Time-Lags in Pore Pressure Measurements

Le facteur temps dans les mesures de pression interstitielle

by R. V. Whitman, Associate Professor of Soil Engineering
and
A. M. Richardson, Jr., Research Assistant ; K. A. Healy, Research Assistant; Massachusetts Institute of Technology, Cambridge, U.S.A.

Summary

This paper is concerned with the effect of a non-rigid pore pressure measuring system upon the pore pressures measured during consolidation tests. An electrical analog is used to develop curves showing the influence of measuring system flexibility. Results obtained earlier at M.I.T. are reviewed to ascertain the possible effects of system flexibility upon the data. A new measuring system is described which has a very rapid response time, and which should be extremely useful for measuring pore pressures in triaxial tests.

Sommaire

Le principal but de cet article est de considérer les effets de la déformabilité des systèmes de mesure des pressions interstitielles durant les essais de consolidation. L'auteur a utilisé une analogie électrique pour arriver à des courbes qui montrent l'influence de la déformabilité des dispositifs de mesure. Il reprend des essais antérieurs faits à M.I.T. pour déterminer les effets possibles de la déformation du système sur les résultats. Un nouveau système de mesurage est décrit qui a un temps de réponse très rapide, et qui devrait être extrêmement utile pour mesurer les pressions interstitielles dans les essais triaxiaux.

The need to measure pore pressure as clay is sheared by applied loads has prompted the M.I.T. Soil Engineering Laboratory staff to take a hard look at the problem of time-lags in pore pressure measuring systems. For two reasons, it has proved desirable to begin with a study of pore pressures within samples undergoing consolidation. First, the development of a pore pressure measuring system with a response time of one second or less is a very difficult problem, and past difficulties with such systems rightly give rise to skepticism concerning any claim of rapid response times. The consolidation tests provide a method for proving such claims. Second, the possible effect of structural viscosity upon excess pore pressures and hence upon strength is of considerable interest. The measurement of pore pressure during consolidation tests provides another means for proving or disproving the existence of such a phenomenon.

Factors affecting measured pore pressures

Figure 1 shows a simple hydromechanical device which models the conditions existing during a consolidation test

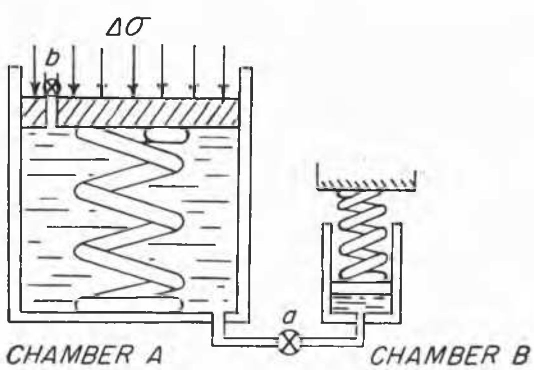

Fig. 1 Hydromechanical analogy.
Analogie hydromécanique.

with drainage at the top surface of the sample and with pore pressures measured at the bottom surface. Chamber *A*, with its spring and two throttle valves *a* and *b*, corresponds to the soil sample in the œdometer. Chamber *B*, with its spring, corresponds to the measuring system. In the following, Δu_A denotes the pore pressure which would exist at the base of a sample if there were no measuring system, and Δu_B denotes the pore pressure as measured.

According to the usual picture of soil behavior, a stress increment $\Delta\sigma$ applied instantaneously to a saturated clay within an œdometer instantaneously produces a pore pressure of equal magnitude; i.e. $\Delta u_A = \Delta\sigma$. Frequently, however, the maximum recorded pore pressure Δu_B is less than $\Delta\sigma$. Assuming that the soil is actually saturated and that there is no side friction within the œdometer, such a result must be caused by one or both of the following :

(a) *Excessive flexibility in the measuring system* : such flexibility has two effects :

(1) It alters the overall compressibility of the pore phase, and hence changes the distribution of total stress between mineral skeleton and pore phase.

(2) It leads to a time-lag in the response of the measuring system, and, since Δu_A changes with time as the soil consolidates, to an error in measuring Δu_A.

(b) *Mineral skeleton of low compressibility* : Interparticle bonding, structural viscosity, and very tight packing of particles are possible reasons why the stiffness of the mineral skeleton might approach that of water.

