Some Deformation Characteristics of a Saturated Remoulded Silty Clay

Quelques caractéristiques de déformation d'une argile silteuse, saturée et remaniée

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SUMMARY

The paper outlines an investigation of certain deformation characteristics of normally consolidated, saturated, remoulded Cambridge Gault clay. It is assumed that the structural deformation behaviour may be considered as linearly viscoelastic. The data obtained from one-dimensional consolidation and triaxial consolidation and undrained tests establishes that the assumption of isotropy can provide only qualitative specification of the principal deformation characteristics. The assumption of radial symmetry enables more precise specification of the observed behaviour, but takes no account of the significantly non-uniform structural deformation occurring in the one-dimensional consolidation tests. A linear viscoelastic model is proposed which will account for this non-uniform behaviour.

SOMMAIRE

Cet article démontre certaines caractéristiques de déformation de l'argile Gault de Cambridge normalement consolidée, saturée et remaniée. Il est pris pour acquis que la déformation de structure peut être considérée comme état visco-élastique et linéaire. Les données provement d'une consolidation à une dimension, d'une consolidation triaxiale et d'essais non-drainés établissent que l'hypothèse d'isotropie ne peut apporter que des explications qualitatives des principales caractéristiques de déformation. L'hypothèse de symétrie radiale permet une description plus précise de la réaction observée, mais ne prend pas en considération les importantes déformations de structure non-uniformes qui se produisent dans les essais de consolidation à une dimension. Un modèle visco-élastique linéaire est proposé qui expliquera ce comportement non-uniforme.

THIS PAPER PRESENTS certain of the more important conclusions derived from an investigation of the non-failure deformation behaviour of normally consolidated, saturated, remoulded Cambridge Gault clay (Thompson, 1962).

THEORETICAL CONSIDERATIONS

The theoretical considerations herein are based on the assumption that the non-failure deformation behaviour of the clay particle structure may be considered as linearly viscoelastic for small strains. Within relatively recent times application of the concepts of viscoelasticity to the study of the significantly time-dependent deformation of clay soils has been widespread (Biot, 1956; Tan, 1953, 1961; Schiffman, 1960).

General stress-strain-time relations for the linearly viscoelastic, porous particle structure are obtained by expressing each of the six fundamental components of stress at a point as an operator function of the corresponding strain components. The viscoelastic operators will, in general, involve both structural parameters and time derivatives. For the particular condition of radial symmetry, usually exhibited by undisturbed clays and developed in all soils during triaxial, consolidometer, and other tests involving radially symmetric boundary conditions, the complete specification of the structural deformation behaviour may be readily shown to involve the determination of five independent operators. The specification of the behaviour of the saturated soil mass necessitates, in addition, the determination of two permeability coefficients. Correspondingly, the assumption of isotropy involves two structural operators and a single permeability coefficient. Here, however, it is generally most convenient to separate the stress and strain tensors into their volumetric and deviatoric components and separately relate them through the two operators—the volumetric and deviatoric operators.

PRELIMINARY STUDIES

The assumption of structural isotropy introduces considerable simplification and has received extensive usage in studies of soil stress-strain behaviour. An investigation was accordingly first made of the applicability of this assumption in specifying the deformation behaviour of the Gault clay. The volumetric and deviatoric operators mentioned above were evaluated respectively from the volumetric strain behaviour in isotropic applied stress triaxial consolidation tests and the axial strain behaviour in constant axial stress

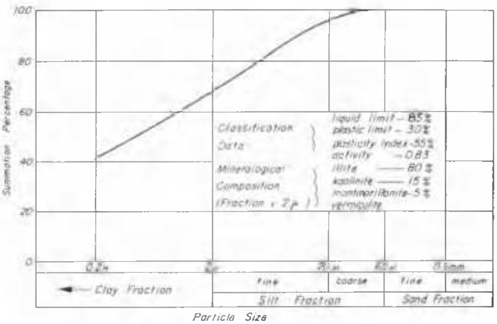

FIG. 1. Properties of clay.

undrained triaxial tests, and their suitability for the prediction of more general behaviour involving both deformation modes investigated by one-dimensional consolidation testing.

Experimental Details

The saturated, remoulded Cambridge Gault clay samples were prepared from a bulk supply having the properties shown in Fig. 1. Every effort was made to obtain complete saturation.

