STATENS GEOTEKNISKA INSTITUT

SWEDISH GEOTECHNICAL INSTITUTE

No. 47

SÄRTRYCK OCH PRELIMINÄRA RAPPORTER

REPRINTS AND PRELIMINARY REPORTS

Supplement to the "Proceedings" and "Meddelanden" of the Institute

Some Experiments on Hollow Cylinder Clay Specimens

A. K. Jamal

STOCKHOLM 1972

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PREFACE

This report describes some experiments with hollow cylindrical specimens which the Author had performed at the Swedish Geotechnical Institute in 1966-67. At that time he had submitted his Ph.D. Thesis at Cornell University, USA. Earlier during the period 1961-64, the Author had been associated with the hollow cylinder test programme at Cornell University, Department of Soil Engineering which was conducted under the general direction of Dr. B.B.Broms for testing undrained soil cylinders. Subsequent to 1964, the Author's primary research effort was directed at understanding of the drained hollow cylinder test. The experiments reported herein were continuation of the Author's research project.

This research work was partly supported through a grant from the Swedish National Council for Building Research (BFR Grant C 202:2Db).

Stockholm, December 1972
SWEDISH GEOTECHNICAL INSTITUTE

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SOME EXPERIMENTS ON HOLLOW CYLINDER CLAY SPECIMENS

By A.K. Jamal, Swedish Geotechnical Institute

SYNOPSIS

A hollow cylinder apparatus for moulded soil specimens with 60 mm outside and 35 mm inside diameter is described in this report. Experimental results of hollow cylindrical specimens of undisturbed clay are presented. The clay cylinders with lubricated ends were consolidated hydrostatically and loaded in axial compression under undrained condition with pore-water pressure measurement. For reference, solid cylinders of 35 mm and 60 mm diameter of the same clay were also tested. Hollow cylinder tests were performed with either

1) equal outside and inside chamber pressures, or
2) constant volume of the inside chamber.

KEY WORDS: Hollow cylinder testing, shear strength, undisturbed clay cylinders, consolidation under hydrostatic pressure, undrained axial compression.

1. INTRODUCTION

Hollow cylindrical specimens are used to study the strength and deformation properties of soil and other compressible materials in a generalized stress field. In the hollow cylinder test, the magnitude, orientation and application of the three principal stresses can be varied independently in any prescribed manner by varying the inside and the outside chamber pressures and the axially applied load. The direction of the principal stress axes can be changed through the application of a torque to the two end surfaces of the cylindrical specimen. The hollow cylinder test in this respect is superior to the standard triaxial test for which solid cylinder specimens are used. However the hollow cylinder behaviour under stress application is influenced by many factors, as for example, the test cylinder geometry and the test boundary conditions. Even for simpler stress systems the hollow cylinder phenomena can be very intricate. A proper appreciation of the hollow cylinder behaviour is necessary for rational interpretation of material property determinations using hollow cylindrical specimens.

This investigation was undertaken to study the hollow cylinder behaviour for particular stress applications and to gain a better understanding of the hollow cylinder test. Undisturbed clay samples were used. Both solid and hollow cylindrical specimens with lubricated end contacts were tested. The test cylinders were consolidated hydrostatically and loaded axially in compression under undrained state.The pore-water pressure changes in the clay during axial compression were measured.

Some 38 tests on cylinders with three different configurations were performed. Dimensions of the test specimens are given in Table 1. Only representative test results of each cylinder configuration will be presented in this report.

Table 1. Test cylinder dimensions

Specimen configuration	Outside diameter mm	Inside diameter mm	Height mm	Number of tests
Solid cylinder	35	-	60	9
Solid cylinder	60	-	60	8
Hollow cylinder	60	35	60	21

Clay samples for this study were obtained from the test site at Skå Edeby of the Swedish Geotechnical Institute. Clay cores of 60 mm diameter were extracted from a depth of between 4 m and 6.7 m in three closely spaced boreholes using a piston sampler which was provided with thin liner tubes.[1)]

This report is confined to a presentation of the factual information only.

2 TEST APPARATUS AND PROCEDURES

Hollow Cylinder Specimens. The hollow cylinder apparatus used in this study is shown in Figs. 1 and 2. A standard Geonor triaxial cell was used which was modified to test hollow samples with 60 mm outside diameter and 35 mm inside diameter, and a maximum height of about 100 mm.

The test specimen is jacketed between an outer and an inner rubber membrane and supported at top and bottom by rigid ring shaped platens. The contact of the specimen with end platens is made over a sandwich of lubricated thin rubber

1) The in-situ properties of the Skå Edeby clay have been described in several of the Institute's publications, for example in HANSBO, S., 1960. Consolidation of Clay, with Special Reference to Influence of Vertical Sand Drains. Swed. Geot. Inst. Proc. No. 18.

