Lateral Stress in One-Dimensional Consolidation

Contrainte Latérale dans la Consolidation à une Dimension

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SYNOPSIS *The e_g (distortional) and e_k (volumetric) strain parameters are described. The odometer test is* discussed and reference made to an alternative test. The lateral stress during one-dimensional consolidation is shown to vary with both time and size of specimen and the importance of the lateral stress indicated. Radial one-dimensional tests are described and results given.

INTRODUCTION

One-dimensional consolidation has been extensively studied during the past half-century. Nevertheless, many aspects of this process are unclear, and certain corrections and procedures are required to enable accurate forecasts to be made of the behaviour of field strata under load. (See, for example Lambe, 1964, *Skempton and Bjerrum, 1957*).

AUTHOR'S MODEL

A simple model has been devised which is especially suitable for "large-strain" soft, saturated soils, such as organic clays and peats, but which may validly be applied to most cohesive soils.

The basis of this method is the separate and independent nature of the two components of strain (a) distortional and (b) volumetric, which together constitute the net total strain in a real soil. Each component must, therefore, be separately measured, evaluated and the two combined by simple superposition. Each takes place at a different rate. The volumetric strain rate depends chiefly on the rate of dissipation of porewater and this rate varies with the size of specimen, or length of drainage path; the size of specimen has little or no effect on the rate of distortional strain. The consequential effects on the soil properties are different for each component; the strength is enhanced with increased volumetric strain, whereas the distortional strain may have a weakening effect.

Many aspects of the method including definitions and methods of measurement of the (e_g and e_k) parameters, and applications of the method to a number of problems are described elsewhere (e.g. Hanrahan, 1974). The following simple experiment, however, illustrates *the nature of the parameters, and also confirms the* validity of superposition of the strain components. A cylindrical specimen of saturated cohesive soil is prepared with provision for radial drainage, and placed in a triaxial cell. A stress system ($\sigma_1 > \sigma_2 = \sigma_3$) is applied and maintained at a constant value throughout the test. Strains are observed during two phases. In phase 1, drainage is not permitted. The strains (assumed to be principal strains) are mainly due to distortion and are termed the e_g strains. The e_g strains are, however, not wholly free from volume change if the soil dilates. (A specimen with some air content would also suffer a volume change in phase 1). In phase 2, which commences when the drainage tap is opened (after all the e_g strains are complete), the strains are *components of the volumetric strain and are termed* the e_k strains. These are not necessarily equal in the three principal directions (Hanrahan, 1971).

If the same stress is now applied to a similar specimen, with the variation that drainage is permitted from the start, the measured strains will be found to be the algebraic sum of those observed previously in the two-phase experiment. (A slight correction is necessary to allow for the e_g strains taking place in the former experiment at a constant and in the latter, at a reducing water-content).

ONE-DIMENSIONAL CONSOLIDATION

The primary purpose of this paper is to consider the application of the method to the important problem of one-dimensional consolidation. The following definitions apply:

e_1, e_3 = major,minor total principal strain.

e_{g1},e_{g3} = major,minor principal component of (distortional) strain.

e_{k1},e_{k3} = major, minor principal component of (volumetric) strain.

z = depth.

t = time.

Adopting the convention of signs (compressive positive tension negative), (Fig. 1).

$$e_1 = e_{g1} + e_{k1} \tag{1}$$

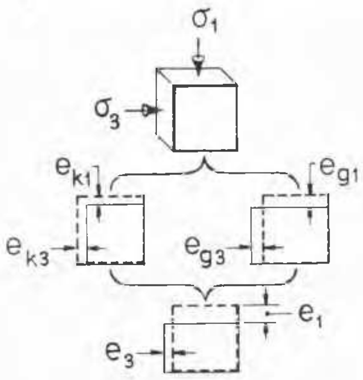
$$e_3 = e_{k3} + e_{g3} \tag{2}$$

The definition of one-dimensional strain thus becomes

$$e_{k3} = e_{g3} \text{ for all values of } t,z \tag{3}$$

Eq. 3 is a more meaningful definition than the usual definition which is

$$e_3 = 0 \text{ for all values of } z,t \qquad (4)$$



$$e_3 = e_{k3} - e_{g3}$$

Fig.1. Showing total strain as sum of e_g and e_k strains.