If Δu_B is less than $\Delta\sigma$, the problem is to decide whether the cause is real (stiff mineral skeleton) or extraneous (flexibility in measuring system). In order to make this decision, there is need for a clear picture of the effect of measuring system flexibility.

Pore pressures during undrained compression

Consider a stress $\Delta\sigma$ applied with valves *a* and *b* both closed. If the ratio of the compressibility of the fluid filling chamber A to the compressibility of the spring is sufficiently small, the entire $\Delta\sigma$ will be carried by an increase in the fluid pressure inside the chamber : i.e. $\Delta u_A = \Delta\sigma$. If valve a is now opened, flow will occur into chamber B until the pressures in the two chambers are equalized. The time required for any level of pressure to be reached in chamber B is a function of the "permeability" of valve a and of the stiffness of the two springs. A typical curve of Δu_B versus time is shown in Fig. 2 (a). The final equilibrium pressure is given by the following expression :

$$\frac{\Delta u_B}{\Delta u_A} = \frac{1}{1 + B} \qquad (1)$$

$B = G/AHm_v$
m_v = coefficient of compressibility (in²/lb.)
G = flexibility of the measuring system (in³ per lb/in²)
H = thickness of sample (in.)
A = area of oedometer (in²)

Typical values, assuming a test on an overconsolidated clay, are :

$H = 0{\cdot}5$ in. $\qquad m_v = 0{\cdot}001$ in²/lb.
$A = 10$ in². $\qquad G = 5 \times 10^{-5}$ in³ per lb/in².

The compliance value of G is that for a good laboratory null balancing system, thoroughly deaired and employing metal tubing. From these numbers, $B = 0{\cdot}01$. Thus, with commonly expected m_v values, a $\Delta u_B/\Delta\sigma$ of essentially unity can be recorded with a standard measuring system. Even a modest amount of air in the measuring system will not introduce great error. The presence in the above system of a bubble 0·1 inches in diameter will increase B only to 0·014.

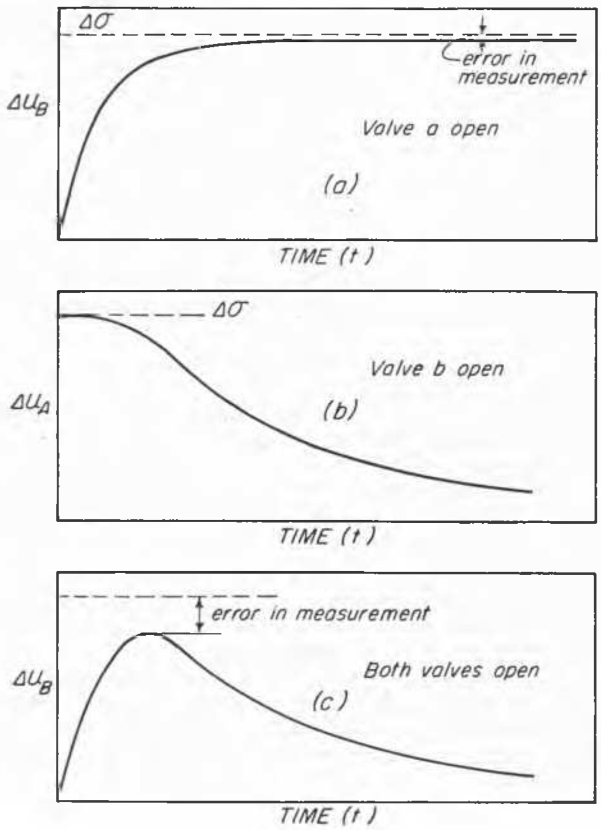

Fig. 2 Typical curve of pore pressure vs. time.
Relation type de la pression interstitielle par rapport au temps.

Now suppose that, for some reason, the mineral skeleton is quite stiff. For example, if $m_v = 2 \times 10^{-5}$ in²/lb., which is about five times the compressibility of water, then $\Delta u_A/\Delta\sigma = 0{\cdot}83$. Using the values of A, H and G given above : $B = 0{\cdot}5$ and $\Delta u_B/\Delta u_A = 0{\cdot}67$, which means that the recorded pressure is much less than the actual pressure. Actually equation (1) will no longer quite apply, since the compressibility of the water within the sample must be considered. It is clear, however, that even a good laboratory null balancing system will be inaccurate if indeed m_v does have extraordinarily low values.