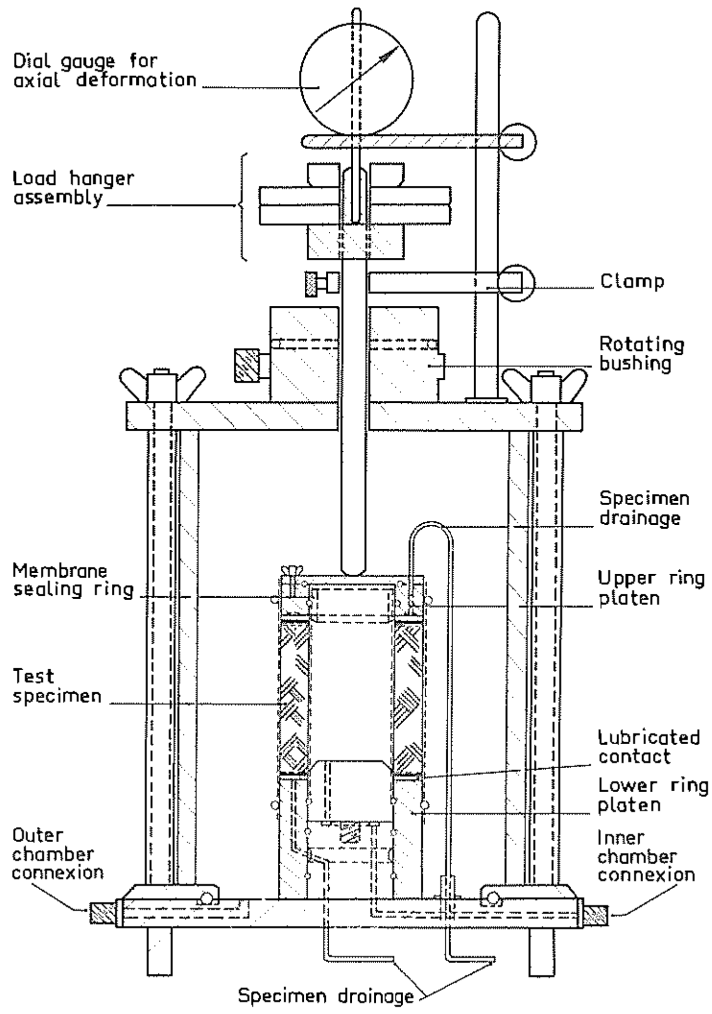


Fig. 1 Hollow cylinder apparatus for clay cylinders

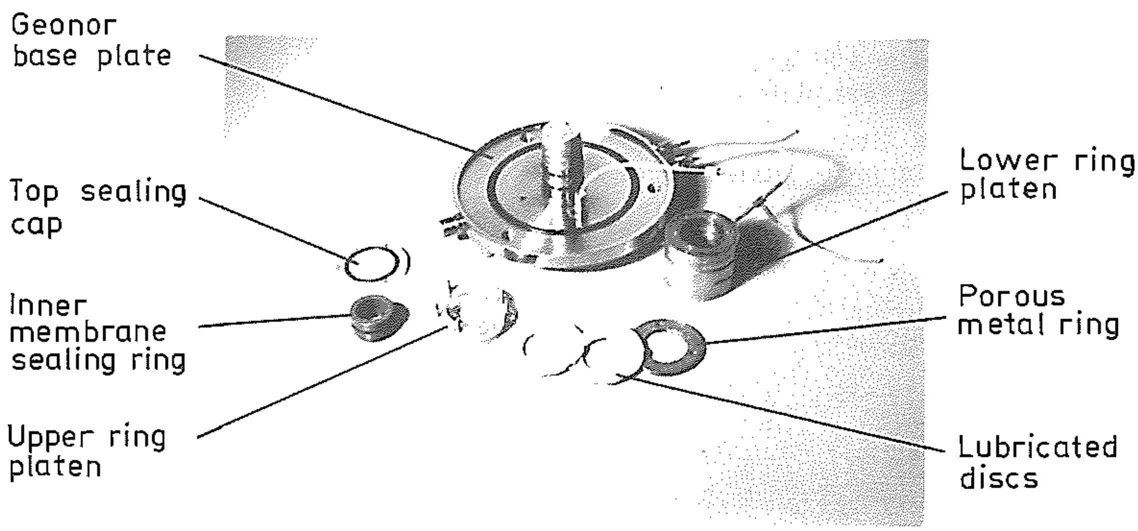
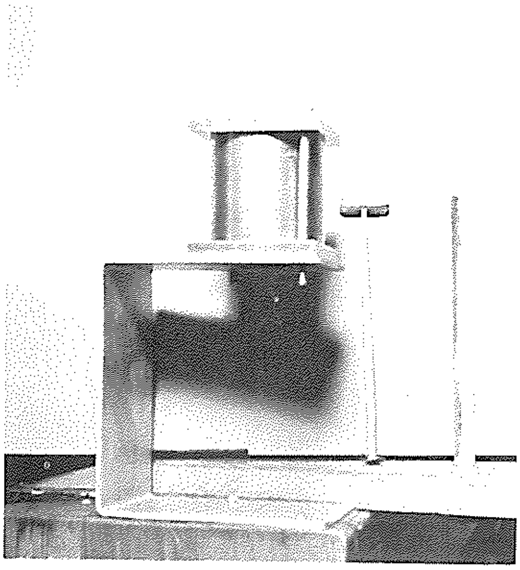
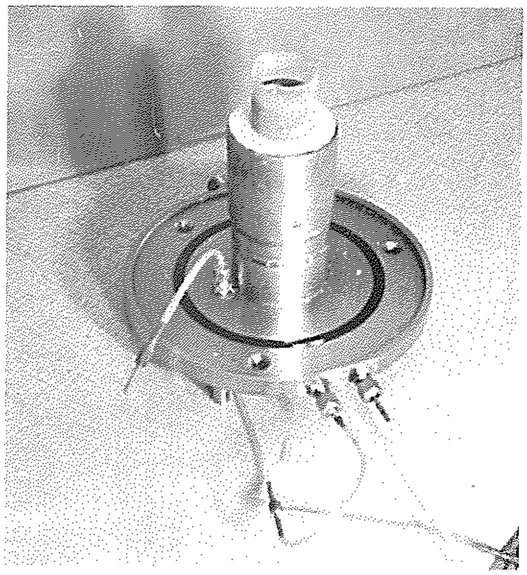