Laboratory studies of the characteristics of the strain components show that each may be described as follows:-

$$e_{g3} = f(t, (\sigma_1 - \sigma_3), G) \qquad (5)$$

$$e_{k3} = f(t, \frac{\sigma_1 + 2\sigma_3}{3}, K, \text{ sample size}) \qquad (6)$$

Expressed in words, the magnitude of the distortional strain components, e_{g3}, is a function of time, principal stress difference and a material property, G, which is analogous to the shear modulus of a perfectly elastic material. This material property is of course, not a simple quantity but is a function of time and magnitude of principal stress difference. Similarly, the magnitude of e_{k3} is a function of time, volumetric stress, a material property, K, which is analogous to the bulk modulus of a perfectly elastic material, and also the length of drainage path (i.e. sample size). The main point of interest is that e_{k3} is controlled by the diffusion process whereas e_{g3} is independent of diffusion.

It follows from the definition of one-dimensional consolidation in eq. 3 that at all depths and throughout the consolidation period, equality between both strain components is being forcibly maintained. By inserting a chosen value for each of the quantities t, σ, G, K and sample size, it follows from eq. 3 that a definite value of σ_3 is obtained. Any change in one of the inserted values will yield a different value of σ_3. These findings have always been confirmed experimentally (e.g. Hanrahan, 1974) and are referred to again subsequently.

It is relevant to the theory of one-dimensional consolidation that

(i) the lateral stress on a specimen, or element varies continuously with time and with size of specimen (or location of element).

(ii) The stress on a thin laboratory specimen during one-dimensional consolidation is not the same as the stresses on a thicker specimen (or element in a stratum) even when all other conditions are equal i.e. same pore-pressure, same vertical stress, same water-content, etc..

IMPORTANCE OF LATERAL PRESSURE IN ONE-DIMENSIONAL CONSOLIDATION

Specimens of soil which are consolidating one-dimensionally are free to deform (strain) in one direction only. This implies that the stress is known only in this one direction (usually vertical). The stress in the other two principal directions must be solved so as to be compatible with eqs. 3, 5, 6 and measured values of e_g, e_k (Hanrahan, 1974).

Excess porewater pressure can be dissipated regardless of whether the total applied stresses remain constant, or whether they are reducing or increasing. Clearly the rate of dissipation is influenced fundamentally by the magnitude and rate of change of the total stresses. A changing value of σ_3 during consolidation is generally agreed, but it is the author's opinion that insufficient attention is paid to this problem in normal practice.

The effect of increasing horizontal stress is of special importance in the consolidation of deep deposits of soft compressible soils. At a location remote from a drainage boundary, the volume change of an element is likely to be negligible, or zero, for a considerable period after loading, Thus, during this period we may write:

$$\Delta V = 0$$

where V = volume of element

$$\Rightarrow \quad e_{k3} = 0$$

since e_{k3} is a component of volumetric strain

Therefore, from eq. 3 it follows that

$$e_{g3} = 0 \qquad (7)$$

The condition represented by eq.7, especially in soft soils, requires that σ_3 must approach σ_1 in value. This, in turn, leads to a build-up in porepressure and, in consequence, a more extended period of consolidation than that predicted by normal consolidation theory.

INSTRUMENTATION FOR ONE-DIMENSIONAL CONSOLIDATION

Because much of the work on one-dimensional consolidation has been done with the odometer, it is pertinent to draw attention to the defects of this apparatus.

(i) The stress on the curved surface of the cylindrical specimen is not known.This stress varies from point to point with depth and throughout the duration of the test.

(ii) The tangential force ("friction") on the curved surface is not defined.

(iii) The specimen is forced to deform as a cylinder, and, thus, conditions of free strain do not obtain.

(iv) The pore-pressure, water-content and effective stress vary sharply on vertical planes.

(v) The vertical stress imposed by rigid end plates on flat surfaces is not known exactly.
(vi) The test is affected by the confining conditions (Calhoun and Triandafilides, 1969) and other influences such as temperature, sensitivity, soil disturbance, degree of overconsolidation, dimension of specimen, stress-increment which have been studied (e.g. Skempton and Bjerrum, 1957; Simons, 1969; Burland and Roscoe, 1969).

For many years the author has used a radially-drained triaxial specimen, consolidated one-dimensionally as an alternative to the odometer. This test is also subject to some of the above defects, but the difficulties under (i) and (ii) above have been eliminated. The stress on the specimen is known and there is no friction on the curved surface.

A standard triaxial cell suffices. Adequacy of drainage must be ensured and piston friction eliminated by using a load cell inside the triaxial cell.

