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Consolidation Testing and Evaluation: Problems and Issues

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The techniques and procedures used in the determination of the one-dimensional consolidation properties of fine-grained saturated soils are presently described in two ASTM standards: (1) D 2435, "Test for One-Dimensional Consolidation Properties of Soils," and (2) D 4186, "Test for One-Dimensional Consolidation Properties of Soils Using Controlled-Strain Loading." The objectives of these standards are to determine engineering parameters to estimate the magnitude (e–p' relationship) and rate (C) of one-dimensional deformation of soils subjected to an effective stress change. The major distinction between the two standards is that the former permits full dissipation of pore pressure prior to application of the subsequent load, whilst the latter procedure measures the pore pressures during loading.

The summary presentation contained herein addresses some main concerns and issues. Full delineation of the various problems and laboratory case studies can be found in the state-of-the-art reports and the other technical papers contained in this volume.

General Areas of Concern

There are at least five distinct areas of concern:

1. *Standard technique:* The general sets of concern relate to such items as disturbance effects, sample storage, nonlinear stress-strain behavior, prior knowledge of initial stress conditions in the soil, and equipment constraints and influence.
2. *New techniques and procedures using the standard oedometer:* The main

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items in this category concern methods of load application (e.g., rapid loading, constant gradient, controlled-strain or controlled-stress (and variations thereof), load increment ratios and durations).

3. *New equipment and associated techniques or procedures:* This category considers the use of new types of "consolidation devices" and associated techniques/procedures (e.g., biaxial and triaxial devices, centrifuge consolidation testing, slurry consolidometers, testing of wick drains, radial and axial drainage).

4. *Problem soils:* Using standard, modified, or new equipment/procedures, the testing of such materials as organic soils, slimes/sludges, gaseous soils, and unsaturated soils requires special attention.

5. *Novel or different methods of data scrutiny and reduction* for determination of "consolidation" properties and characteristics.

Standard Technique

The standard techniques described in ASTM D 2435 and D 4186, which cover testing methodologies and prescribed methods for calculation of C_v, C_c, and C_r from test measurements, are generally considered conventional tests. The record shows that the coefficient of consolidation C_v obtained varies with the level of effective stress established. Test results also show that C_v calculated from measured excess pore pressures differ significantly from C_v values determined from laboratory settlement-time measurements. The "bottom line" to this set of discussions is the realization that determination of consolidation performance parameters or properties is indeed sensitive to the effective stress-deformation relationship established. Not only is the method of laboratory determination of this relationship important, so is the methodology used in calculating this relationship.

The above problem bears testimony to the highly complex nature of clay soils and the need to obtain a clearer understanding of the mechanisms involved in the demonstration of load-deformation-time relationships. The influence of sample preparation and initial state of the soil, including stress and strain histories, on subsequent performance under load cannot be ignored or overlooked. The discussions provided by Olson in his state-of-the-art report and by some of the other papers in this volume show clearly this concern.

"Standard" Oedometer: New Techniques/Procedures

In recognition of many of the problems identified above, and in keeping with the desire to maintain a "standard" test cell as a base reference condition, new techniques and procedures have focussed on the scrutiny of load-deformation-time relationships. Several methods and procedures for load application have been described (e.g., controlled stresses, strains, time and pore pressure responses). The effect of any of these new techniques/procedures is generally demonstrated in terms of relationships for load and deformation, with time as a factor implicitly considered in the relationships or evaluated through data reduction methods. The evidence shows that the demonstrated load-deformation-time relationships between each of these new techniques/procedures, and also between these new techniques and the standard procedures, are not likely to be similar.

Recognizing that the end point of any of these techniques is the determination of the C_v, C_c, C_r, and p'_c values—via laboratory testing of representative samples—and recalling that clay soils are indeed complex materials, it is pertinent to ask: "Is there such a thing as a true value of C_v, C_c, C_r, or p'_c?" Given the realization of the highly variable state of clay soils, due in part to the compositional characteristics and in part to the response of these soils to various stress path loadings and boundary conditions, uniqueness as a condition in clay soils is not a realistic fact. Thus one now needs to ask whether research and development efforts should continue to seek "true" values, or concentrate on seeking a better appreciation of the many factors and conditions that participate in the production of a demonstrated load-deformation-time relationship. This attitude is motivated by the knowledge that the field environmental, initial, and boundary conditions are not generally modelled in laboratory consolidation testing and therefore, by extension, the C_v, C_c, C_r, and p'_c values existent in the field may not be similar to those determined from laboratory tests. It would appear that the new techniques and procedures which focus on methods of sample stressing are indeed directed towards this set of concerns. It now remains to expend further effort in evaluation and assessment of the significance of the laboratory-determined load-deformation-time relationships vis-à-vis field problems.

New Equipment, Associated Techniques, and Problem Soils

The development of new devices and associated testing techniques for the laboratory study of consolidation performance is generally prompted by one or more of the following motivations:

1. The desire and need to make laboratory test conditions conform with field loading and performance expectations (e.g., biaxial and triaxial consolidation devices, radial flow consolidation tests, restricted pore pressure dissipation tests).
2. The availability of new test techniques (e.g., centrifuge) or more sophisticated instrumentation and controls that permit measurements of various performance characteristics (and properties) not previously considered as measurable.
3. The need to address problem soils not heretofore considered as standard material for consolidation testing (e.g., organic soils, gaseous soils, slimes/sludges, unsaturated soils).
4. The development of new or extended concepts concerning load-deformation-time performance modelling and the availability of more sophisticated methods of analyses and computational tools.