Fig. 2 Component parts of the hollow cylinder apparatus



(a)



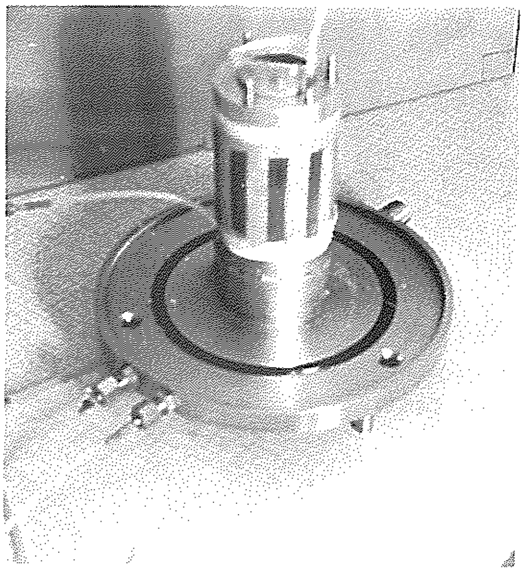
(b)

Fig. 3

(a) above. Brass sleeve containing clay core is mounted on stand; 1 cm dia. hand auger and curved blade

(b) above right. Hollow cylinder specimen contained in brass sleeve is assembled on test platen

(c) below right. Brass sleeve removed and filter paper strips wrapped around the cylinder surface



(c)

sheets placed over smooth teflon discs which in turn rested upon porous metal rings as shown in Fig. 1. By this manner contact friction between the specimen and the test platens was minimized. Thin strips of filter paper with about 10 mm width were wrapped around the outer circumference of the clay cylinder, see Fig. 3c. The filter paper strips extended to porous metal rings at top and bottom to provide drainage during consolidation of the clay cylinder.

A load hanger assembly was designed, as shown in Fig. 1, to measure axial deformations of the test cylinders during the consolidation phase of each test. A dial gauge was mounted on the plunger. Counter-weights equal to the uplift force exerted upon the plunger by the hydrostatic pressure were added to the loading pan so that the plunger remained in contact with the test specimen cap during consolidation.

Hollow Cylinder Specimen Preparation. The hollow specimens were prepared by first placing the 60 mm diameter clay core, contained in a brass sleeve, between two plates on a vertical stand as shown in Fig. 3a. Each plate had a hole of 35 mm diameter at the centre. A small pilot hole of about 10 mm diameter was made through the centre of clay core with a small auger. This hole was then enlarged to 35 mm diameter by gradually removing the clay in thin circumferential slices using a sharp blade.