Pore pressures during drained compression (Consolidation)

If, after $\Delta\sigma$ has been applied with both valves closed, valve b is opened, consolidation will occur. A plot of Δu_A versus time would be similar to Fig. 2 (b). If, however, after the application of $\Delta\sigma$, both valves are opened, Δu_B will depend upon a combination of the two effects previously described, with the result illustrated in Fig. 2 (c).

The theoretical determination of a curve such as that shown in Fig. 2 (c) involves the solution of the one-dimensional consolidation equation :

$$c_v \frac{\delta^2 u}{\delta z^2} = \frac{\delta u}{\delta t} \qquad \ldots\ldots (2)$$

with the following boundary condition at the base of the sample :

$$\Delta u_B = \frac{1}{G} \frac{Ak}{\gamma_w} \int_0^t \frac{\delta u}{\delta z} \, dt \qquad (3)$$

An approximate solution of this equation was obtained using the ten lump electric analogue illustrated schematically in Fig. 3. The system was charged by applying a voltage across

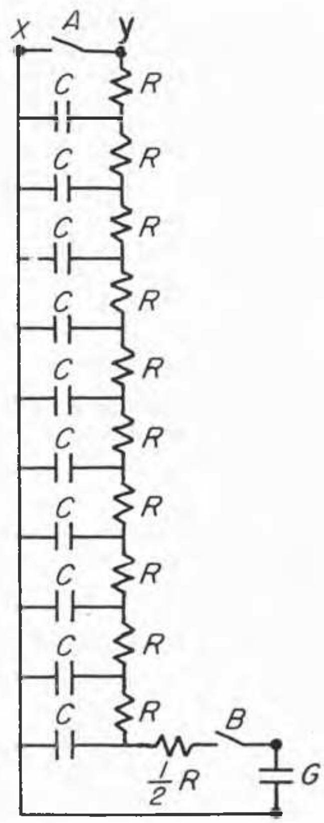

Fig. 3 Electrical analogy.
Analogie électrique.

points x and y with switches A and B open. Switches A and B were then closed simultaneously, and the voltage across condenser G was recorded as a function of time. The capacitance of G is analogous to the compliance of the measuring system and the voltage across G is analogous to Δu_B. Solutions obtained in this manner are plotted in dimensionless form in Fig. 4, which shows $\Delta u_B/\Delta u_{A_0}$ as a function of the average consolidation ratio for the sample as a whole, where Δu_{A_0} denotes the initial value of Δu_A. These solutions are based on the assumption that m_v is the same for both consolidation and rebound. This assumption is reasonable in the case of overconsolidated soils, and the error resulting from this assumption tends to decrease the calculated response time of the measuring system in normally consolidated soils. Therefore, if the curves of Fig. 4 are used in the design of a measuring system, a conservative indication of its performance will be obtained.

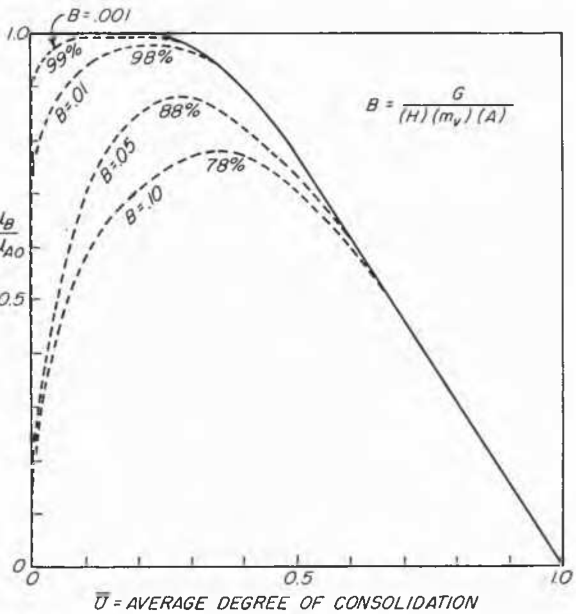

Fig. 4 Effect of measuring system compliance upon measured pressures.
Effect de la déformabilité des systèmes de mesure sur les pressions mesurées.