The isotropic stress consolidation tests employed end drainage conditions to closely simulate the one-dimensional consolidation test conditions. Leakage was virtually eliminated by enclosing the samples within two rubber sleeves greased at their interface. Conventional filter paper radial drains were employed in the constant axial stress undrained tests to facilitate pore water pressure equalization.

The principal innovation in the one-dimensional consolidation tests was the use of externally greased, thin rubber sleeves around the samples, an arrangement previously found to practically eliminate side-friction forces (Thompson, 1961).

Test Results

The volume reduction in the isotropic stress consolidation tests with end drainage increased linearly with the square root of time for small values of time. The appropriate differential equation for this behaviour corresponds directly to the differential equation of the Terzaghi one-dimensional consolidation theory

$$\partial u/\partial t = c(\partial^2 u/\partial z^2) \qquad (1)$$

where c = coefficient of volume consolidation. Equation 1 and the Terzaghi theory essentially imply a linear stress-strain or elastic structural deformation behaviour; hence, an appropriate first-order structural model representation for the volumetric deformation is simply a single spring element, as shown in Fig. 2a.

At greater times, however, the volume reduction was at variance with the behaviour predicted by Eq (1). For applied isotropic stresses up to 25 psi, the volume reduction

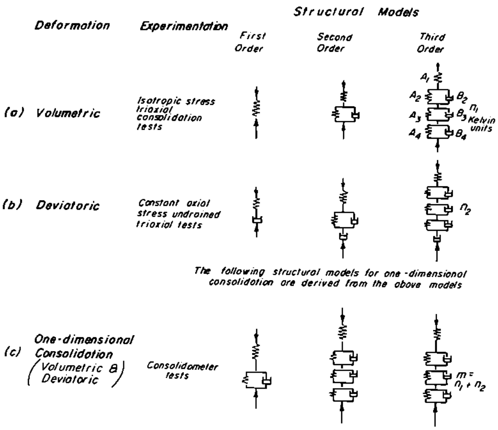

FIG. 2. Viscoelastic model representations for volumetric, deviatoric, and one-dimensional structural deformation.

terminated on dissipation of the pore water pressures, as also observed by Lo (1959), and the structural deformation could then be closely specified by the second-order model shown in Fig. 2a. For applied stresses exceeding 25 psi, there were continuing volume reductions subsequent to dissipation which occurred at approximately constant rates with the logarithm of time; these secondary consolidation rates were significantly smaller than those observed in the one-dimensional consolidation tests, and it is probable that this behaviour is due, in some measure, to the non-uniformity of the stresses imposed in the triaxial apparatus.

The third-order structural model in Fig. 2a gives both a linear strain variation with the square root of time for small values of the time, as with the first- and second-order models, and also satisfactorily represents the behaviour for greater times prior to pore-water-pressure dissipation for all applied pressures. At subsequent times the deformation is essentially a creep action of the structure under constant effective stress or, in terms of the model, the retarded straining of the series-connected spring-dashpot or Kelvin units. However, the deformation of such units under constant stress increases at an exponentially decreasing rate with increasing time, thus

$$\Delta v = \Delta\bar{\sigma}'\left\{\frac{1}{A_1} + \sum_{N=2}^{n_1}\frac{1}{A_N}\left(1 - \exp\frac{-A_N}{B_N}t\right)\right\}. \qquad (2)$$

Hence, the third-order model can only approximate the observed constant rate of volume reduction with the logarithm of time for large times. Clearly, the greater the number of Kelvin units n_1, the more improved will be the approximation for a given time period.

In the constant axial stress undrained triaxial tests the axial straining occurred in three stages—an immediate elastic stage with load addition, followed by a retarded or viscoelastic stage, and a final continuing straining approximating viscous action. The behaviour was thus essentially similar to the angular strain-time behaviour observed by Geuze and Tan (1954) in their torsion plastometer tests on a pottery clay. Appropriate structural model representations for the observed behaviour are shown in Fig. 2b.

The settlement behaviour in the one-dimensional consolidation tests was essentially the same as the volume reduction behaviour in the isotropic stress consolidation tests with end drainage for applied stresses greater than 25 psi. Thus, the settlements at small values of time increased linearly with the square root of the time, establishing that the structural deformation was initially elastic. At greater times the settlements were retarded as a consequence of structural viscosity, while at times subsequent to pore-water-pressure dissipation the settlements increased at an approximately constant rate with the logarithm of time. The structural models in Fig. 2c were derived from the corresponding volumetric and deviatoric models. The first-order model is that employed by Tan (1953) and Lo (1959) in their one-dimensional consolidation theories. Thus, the derived models satisfactorily represented all but the settlement behaviour at large times in the manner outlined previously in connection with the isotropic stress consolidation tests.