The tubular clay sample contained in brass sleeve was thereafter placed on the lubricated pedestal of the base plate, as shown in Fig. 3b. The upper pedestal was assembled making sure that the inner rubber membrane was in contact with the inside face of the tubular core. The brass sleeve was then removed and filter paper strips were wrapped around the outer surface, Fig. 3c. The outside rubber membrane was thereafter placed around the sample. The test specimen was sealed then by O-rings stretched over the top and bottom pedestals.

Freshly boiled water was circulated slowly from the bottom to the top of the test specimen to displace air bubbles which might become entrapped in the test cylinder during setting-up. The sealed test cylinder was next subjected to a negative pressure by lowering the drainage burette about 10 mm, to remove the excess water which had accumulated during saturation of the test cylinder.

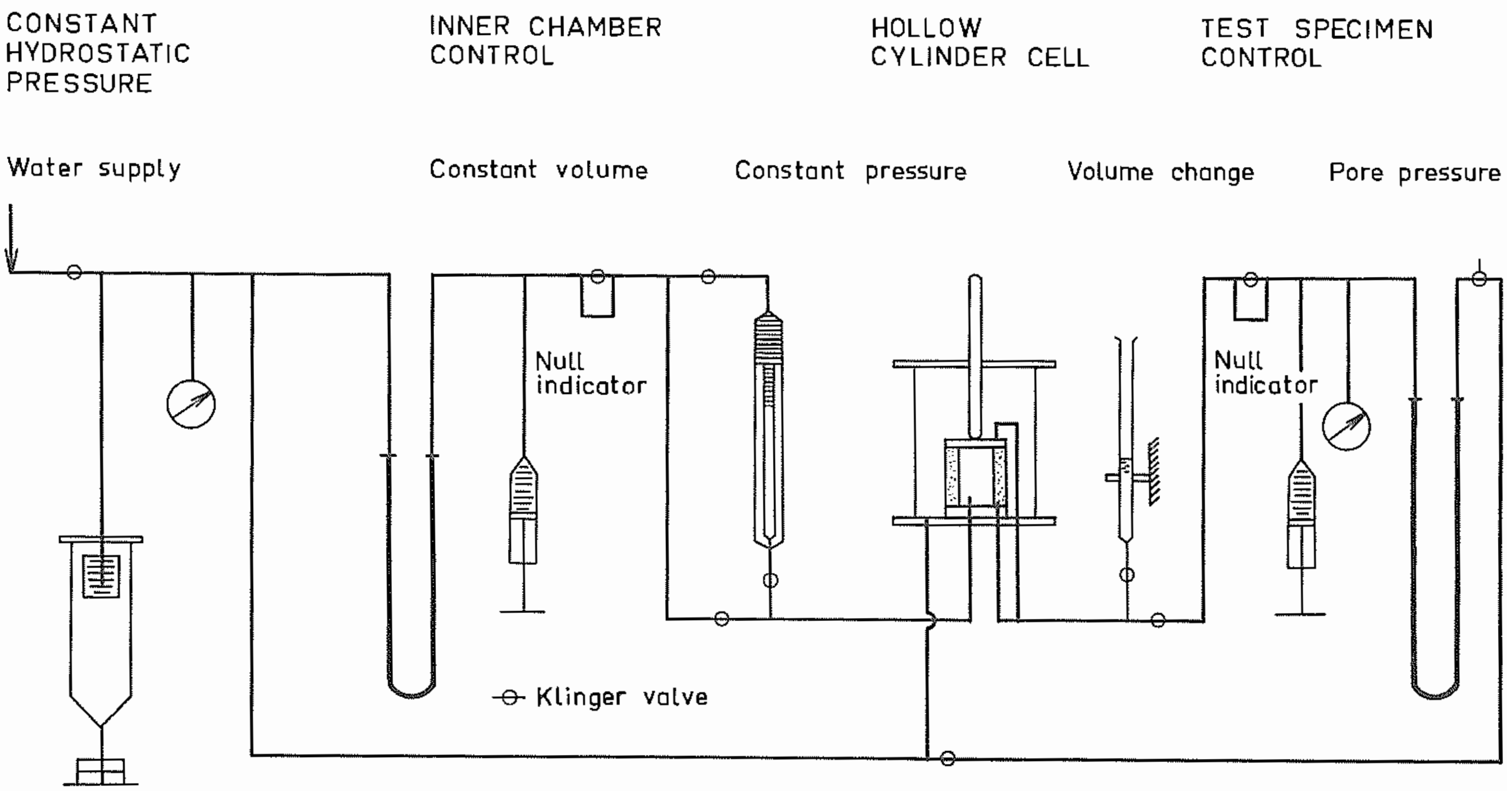


Fig. 4 Apparatus arrangement for hollow cylinder test

The inner chamber of the tubular cylinder was then filled with water. The top sealing cap was attached while the water was overflowing from the inner chamber.

