a second single-carriage flow pump (*C*), equipped with a stainless steel syringe, that provides a means to control the chamber fluid pressure. The use of a flow pump for controlling the chamber fluid pressure is an alternative to the bellofram and air-pressure regulator that control the chamber fluid pressure in the more conventional triaxial system in Figure 4.

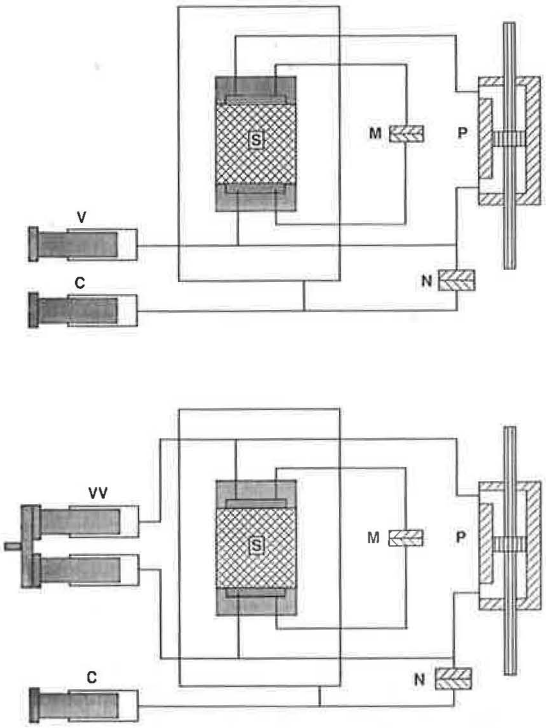

FIGURE 7 Triaxial cells equipped with one flow pump (*P*) that infuses and withdraws identical rates of flow across opposite ends of a specimen (*S*), differential transducers (*M* and *N*) that measure the pressure difference across the specimen (*M*) and the pressure difference between the pore fluid and the chamber fluid (*N*), and additional flow pumps for controlling the chamber fluid pressure (*C*) and the effective stress or the volume of a test specimen (*V* and *VV*).

The systems in Figure 7 each have a third flow pump for controlling the volume of pore fluid in the specimens. In the upper system pore fluid is transmitted to or from one end of the specimen with one stainless steel syringe mounted in a single-carriage flow pump. In the lower system, pore fluid is transmitted to or from both ends of the specimen simultaneously with identical stainless steel syringes mounted in a dual-carriage flow pump. In both systems, the third pump provides a means to vary the effective stress or volume of the specimen continuously and to superimpose hydraulic-conductivity measurements on this process. The systems differ in the lengths of their drainage paths for consolidation or rebound of the specimen.

Data obtained with the upper system in Figure 7 on a 2-in. (5.08-cm) diameter by 1-in. (2.54-cm) thick specimen of sandstone from the Michigan Basin are shown in Figure 8. The bottom plot shows the effective stresses applied to the specimen versus time. The middle plot shows the hydraulic conductivity values obtained during each loading step. The

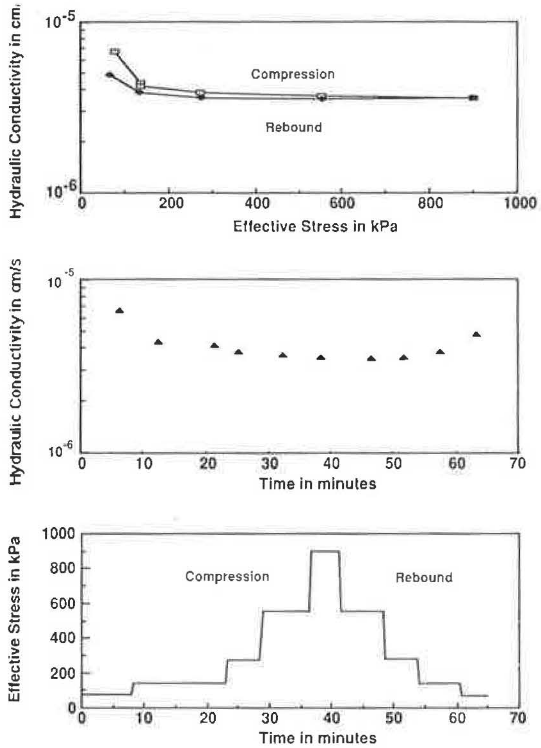

FIGURE 8 Time history of loading (bottom) and hydraulic-conductivity measurements (middle) on a specimen of sandstone from the Michigan Basin in triaxial system illustrated in Figure 7 (top); hydraulic-conductivity versus effective stress relationshp from data in the middle and bottom plots (top).