Discussion

The preliminary studies established that the assumption of isotropy enabled some qualitative specification of the structural deformation for given boundary conditions from a knowledge of the volumetric and deviatoric deformation behaviour. However, no satisfactory quantitative correlation was obtained and, in addition, there were many other facets of the observed behaviour, beyond the scope of this paper, of which no account could be made on the basis of the assumption of isotropy.

It was therefore apparent that, for a more accurate specification of the structural deformation behaviour, it was necessary to involve the assumption of a radially symmetric structure. In the further studies thus indicated, particular attention was devoted to the important fact that in the preliminary consolidation tests the mode of deformation was not uniform throughout the sample. The remainder of this paper is devoted to the detailed study made of the non-uniformity of the structural deformation occurring in one-dimensional consolidation or, in the revised theoretical context, the study of the form of the confined uniaxial compression operator.

NON-UNIFORM CONFINED UNIAXIAL COMPRESSION

Test Results

The one-dimensional consolidation tests were conducted in the same manner as in the preliminary studies. As before, the settlements increased linearly with the square root of time at small values of the time, thereby indicating that the initial structural deformation was elastic; significant disparities from elastic behaviour occurred at larger times, which could be only approximately accounted for on the basis of structural viscoelasticity.

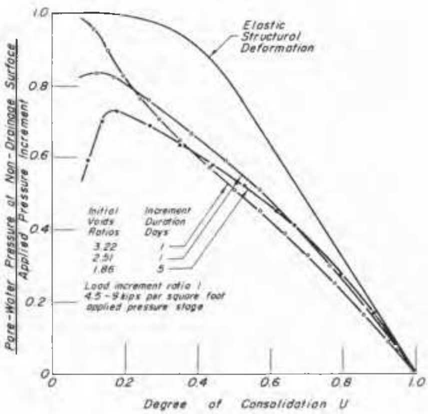

FIG. 3. Pore-water-pressure dissipation in one-dimensional consolidation.

A detailed study of the base pore-water-pressure behaviour of single-drainage samples indicated significant disparities from the behaviour predicted on the basis of structural deformation appropriate to the settlement behaviour. The typical data presented in Fig. 3 clearly illustrate that the disparity with respect to the behaviour predicted on the basis of elastic structural deformation was most pronounced at small times, during which the settlements clearly indicated elastic behaviour, the pore water pressures developing at a decreasing rate and attaining decreasing maximum values with decreasing initial voids ratio and increasing increment duration. Some confirmation of these and other observed features of the pore-water-pressure behaviour has been provided by Geuze (1957).

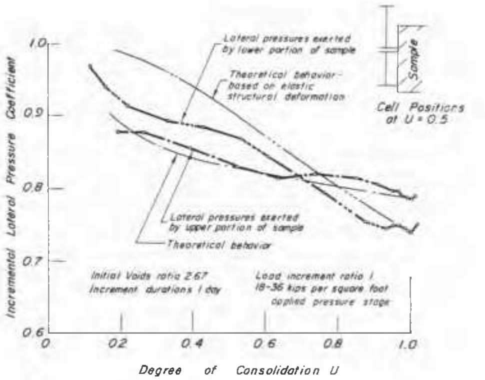

FIG. 4. Total lateral pressures exerted in one-dimensional consolidation.

Now it is apparent that the settlements occurring at small times are primarily due to the structural compression within portions of the sample nearest the drainage surface, while the base pore water pressures essentially reflect the structural deformation within portions of the sample furthest from the drainage surface. The occurrence of non-uniform structural deformation was thus clearly indicated. In order to verify this feature, a series of single-drainage tests was performed in which the total lateral pressures exerted at various depths were measured by a pressure-measuring cell employing electrical resistance strain gauges. Details of this study have been previously reported (Thompson, 1963). The principal conclusions, illustrated by the typical data presented in Fig. 4, were that with increasing distance from the drainage surface there was a significant decrease of the lateral pressure coefficient at equilibrium (pore water pressures essentially zero) and increasing disparity, particularly at small times, from theoretical behaviour based on elastic structural deformation.