During undrained compression, the time-lag did not affect the peak value of Δu_B — only the time required to achieve this peak value. Now, however, the time-lag in the measuring system is important, for Δu_A is time variant. The effect of the lag is revealed by the following tabulation :

B	max. $\Delta u_B/\Delta u_{A_0}$	
	Undrained (Eq. 1)	*Drained* (Fig. 4)
0·001	1·00	0·99
0·01	0·99	0·98
0·05	0·95	0·88
0·10	0·91	0·78

Thus, if B is much greater than 0·01, the peak measured Δu_B in a drained compression test may be much less than the actual initial Δu_A. In such a test, therefore, the presence of a modest amount of air in the measuring system may be disasterous.

Note that the permeability k and the absolute time of response of the pore pressure measuring system do not enter into the solution. It is the ratio of the response time to the consolidation time which determines the error caused by non-rigidity in the measuring system.

Past studies at M.I.T.

Taylor (1942) reported upon a comprehensive experimental investigation into the consolidation process. Pore pressures were measured through a porous stone at the bottom of the oedometer, and a null balancing system was used. The soil was remolded Boston clay. Taylor in some tests observed time patterns of overall sample compression U and pore pressure at the bottom of the sample Δu_B which did not agree with those predicted by the usual consolidation theory, and hence he developed a theory for taking into account the effects of interparticle bonding and structural viscosity. The greatest deviations from the usual theory occurred when small pressure increment ratios were used, and particularly when a sample had consolidated for a long time under the previous load increment.

Marsal (1944) continued this work, using a similar technique for measuring pore pressures, and included tests on undisturbed Boston clay. Aldrich (1951) and De Wet (1953) studied the behavior of precompressed undisturbed Boston clay, using a needle inserted at the mid-plane of the test sample for the measurement of pore pressure. These additional studies suggested that, if anything, bonding and structtural viscosity were less important in undisturbed clay than in remolded clay. Indeed, the closest agreements between experimental results and the usual theory were obtained with undisturbed samples loaded to less than the preconsolidation pressure.

The question of the validity of these data is very complex, involving the effects of side friction, incomplete saturation, and pore pressure measuring system flexibility. The work reported in the previous section provides a basis for judging the possible adverse effects of system flexibility. A few selected curves have been reproduced in Fig. 5. Curve A is very similar to the curves in Fig. 4, in that it peaks at $\Delta u_B/\Delta\sigma < 1$, but then fairs into the theoretical curve. Thus the deviation of Curve A from the theoretical curve is probably the result of measuring system flexibility. Curve B appears to show

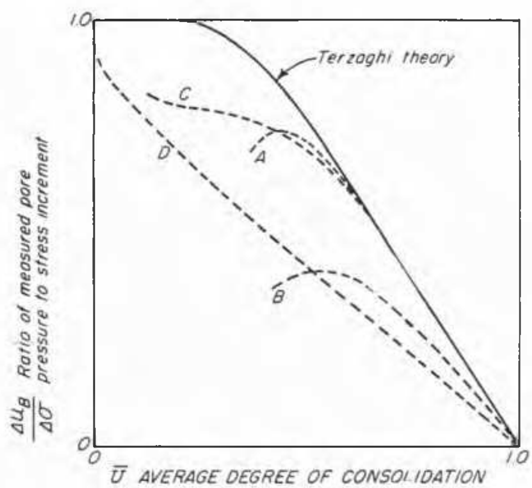

Fig. 5 Selected results from earlier work.
Résultats choisis dans les travaux antérieurs.

extremely adverse effects of system flexibility, although it does not fair into the theoretical curve as would be expected if system flexibility were the only cause of deviation from theory. It appears that the measuring system used to obtain curves *C* and *D* responded very quickly and that the deviations of these curves from theory were certainly the result of factors other than measuring system flexibility.