Solid Cylinder Specimens. Solid cylinder specimens with 35 mm and 60 mm diameter were tested in standard Geonor triaxial apparatus. The 35 mm test cylinders were trimmed from the 60 mm core samples.

The friction at top and bottom of the specimen was minimized by the use of thin rubber sheets which were smeared with silicone grease and a smooth teflon disc inserted between the test cylinder and the porous stones, in the same manner as described for the hollow cylindrical specimen. Filter paper strips were wrapped around the specimen circumference to facilitate pore water drainage to the upper and lower porous plates.

Consolidation under Hydrostatic Pressure. All specimens were consolidated for about 22 hours at an all-round pressure of 2 kg/cm^2 (200 kN/m^2), which was applied in one increment. Arrangement of the test apparatus during consolidation and during axial compression phases of the test is shown schematically in Fig. 4.

For all specimens, axial deformations Δh and volume changes $(\Delta V)_s$ were measured during the consolidation. Recordings of these deformation parameters were made at regular intervals of time during the initial phase of consolidation, over a period of about 8 hours.

Some of the hollow clay cylinders were consolidated at inside chamber pressure σ_{ri} which was equal to the outside chamber pressure σ_{ro}. For this case with equal boundary radial stresses $\sigma_{ro} = \sigma_{ri}$ the volume changes $(\Delta V)_i$ of the inner chamber were measured by a gauge connected in series with the constant cell pressure system as shown in Fig. 4.

The volume of the inner chamber was held constant for the remainder of the hollow cylinder tests. The resulting pressure changes $\Delta\sigma_{ri}$ in the inner chamber were measured by a null indicator and a differential mercury manometer (see Fig. 4) which registered the pressure difference between the outer and the inner chamber of the hollow cylinder.

Undrained Axial Compression. At the completion of consolidation, the test cylinders were subjected to axial compression at a constant strain rate of approximately 0.03 percent per min. The pore-water pressures generated in the test cylinders were recorded. The compression tests were terminated, generally, when the axial load measured by proving ring reached a terminal value.

Some of the hollow cylinders were tested in axial compression with equal outside and inside chamber pressures. The corresponding volume changes $(\Delta V)_i$ for the inner chamber were recorded. Generally the hollow cylinders which had been consolidated at equal chamber pressures $\sigma_{ro} = \sigma_{ri}$ were also tested in axial compression at equal chamber pressures $\sigma_{ro} = \sigma_{ri}$.

The hollow cylinders which had been consolidated at constant volume of the inner chamber were tested in axial compression at constant volume of the inner chamber. The inner chamber was sealed during these tests. The corresponding pressure changes, $\Delta\sigma_{ri}$, in the inner chamber were recorded as during the consolidation phase of test.

3 EXPERIMENTAL RESULTS

Experimental results from four representative tests of each specimen configuration are presented herein. The stress and strain parameters for each test were computed as per the formulae given in the Appendix. For convenience the test results for consolidation and axial compression phases of each test are treated separately.

Consolidation under All-round Hydrostatic Pressure. The volumetric strain $(\Delta V/V)_s$, axial strain ε_z , as well as the boundary strains $\varepsilon_{\theta o} = \varepsilon_{ro}$ for the solid cylinder specimens during consolidation are shown in Figs. 5 and 6. The consolidation behaviour of the solid clay cylinders with 35 mm and 60 mm diameter show similar characteristics. The boundary strains $\varepsilon_{\theta o} = \varepsilon_{ro}$ at the completion of consolidation were approximately equal to the axial strain ε_z .