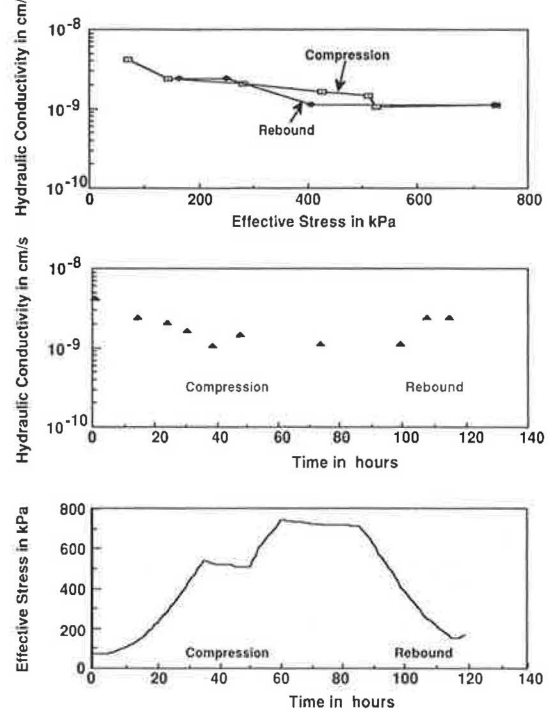

FIGURE 9 Time history of loading (bottom) and hydraulic-conductivity measurements (middle) on a shale specimen in the triaxial system illustrated in Figure 7 (top); hydraulic-conductivity versus effective stress relationship from data in the middle and bottom plots (top).

top plot shows the variation of hydraulic conductivity with effective stress. Ten hydraulic conductivity determinations were obtained after each 9 changes in effective stress in about 1 hr. Note that the hydraulic conductivity is relatively high at low effective stresses, even though the sandstone specimen appeared to be rigidly cemented. The variation of hydraulic conductivity with effective stress in these samples is presumed to reflect the behavior of cracks in the specimen, instead of changes in the permeability of its matrix.

Data obtained with the lower system in Figure 7 on a 4-in. (10.16-cm) diameter by 1-in. (2.54-cm) thick specimen of shale from Oklahoma are presented in Figure 9, using the format in which the data on the sandstone specimen were presented in Figure 8. The bottom plot of Figure 9 shows the effective stress first increased continuously in two steps, each followed by a period of nearly constant effective stress. These steps were accomplished by using the dual-carriage flow pump to withdraw pore fluid from the ends of the specimen at identical rates. During the periods following each step, the flow pump was shut off. Following the latter period, the effective stress was decreased continuously by infusing fluid into the ends of the specimen with the dual-carriage flow pump. The middle plot of Figure 9 shows hydraulic-conductivity measurements obtained both during and between the time intervals when the specimen was being continuously loaded and unloaded.

Finally, the top plot shows the variation of hydraulic conductivity with effective stress derived from the data in the middle and lower plots. Note that the hydraulic conductivity is extremely low, on the order of 10^{-9} cm/sec, and 10 hydraulic-conductivity measurements were obtained over a range of effective stresses in about 125 hr or 6 days. The response times for the hydraulic conductivity measurements were on the order of 1 to 2 hr. It is noted that high pore fluid pressures were needed to obtain response times of this magnitude. Apparently, the high pressures were needed to drive all the undissolved air in the pore fluid into solution. A flow pump was used to infuse or withdraw fluid from the triaxial chamber, and the plastic cylinder in the triaxial chamber was replaced with a stainless steel cylinder, resulting in pore pressures elevated to more than 300 psi.