Control of consolidation is simple. The stresses are continuously altered so as to maintain, throughout the test, the equality

$$\Delta V = \Delta h . A. \qquad (8)$$

where ΔV = volume of water expelled (measured in burette).
Δh = change in height of specimen.
A = area of specimen (constant).

Adjustment of the stress system is always necessary, otherwise the cross section of the specimen does not remain constant. Adjustment may be effected in two ways (i) by keeping σ_3 constant and increasing σ_1 or (ii) by keeping σ_1 constant and decreasing σ_3. The latter method which more closely resembles the odometer, is simple and convenient, but has the disadvantage of causing a small amount of over-consolidation in the peripheral layers. Both methods yield similar results, the outstanding feature of which is the pronounced linearity between volumetric strain and observed principal stress ratio (σ_3/σ_1) (Fig. 5).

LABORATORY TESTS

Figs. 2-5 show the results of one-dimensional, radial consolidation tests, carried out on small and large remoulded saturated specimens, respectively, in accordance with the author's method on three soil types. In these series, σ_3 was kept constant, and σ_1 increased continuously so as to maintain a constant cross-sectional area of specimen.

Fig. 2 shows the observed rate of increase of σ_1. Fig. 3 shows the rate of volumetric strain. Fig. 4. shows the rate of decrease of porewater pressure measured at the centre of the base of the specimen. Fig. 5 shows the remarkable relationship between volumetric strain $\Delta V/V_0$ and the principal stress ratio σ_3/σ_1. Each curve is an average of three separate determinations.

Table 1 gives information on soils, specimens, and test conditions.

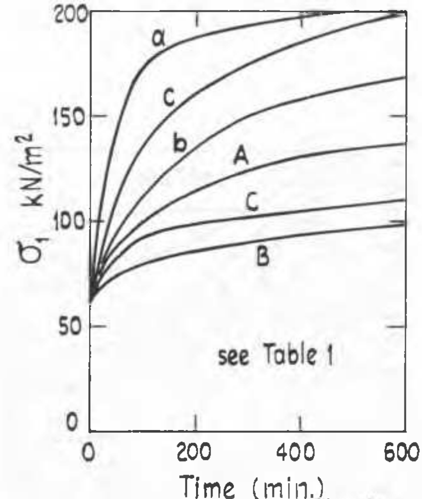


Fig. 2. Observed rate of application of σ_1 to maintain one-dimensional consolidation.

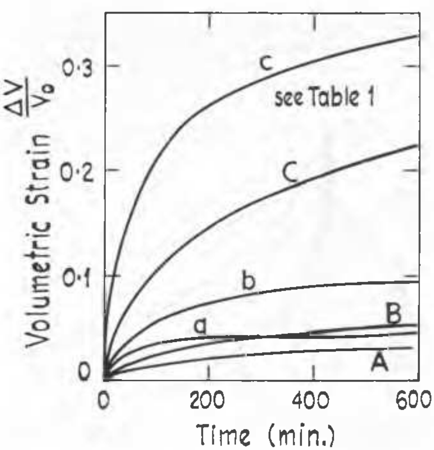


Fig. 3. Observed rate of volumetric strain for one-dimensional consolidation.

COMMENTS ON TEST RESULTS

The tests confirm the continuous variation of σ_3 with time and with size of specimen which is required by the foregoing discussion for specimens consolidating one-dimensionally. The linearity, after an initial curvature, of the relationship between volumetric strain $\Delta V/V_0$ and principal stress

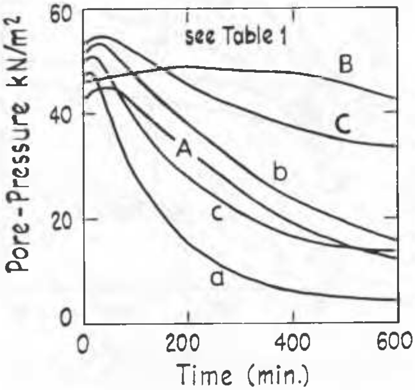


Fig. 4. Observed rate of pore-pressure change for one-dimensional consolidation.

ratio σ_3/σ_1 is of special interest, and is always observed (Hanrahan and Mitchell, 1969).

Reference to Fig. 2, which shows the required rate of application of σ_1 to maintain a constant diameter indicates the practical difficulty, after about 600 min., of maintaining one-dimensional consolidation, unless σ_3 is also permitted to vary. (A similar greatly diminished rate of change of stress after about 600 min. is also experienced with the alternative method of carrying out the test, whereby σ_1 is kept constant and σ_3 allowed to vary.