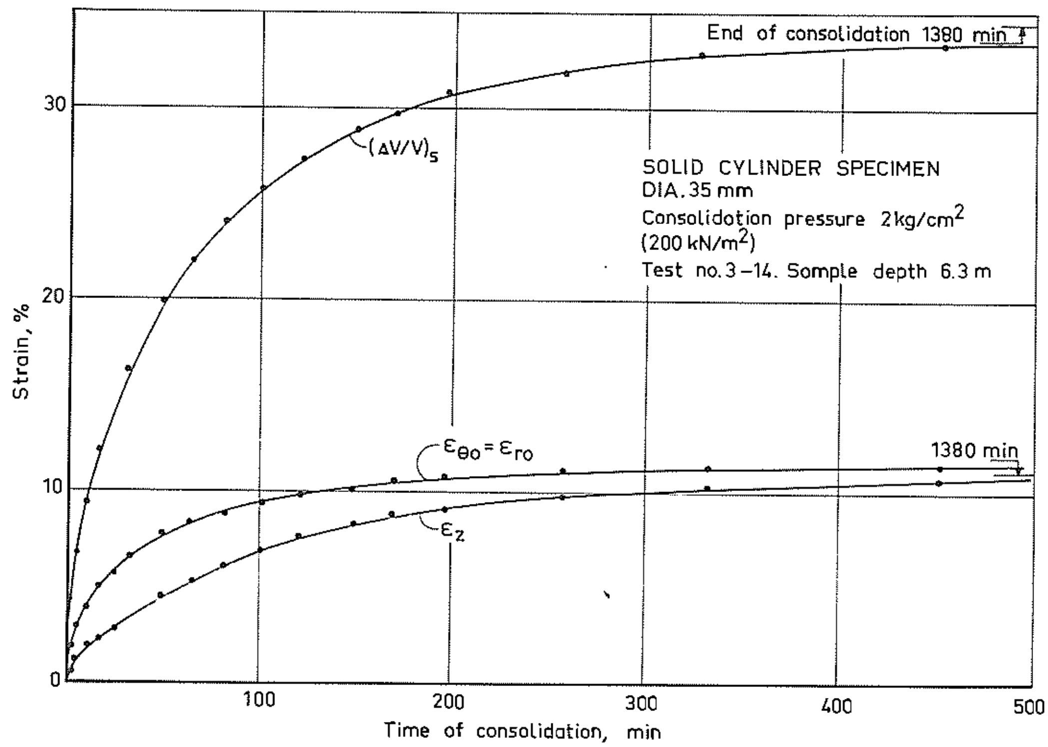


Fig. 5 Consolidation test parameters. Solid cylinder specimen dia. 35 mm

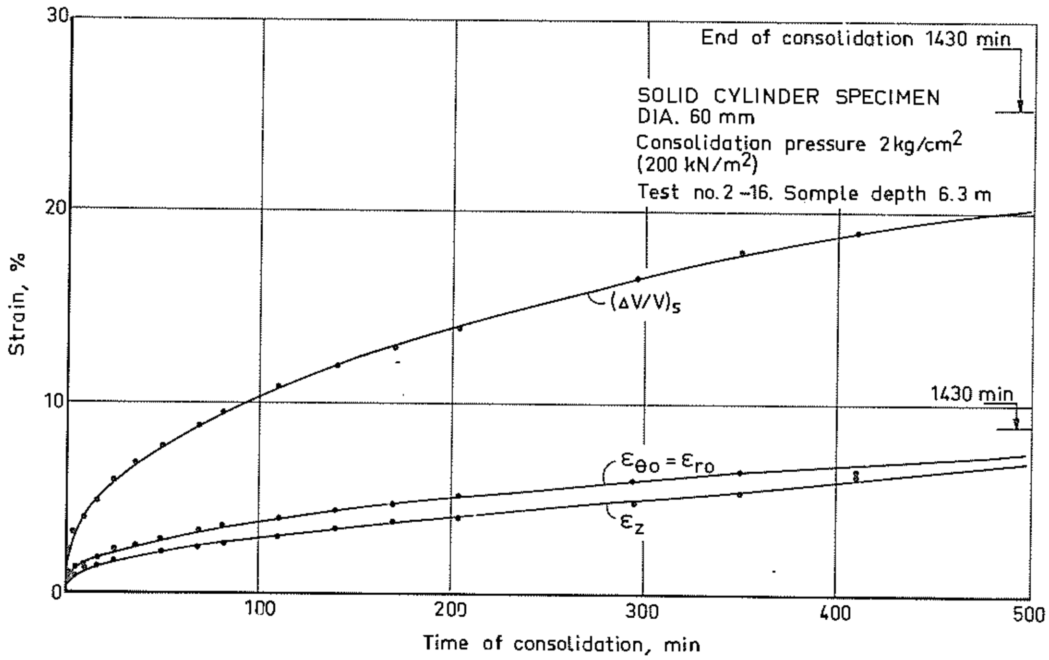


Fig. 6 Consolidation test parameters. Solid cylinder specimen dia. 60 mm

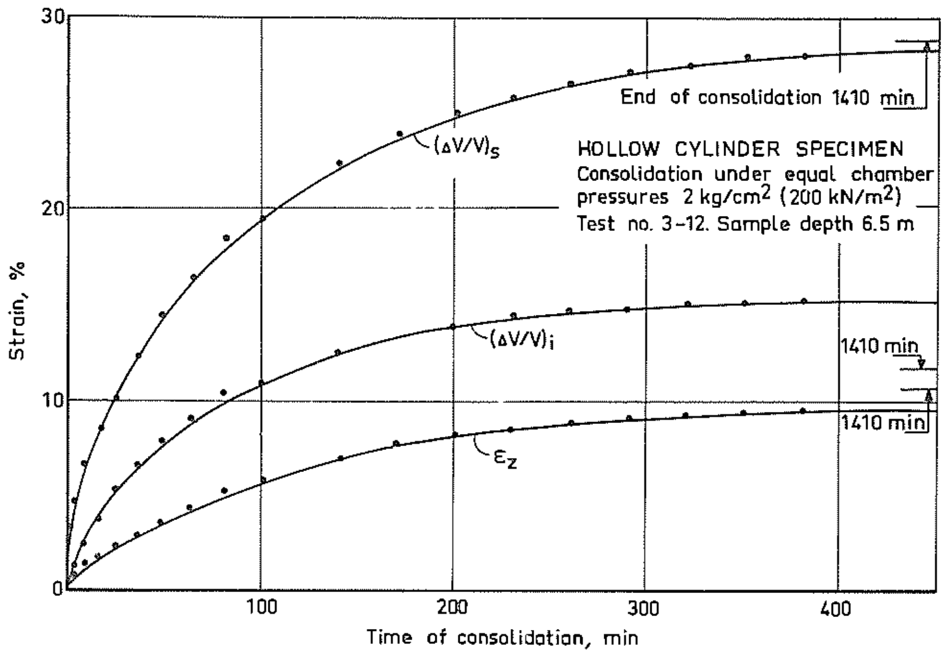