VOLUME-CONTROLLED SPECIMENS IN ONE-DIMENSIONAL CONSOLIDOMETERS

Beginning with an Anteus backpressured one-dimensional consolidometer, Gill (*21*) used two flow pumps to conduct constant-flow hydraulic-conductivity measurements during constant-rate-of-deformation (CRD) consolidation tests, as illustrated in Figure 10. One pump (*F*) transmits fluid to the load pressure chamber (*L*) and thereby provides a means to consolidate a test specimen (*S*) at a constant rate of volume change, which is commonly referred to as a CRD test. The second flow pump (*D*) controls pore-fluid movement across the base of the specimen and thereby provides a means to

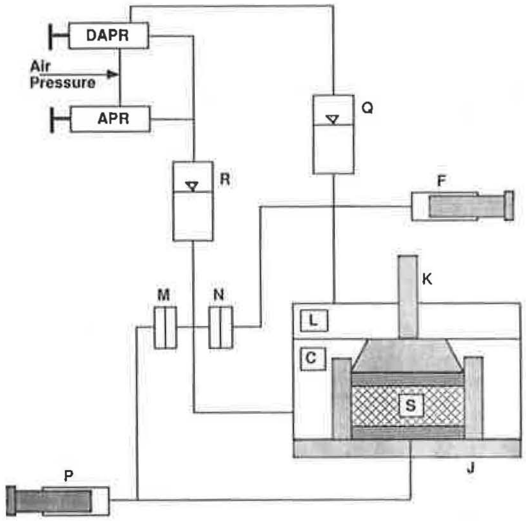

FIGURE 10 Diagram of a back-pressured consolidometer (*J*) equipped for constant-flow hydraulic-conductivity measurements on a volume-controlled specimen (*S*).

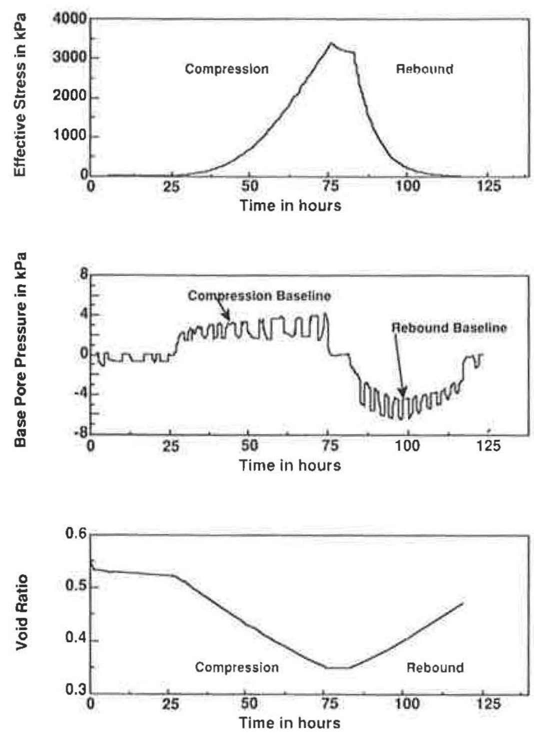

FIGURE 11 Time history of simultaneous constant-flow hydraulic-conductivity and continuous-loading compressibility measurements in the one-dimensional consolidometer illustrated in Figure 10; constant-flow hydraulic-conductivity tests are designated as *k*-tests.

conduct constant-flow hydraulic-conductivity tests simultaneously with a CRD consolidation test.

For a conventional CRD test, the second flow pump (*P*) is shut off so as to maintain zero flow across the lower boundary of the specimen while the pore fluid expelled from the sample during consolidation flows into the back-pressure chamber (*R*) and then to the bellofram, where the pressure in the back-pressure chamber (*R*) is externally controlled by the absolute pressure regulator. The sample thickness is monitored with an LVDT (*K*). The effective stress at the top of the specimen, which is proportional to the pressure difference between the load pressure chamber (*L*) and the back-pressure chamber (*R*), is monitored with one differential pressure transducer (*N*). The pore-pressure increase at the base of the specimen resulting from the consolidation process is monitored relative to the back pressure with the other differential pressure transducer (*M*). APR and DAPR are air pressure and differential air pressure regulators, respectively. DAPR and the back-pressure chamber (*Q*) provide a means to apply an initial seating load on the specimen.