While it is hazardous to attempt to simulate the geological process of consolidation by means of a short-term laboratory test, it is of interest to speculate on the significance of the straight 'tails' of the curves in Fig. 5. If linearity persists, a negative value of σ_3/σ_1 would ultimately be required to maintain one-dimensional deformation. This could only be achieved by σ_3 becoming tensile. This process would explain the formation of fissures in clays and sedimentary deposits.

A phenomenon, not altogether unrelated, may be observed when a specimen of a highly compressible soil, such as peat, is off-loaded after years of consolidation in a large odometer. An annular space may be observed between the specimen and the wall of the odometer. The width of space increases with duration of consolidation, and may be closed by immediate re-application of load. However when the material reaches an ultimate condition of hardness and brittleness, deformation of this magnitude would not be possible without tensile failure on vertical planes.

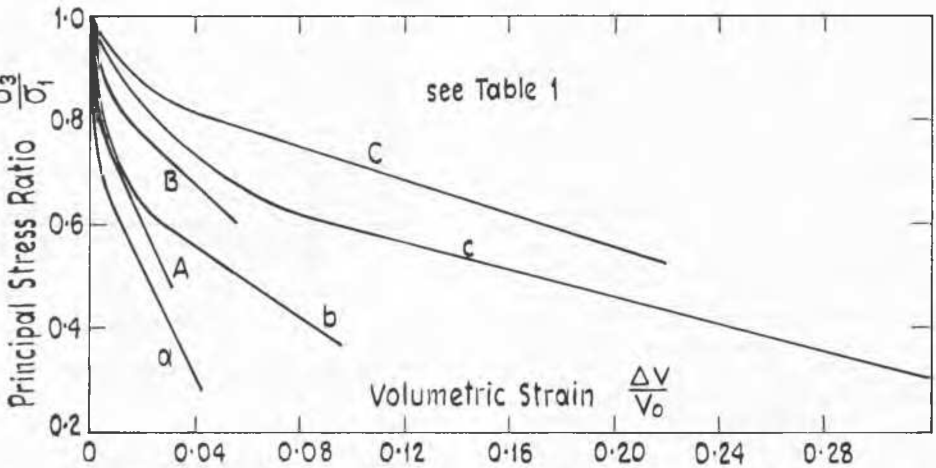


Fig. 5. Observed rationship between principal stress ratio and volumetric strain.

Table 1

Soil Type	Curve	Size of Specimen mm	W_L	W_P	Water-Content w%	Cell Pressure kN/m²	σ1 kN/m²
Boulder clay	A	203 x 102	22	9	13	60	Increasing
Boulder clay	a	76 x 38	22	9	13	60	"
Silt	B	203 x 102	70	30	33	60	"
Silt	b	76 x 38	70	30	33	60	"
Peat	C	203 x 102	800	-	265	60	"
Peat	c	76 x 38	800	-	265	60	"

The instantaneous opening of fissures in clay which takes place when a load is removed followed by closing of the fissures as water is absorbed is an example of the volumetric and distortional strain taking place at different rates.

EFFECTIVE STRESS

It is usually assumed that it is possible to relate total strain to effective stress only, without reference to time. However, the fact that the e_g strain is, and the e_k strain is not independent of the diffusion process, raises doubts concerning the validity of this procedure. Thus comparing two specimens, one large and one small of similar soil, the time required for dissipation of a fixed amount of initial porepressure is clearly greater for the large than for the small. But in the longer time interval, more distortional (e_g) strain will have developed in the larger specimen than in the small. Thus the total strain will be greater in the larger than in the small although the effective stress in both is the same.

CONCLUSIONS

The lateral stress is shown to vary throughout the period of consolidation and also with size of specimen. The lateral stress must be able to be estimated if accurate forecasts are required. It is not possible to relate total strain to effective stress only, without reference to time.

ACKNOWLEDGEMENTS

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Corrigenda

(i) With the exception of the laboratory tests which are described in Figs. 2-5 inclusive and Table 1, the term "One-dimensional consolidation" throughout the paper implies a constant value of σ_1. Thus a variable principal stress ratio σ_3/σ_1 implies a variable value of σ_3.

(ii) Eqn. (2) should read

$$e_3 = e_{k3} - e_{g3} \quad \ldots\ldots\ldots\ldots\ldots(2)$$