Item (1) by and large speaks for itself. As one continues to further one's appreciation of the differences between laboratory and expected field performance characteristics of the soil, either because of site specificity or because of load boundary conditions, the normal response of the researcher or tester is to ensure that the test system closely matches the demands of the field situation. Thus, for example, biaxial and triaxial consolidation test systems with specific load application procedures that have been developed to model drainage conditions expected in the field can be readily seen to be a first-order adaptation of conventional procedures for assessment of the laboratory consolidation behavior of the soil. Not only are the questions of anisotropic properties handled with this system, so are the problems concerned with specification of vertical and horizontal stresses. Quite obviously, the load–deformation–time relationships obtained will be directly related to the test system itself and the procedures used; hence the C_v, C_c, C_r, and p'_c values calculated will be specific to the test. It is not likely that these values will match those obtained if the same soil samples were tested in the conventional manner using standard procedures. These points have been recognized by researchers and practitioners. It now remains to determine whether there is a need to establish (1) standard methods which will handle a representative range of conditions now being examined by these types of devices, and (2) recommended procedures for data reduction and computation of consolidation properties.

Another driving force for the development of new test systems and techniques is the need to determine consolidation properties of problem soils. Two examples are the consolidation behaviors of organic soils and soft sediments. Because of the anticipated large strain performance of each of the materials under load, and because of the high initial void ratios and water contents, conventional test systems and theories cannot properly handle the consolidation testing of these materials. Consolidation testing of organic soils using larger oedometers with specialized control on low load application has been attempted with varying degrees of success. The problems that arise are the interpretation of the load-deformation-time relationship obtained and the evaluation of the phenomenon of secondary compression.

Greater awareness of the capabilities of centrifuge testing has prompted researchers with centrifuge facilities to investigate the use of such a facility in conducting consolidation testing of very soft sediments. The combination of the various demands in centrifuge testing and soft sediment performance requires considerable effort in seeking a proper understanding of the types of results obtained and the kinds of analyses required to obtain representative consolidation properties.

A closely similar problem exists in the study of the settling performance of slimes and sludges. The slurry-state of these materials requires test samples sufficiently high (long) that the near self-weight characteristics of sedimentation/consolidation be properly assessed. The development and use of slurry consolidometers are seen as one direction to follow in the laboratory determination of pertinent sedimentation/consolidation properties. The coupling of the slurry consolidometer with centrifuge testing techniques is a further extension of this test procedure. Again, the problems arising with respect to data scrutiny and analyses need to be fully addressed.

Gaseous and unsaturated soils pose problems more directly associated with theory and experimental/testing. Because of the presence of the third phase (gas or air), one is left with two choices: (1) to introduce back–pressuring procedures to produce a fully saturated test sample (presuming this can indeed be successful) and to conduct the conventional consolidation test thereafter, or (2) to test the sample "as-is" and to seek methods or analytical models that would permit one to work with the test data obtained. It is not immediately clear if either of these procedures would provide one with a true picture of the problem behavior at hand. It is clear, however, that much work remains to be done in this particular area.

The introduction of man-made materials (i.e., wick drains) to enhance consolidation of clayey soils calls attention to new test techniques and equipment to evaluate performance, and a resurrection of radial flow theories for predictions. Tests measuring hydraulic conductivity of drains subjected to "kinks" and bends and *in situ* lateral stresses address this concern. Eventually, it is expected that standards will evolve for this particular area.

Different Methods of Data Scrutiny

With greater capability in measurement of conventional and "other" performance parameters, and with attention given to the testing of other kinds of soil material not previously considered in conventional consolidation tests, it is clear that different methods of data scrutiny and analysis are required. A case in point is the phenomenon of secondary compression. Not only is one interested in the characteristics of performance in the so-called secondary compression phase of "consolidation", but the specification of when such a phenomenon occurs is also of interest. The evidence at hand indicates that secondary compression characteristics are indeed influenced by the response performance characteristics of the material in the regular consolidation phase. This observation is not easily quantified, since the point at which secondary compression occurs cannot be readily identified. The problem lies as much in one's concept or definition of secondary compression as in one's belief that this phenomenon is an active partner in the description of the total e-log p curve derived from consolidation testing. Since classical consolidation theory deals with the phenomenon of pore pressure dissipation rates, the facile argument that everything that is not covered by classical consolidation theory is secondary compression provides little comfort to the researcher concerned with measurements that show "nonclassical" results.

At the opposite end of the spectrum is the sedimentation/consolidation problem. What is needed is to distinguish the void ratio at which sedimentation ceases and pore pressures (effective stresses) due to self-weight loading are generated. Obviously, classical consolidation theory is inappropriate for describing sedimentation phenomena.

Concluding Remarks: Problems and Issues

Various problems and issues can be deduced from the discussion dealing with the areas of concern. There are undoubtedly many other areas of concern that have not been addressed in the above discussion. A brief summary of pertinent issues can be given as follows:

1. *Load application procedures*—conventional and nonconventional test systems, criteria, data reduction and analyses, standardization.
2. *Pore pressure measurements*—routine measurements, criteria for use in control of loading, application in analysis of C_v, and C_c.
3. *Biaxial and triaxial test systems*—test procedures, standardization, test data scrutiny and analyses.
4. *Special tests for problem soils and man-made materials*—partly saturated, stiff residual, large particle soils, organic, gaseous, slimes, wick drains.
5. *Sedimentation and secondary compression*—specification and definition, influence on e-log p, evaluation, and prediction.