From this examination, it can be seen that system flexibility did influence, to a greater or lesser extent, some but not all of the pore pressure data from these investigations. It is apparent that it is dangerous to assess the agreement between theory and experimental results solely on the basis of the peak recorded $\Delta u_B/\Delta\sigma$. In some tests, $\Delta u_B/\Delta\sigma \approx 0{\cdot}6$ was recorded solely because of measuring system flexibility. On the other hand, certain tests which showed an initial $\Delta u_B/\Delta\sigma \approx 1$ (i.e. curve *D*) provided the best proof of the existence of important structural viscosity. TAYLOR paid much more attention to the final slope of the U versus $\Delta u_B/\Delta\sigma$ curve than he did to the peak value of $\Delta u_B/\Delta\sigma$. By attacking the problem this way, he and the subsequent workers showed that bonding and structural viscosity were indeed important in certain cases.

A new measuring system

Significant progress has been made toward development of an improved pore pressure measuring system using an electrical transducer. The arrangement is shown in Fig. 6. The pressure transducer was manufactured by the Dynamic Instrument Company of Cambridge, Massachusetts, and employed unbonded strain wires attached to a diaphragm. With the transducer excited at six volts, a pressure increment of 150 lb/in^2 gave an output of about twenty-four millivolts. The output of the transducer was recorded by an oscilloscope with a sensitivity of one millivolt/cm.

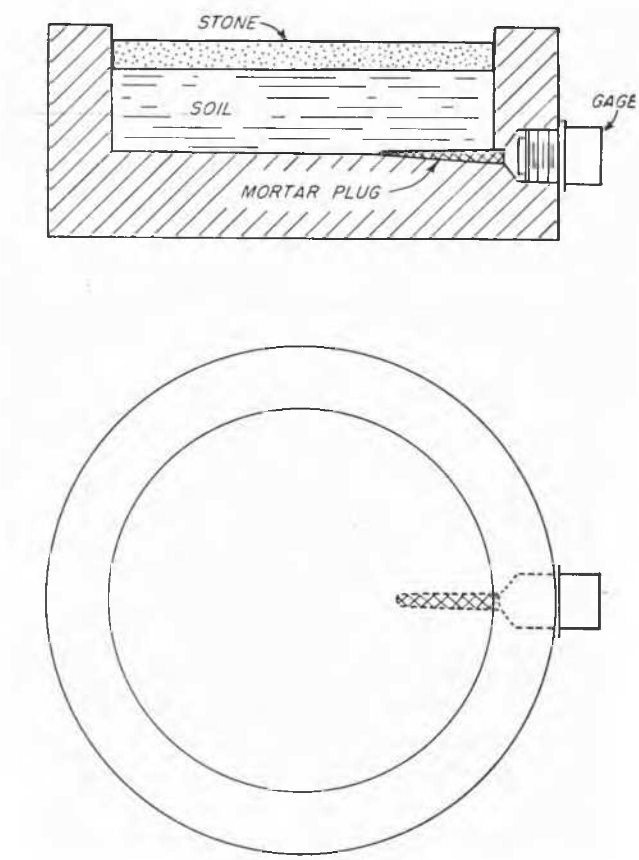

Fig. 6 New measuring system.
Nouveau dispositif de mesurage.

The flexibility of the transducer itself was 4×10^{-7} in^3 per lb/in.^{2} The compressibility of the water adjacent to the diaphragm and within the mortar increased the overall flexibility of the measuring system to 5×10^{-7} in^3 per lb/in^2. Note that little advantage would be gained from a less compliant transducer, since the stiffness of the present transducer is approaching the stiffness of the water in the measuring system and already exceeds the stiffness of the water within a test sample. The mortar was saturated by draining deaired water back and forth through it many times and the transducer was inserted while the œdometer was submerged in deaired water. The conductance of the mortar plug was measured to be $0{\cdot}74 \times 10^{-4}$ in^3/sec. per lb/in^2.