Fig. 7a Consolidation test parameters. Hollow cylinder specimen with drained inner chamber and $\sigma_{ro} = \sigma_{ri}$

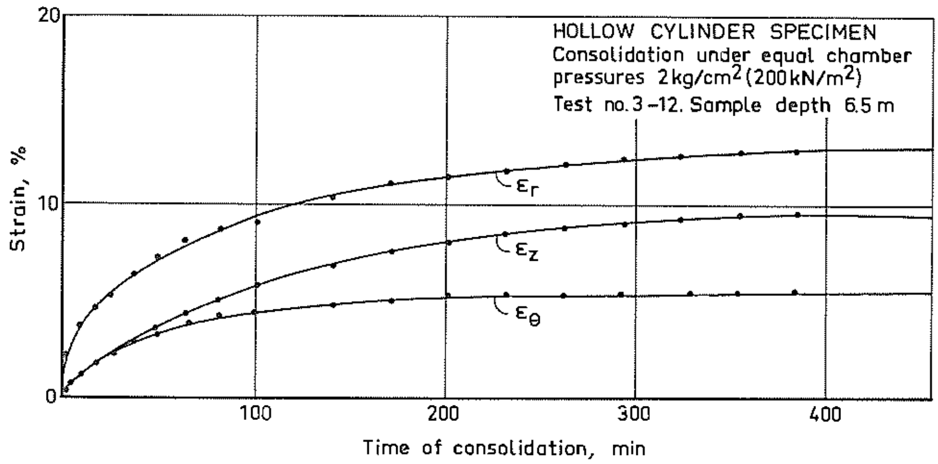


Fig. 7b Principal strains during consolidation. Hollow cylinder specimen with drained inner chamber and $\sigma_{ro} = \sigma_{ri}$