The one-dimensional consolidation tests thus established the occurrence of non-uniform structural deformation at small values of the time, and it appears probable that such

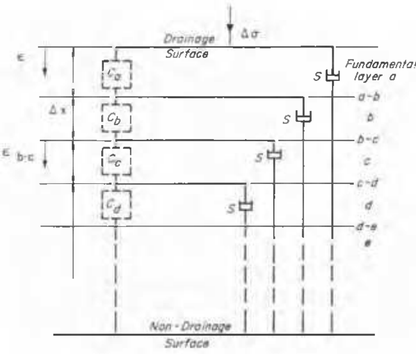

FIG. 5. General linear viscoelastic model representation for one-dimensional consolidation accounting for non-uniform structural deformation.

behaviour must persist throughout a consolidation process. A linear viscoelastic model is now presented which is capable of representing the observed non-uniformity and which will accordingly allow its future detailed evaluation.

Viscoelastic Model Accounting for Non-Uniform Structural Deformation

The model is essentially composed of distinct linear viscoelastic units representing the structural deformation behaviour of fundamental layers of the sample.

The application of this model for the representation of the confined uniaxial compression or one-dimensional consolidation of a single drainage sample is shown in Fig. 5. In this figure each layer *a*, *b*, *c* . . . corresponds to a fundamental layer of thickness Δx of the sample. The dashpots of parameter S represent the restriction to pore water flow through the layers, while the dashed-line squares are employed as arbitrary representations of structural deformation behaviour of operator forms C_a, C_b, . . . for the purpose of generality. The structural or effective stress σ' in any layer, say *b*, is the stress in the structural model of operator form C_b. The pore water pressure u_b is equal to the applied total stress σ less the effective stress σ_b', which clearly equals the sum of the stresses in the dashpots of layer *a* and *b*, thus:

$$u_b = \sigma - \sigma_b' = S\Delta x^2\left(\frac{d\epsilon}{dt} + \frac{d\epsilon_{a-b}}{dt}\right). \quad (3a)$$

Similarly $$u_c = \sigma - \sigma_c' = S\Delta x^2\left(\frac{d\epsilon}{dt} + \frac{d\epsilon_{a-b}}{dt} + \frac{d\epsilon_{b-c}}{dt}\right); \quad (3b)$$

$$u_d = \sigma - \sigma_d' = S\Delta x^2\left(\frac{d\epsilon}{dt} + \frac{d\epsilon_{a-b}}{dt} + \frac{d\epsilon_{b-c}}{dt} + \frac{d\epsilon_{c-d}}{dt}\right). \quad (3c)$$

From these equations we may obtain

$$(u_b - u_c) - (u_c - u_d) = -S\Delta x^2\left(\frac{d\epsilon_{b-c}}{dt} - \frac{d\epsilon_{c-d}}{dt}\right) \quad (4)$$

and hence

$$\frac{(u_b - u_c) - (u_c - u_d)}{\Delta x^2} = -S\frac{d\epsilon_c}{dt}. \quad (5)$$

The left-hand side of this equation is the finite difference approximation of d^2u/dx^2; thus, in partial differential terms

$$\partial^2 u/\partial x^2 = -S(\partial\epsilon/\partial t) \quad (6a)$$

or

$$\partial^2\sigma'/\partial x^2 = S(\partial\epsilon/\partial t). \quad (6b)$$

These equations are seen to correspond to the fundamental flow relation involved in the great majority of one-dimensional consolidation theories.

The evaluation of appropriate linear viscoelastic models corresponding to the operator forms C_a, C_b, C_c . . . will clearly provide a linear representation of confined uniaxial compression or one-dimensional consolidation accounting for non-uniform structural deformation. A special consolidometer has been devised which will allow the determination of the strains and pore water pressures throughout samples, and thereby enable the determination of these models and their parameter values. From such studies it is intended to establish the nature of the variables influencing the non-uniformity and thereby allow the formulation of a general expression for the confined uniaxial compression operator.

CONCLUSIONS

The preliminary studies established that the assumption of structural isotropy allows but qualitative specification of the deformation behaviour of the saturated, remoulded Gault clay. Detailed investigations of confined uniaxial compression or one-dimensional consolidation have established the occurrence of significantly non-uniform structural deformation at small times, and a means of accounting for this non-uniformity has been proposed on the basis of assumed linear viscoelastic structural deformation. Further consolidation tests in the triaxial apparatus, employing both isotropic and anisotropic applied stress, have indicated distinct similarities in the mode of structural deformation, and it is accordingly conceivable that the five operators required for the complete specification of the radially symmetric structure may be essentially similar in form for non-failure behaviour.

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