Tests have been carried out using a backswamp clay with $L_L = 70$ and $P_L = 30$. The œdometer was filled with water, and the clay in powder form spooned into the water to form thin layers. A vacuum was applied following the placement of each layer, and in this way a deaired slurry was formed. Loads were applied to the porous stone by an air-operated Karol-Warner loading frame. Fig. 7 shows typical results

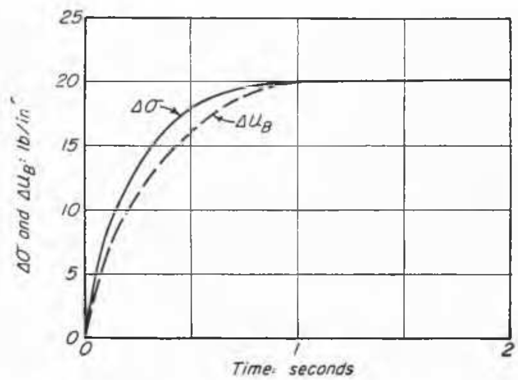

Fig. 7 Typical result for positive stress increment.
Effet type d'une augmentation de pression positive.

from such a test. A series of results for successive load increments on a single soil sample are given in Table 1. The agreement between the peak recorded pore pressure and the applied stress increment was remarkable, while the time-lag of the measuring system was on the order of only 0·1-0·2 seconds. The results of the last unloading increment are particularly

Table 1
Results using New Measuring System
Resultats employant la nouvelle méthode de mesure

Initial σ lb./in^2	$\Delta\sigma$ lb./in^2	Peak Δu_B lb./in^2	Time in seconds		Increment duration hours
			To max. $\Delta\sigma$	To peak Δu_B	
0·7	0·7	0·7	0·25	0·50	24
2·3	1·6	1·6	0·25	0·30	26
4·0	1·7	1·7	0·25	0·30	2·7
8·0	4·0	3·9	0·35	0·45	1·5
16·0	8·0	8·0	0·60	0·70	22·6
8·0	— 8·0	— 8·0	*	0·50	1·5
0·0	— 8·0	— 8·0	*	0·50	188
20·0	20·0	20·0	0·85	1·00	6
0·0	— 20·0	— 20·0	*	0·50	—

* Not recorded.

interesting, in that a pore pressure 5 lb/in^2 below absolute zero was recorded. As is shown in Fig. 8, this large negative pressure was maintained for about two seconds before cavitation occurred somewhere in the system.

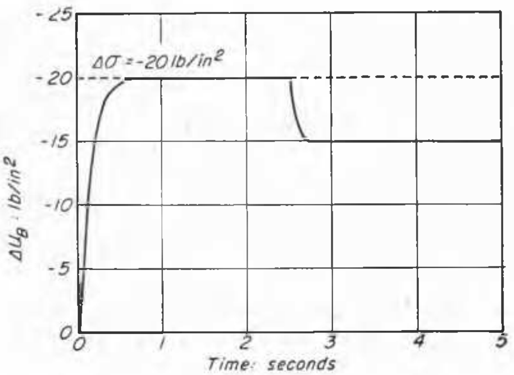

Fig. 8 Result for negative stress increment.
Résultat d'une augmentation de pression négative.

These tests in the œdometer have proved that fast, accurate response can be obtained with the new measuring system. Now the system can with confidence be used to study situations in which structural bonding or viscosity effects are thought to be important. Development of a system, employing a needle in conjunction with the transducer, to measure the pore pressure within the central zone of triaxial compression samples is already underway. Another use for the transducer is described by LAMBE (1961).

Conclusions

(a) The effect of measuring system flexibility on pore pressures measured during consolidation tests has been found from theory, thus providing design criteria for development of new and better systems. It is particularly difficult to measure pore pressures accurately whenever the stiffness of the mineral skeleton approaches that of water.

(b) Review of data obtained earlier at M.I.T. showed that the peak measured pore pressures were in some cases influenced by measuring system flexibility. When using pore pressures measured during consolidation to establish the presence or absence of effects such as structural viscosity, it is important to study the whole pattern of pore pressure versus time, and not attach too much significance to the peak measured pore pressure alone. The data obtained earlier at M.I.T. do show that there are serious deviations from the standard consolidation theory in some cases.

(c) A new pore pressure measuring system, utilizing an electrical pressure transducer, has been developed. Preliminary tests have shown that the system has a response time of less than 0·5 second when used with an impermeable clay. The system has also recorded pore pressures less than absolute zero. Measuring systems using very stiff electrical transducers appear to have great promise for use with rapid triaxial shear tests and for many other laboratory tests.

Acknowledgement

This work was sponsored by the Waterways Experiment Station, Corps of Engineers, U.S. Army, as part of a program to study the effect of very rapid strain-rates upon the shear strength of soils.

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