The conventional CRD test just described can be modified by periodically using the second flow pump (*P*) to superimpose an arbitrary constant flow rate through the consolidating specimen. Hydraulic-conductivity values are obtained from the components of the pore-pressure difference across the sample that are induced by the superimposed constant-flow rates. Thus, direct measurements of hydraulic conductivity can be obtained during a CRD test.

Data obtained with this approach on an undisturbed specimen of silty clay from Maryland having 30 percent finer than 2μ and a plasticity index (PI) of 33 percent are presented in Figure 11 (*21*). The specimen was first equilibrated under a small and constant seating load for more than 25 hr. The void ratio initially decreased slightly and then remained almost constant. Hydraulic conductivity was measured periodically by withdrawing pore fluid from the base of the specimen at a constant rate and monitoring the induced pore-pressure changes at the base of the specimen. Following this initial period, the specimen was consolidated at a constant rate of deformation until the total elapsed time reached about 75 hr. The top graph shows the buildup of vertical effective stress with time, and the middle graph shows the consolidation-induced pore pressure at the base of the specimen, designated as the "compression baseline." Superimposed hydraulic conductivity tests (*k*-tests) are reflected in periodic changes in base pore pressure from the compression baseline that were induced by withdrawing pore fluid from the base of the sample at a constant rate. When compression was terminated, the base pore pressure returned to zero, and the vertical effective stress decayed somewhat, as a result of secondary compression. During rebound, the effective stress decreased with time [Figure 11 (top)], and the rebound-induced change in base pore pressure, designated as the rebound baseline in Figure 11 (middle), was negative. The changes in base pore pressure induced by superimposed constant-flow hydraulic conductivity tests were clearly evident. Void ratio, specific storage, and hydraulic conductivity versus effective stress relationshps are shown in Figure 12 for the test data in Figure 11. Specific storage is a measure of compressibility that is calculated from the slope of the void-ratio versus effective-stress relationship. Specific storage and hydraulic conductivity values were obtained concurrently and independently from direct measurements, whereas, by using conventional consolidation testing methods, hydraulic conductivity can only be obtained indirectly from coefficient-of-consolidation measurements or di-

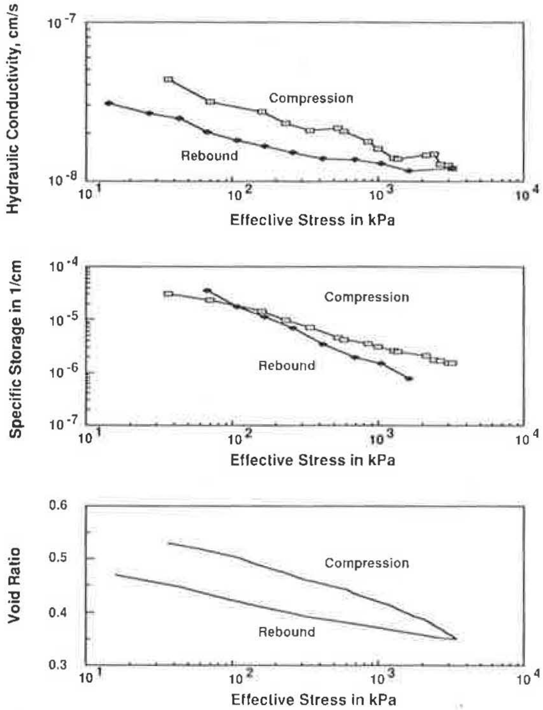

FIGURE 12 Hydraulic conductivity, specific storage, and void ratio versus effective stress for the test data in Figure 11.

rectly between consolidation increments. Finally, note that the duration of the combined test is not affected by the frequency and duration of hydraulic conductivity tests. The total elapsed time is governed solely by the deformation rates used for consolidating and rebounding the specimen.

VOLUME-CONTROLLED SPECIMENS IN TRIAXIAL SYSTEMS

CRD-consolidation and constant-flow hydraulic conductivity tests can also be integrated in the triaxial systems illustrated in Figure 7, provided that the specimens are fully saturated. Volume changes generated by infusing or withdrawing fluid to or from the ends of the specimen can be calculatd from the flow rates and time intervals employed. The total specimen volume is not affected by hydraulic conductivity measurements because the inflow and outflow rates are identical. With a system having the capabilities illustrated in Figure 7 (top), the data in Figure 13 were obtained for a specimen of Standard Air Floated (SAF) clay that is marketed by the Georgia Kaolin Company. The specimen was molded from a slurry having a water content of about 110 percent. The slurry was prepared by absorption of distilled and deaired water by dry clay powder under vacuum in a dessicator. To form the specimen, the slurry was poured into a cylinder 5.08 cm in diameter × 10 cm in length, whose base was capped by a porous stone and submerged under water in a bucket. A porous stone and a piston were placed on the slurry at the top of the cylinder. The entire assembly was mounted in a loading press, where the sample was consolidated slowly at a constant rate of deformation to a predetermined volume that

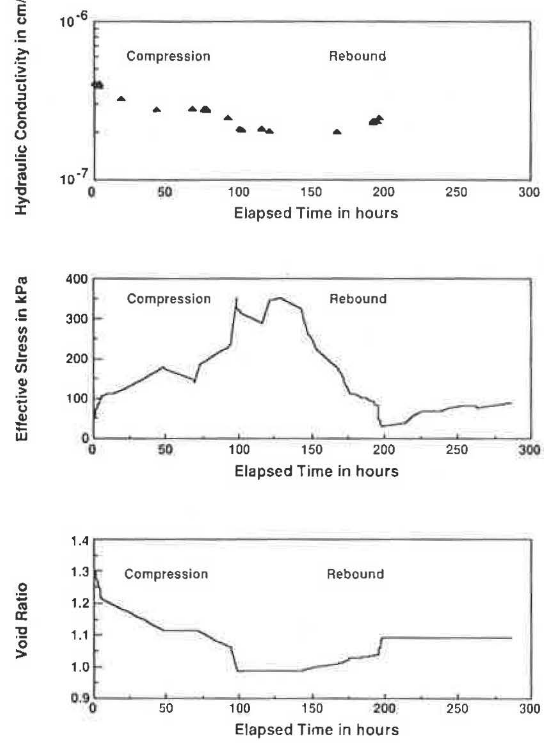

FIGURE 13 Time history of hydraulic conductivity (top), effective stress (middle), and void ratio (bottom) data obtained during simultaneous constant-flow hydraulic-conductivity and continuous-loading compressibility measurements on a kaolinite specimen in the triaxial system illustrated in Figure 7 (top).

would yield a loosely consolidated specimen with sufficient strength to be trimmed and mounted in a triaxial cell. Finally, the material was extruded from the cylinder, cut to a convenient length (about 3 cm), jacketed with impermeable membrane, and mounted in the triaxial cell between the base pedestal and top cap.

The data in Figure 13 show constant-flow hydraulic-conductivity and continuous-loading consolidation measurements on a triaxial test specimen. These data are similar to those illustrated for the one-dimensional consolidometer in Figure 11 in that the duration of the combined test is not affected by the frequency and duration of hydraulic conductivity tests. The total elapsed time is governed solely by the deformation rate used for consolidating and rebounding the specimen.

These measurements began after the specimen had been equilibrated to a void ratio of 1.305 under an effective stress of 34.5 kPa. Several flow rates were used to consolidate the specimen with the single-carriage pump, as reflected in different slopes of the void-ratio versus time relationship. This procedure was done to explore the behavior of the experimental system, whereas a constant rate of deformation is needed to obtain consolidation data applicable in practice. The effective-stress values are differences between the chamber pressure and the pore pressure at the base of the specimen. Hydraulic-conductivity measurements were obtained during the course of consolidation or rebound, generated by the

single-carriage pump, by superimposing flow through the specimen with the infuse/withdraw pump and measuring the head difference induced thereby. Some of the relationships that are readily obtained from these data are presented in Figure 14. It should be recognized that the significance of these relationships may be limited because the rate of volume change used to consolidate the specimen was not constant.

SUMMARY AND CONCLUSIONS

The fundamental advantage of the constant-flow method compared with conventional constant-head and falling-head methods is that hydraulic conductivity measurements can be obtained much more rapidly and at substantially smaller hydraulic gradients. This advantage was first exploited in the mid-1960s for fundamental research studies on rigidly confined specimens in one-dimensional consolidometers. Beginning in the late 1970s, applications of the constant-flow method have been expanding in both research and practice. In most applications to date, hydraulic-conductivity tests have been conducted following conventional loading increments in one-dimensional consolidometers and following increments of three-dimensional consolidation in triaxial cells.

More recent innovations include a new flow-pump actuator that enables identical flow rates to be infused and withdrawn across opposite ends of a test specimen and the use of additional flow pumps to control the effective stress or the volume of a test specimen. These innovations provide a convenient approach for obtaining hydraulic conductivity versus effective stress data in triaxial cells on a wide variety of materials, including sandstones and shales that cannot be trimmed and mounted in either fixed-ring permeameters or one-dimensional consolidometers.

In addition, these innovations provide a means to integrate constant-flow hydraulic conductivity measurements with continuous-loading consolidation tests on fully saturated specimens in both back-pressured consolidometers and in triaxial cells. This combined approach inherits the individual advantages of the constant-flow hydraulic-conductivity and continuous-loading consolidation methods compared with conventional incremental loading, constant-head, and falling-head methods. The hydraulic gradients induced during consolidation and those involved in hydraulic-conductivity measurements are small; a specimen can be consolidated at a constant rate of deformation; and both tests can be run far more quickly than the conventional alternatives. Another advantage of the combined methods is that direct measurements of both hydraulic conductivity and compressibility can be obtained while the specimen is being consolidated at any constant rate of deformation. This avoids the minimum deformation rate required in a CRD test to elevate the pore pressure at one end of the specimen by an amount sufficient for interpreting coefficient-of-consolidation or hydraulic-conductivity values or both. Finally, the time required for a combined test is governed solely by the selected deformation rate; hydraulic-conductivity measurements can be obtained as frequently as desired without affecting the duration of the test.

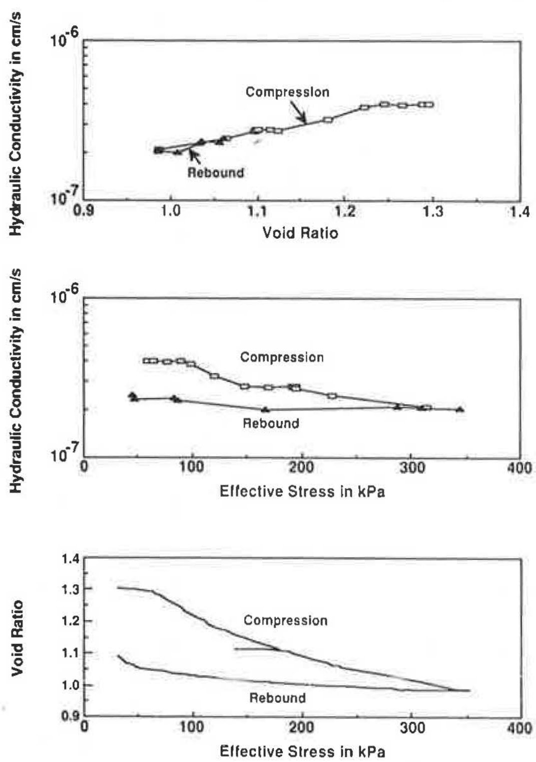

FIGURE 14 Void ratio versus effective stress (bottom), hydraulic conductivity versus effective stress (middle), and hydraulic conductivity versus void ratio (top) relationships for the test data in Figure 13.

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