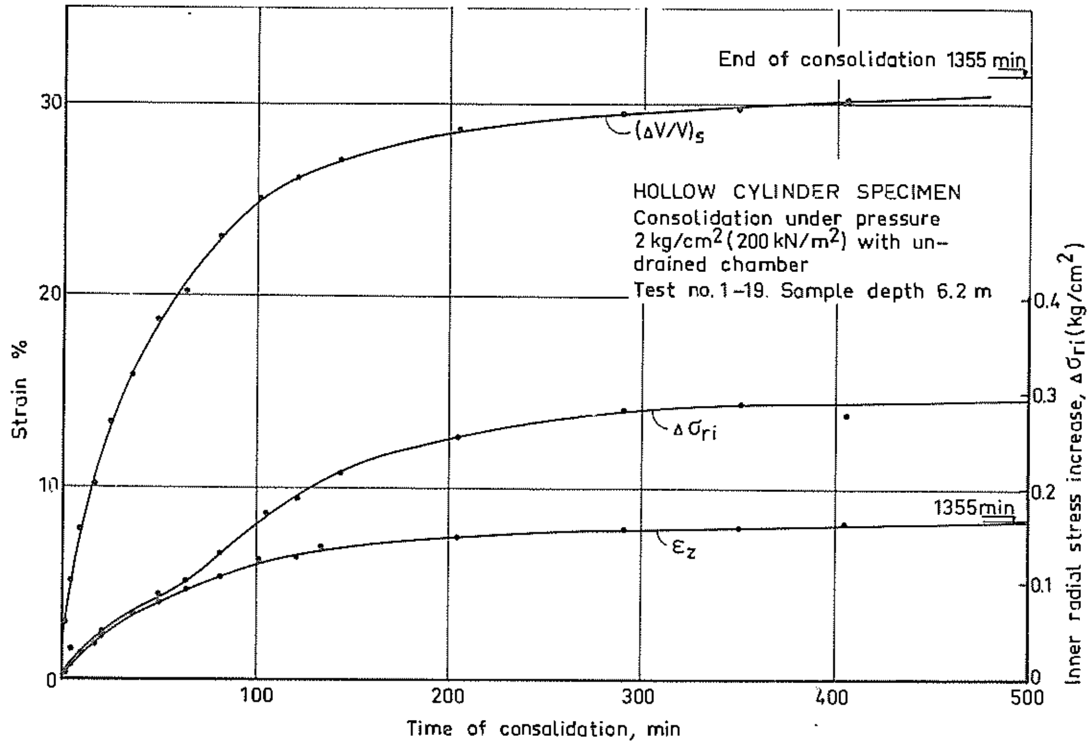


Fig. 8a Consolidation test parameters. Hollow cylinder specimen with undrained inner chamber

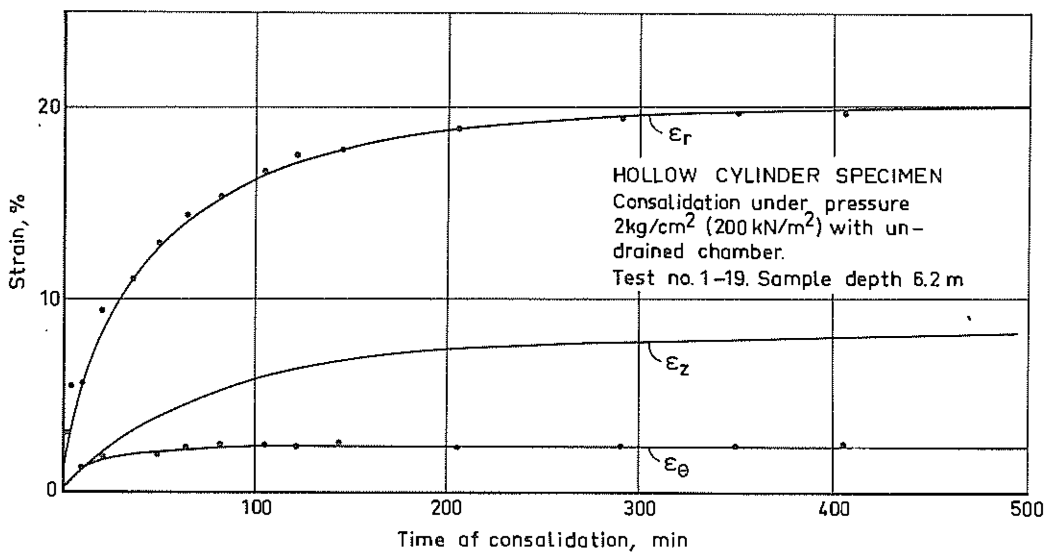


Fig. 8b Principal strains during consolidation. Hollow cylinder specimen with undrained inner chamber

Test results of hollow cylinder specimen consolidated under equal outside and inside chamber pressures, $\sigma_{ro} = \sigma_{ri}$, are shown in Figs. 7a and 7b. It is seen that the measured volumetric strain $(\Delta V/V)_i$ for the inner chamber is lower than the clay cylinder strain $(\Delta V/V)_s$ for the entire consolidation period. The volumetric strains $(\Delta V/V)_i$ and $(\Delta V/V)_s$ have been converted into the average strains[2] ε_θ and ε_r and the latter are plotted in Fig. 7b. It is noted that the radial strain ε_r is about two to three times the circumferential strain ε_θ . This constitutes a significant experimental finding[3]. This behaviour was consistently noted for all hollow samples which were consolidated under equal outside and inside chamber pressure condition of $\sigma_{ro} = \sigma_{ri}$.

Figs. 8a and 8b show the consolidation results of hollow cylinder specimen when the inner chamber volume was kept constant. The important finding here is that the inner chamber pressure σ_{ri} which is equal to the radial stress at the inside face of specimen, increased during the consolidation relative to the constant outer chamber pressure σ_{ro} . An increase in inner radial stress $\Delta\sigma_{ri}$, of between 10 to 15 percent of the constant maintained σ_{ro} was consistently noted for all hollow clay cylinders which were consolidated under this boundary condition. The computed radial strain ε_r , for this test case is about seven times the corresponding circumferential strain ε_θ as shown in Fig. 8b.

Apart from the noted differences in the circumferential and radial strains ε_θ and ε_r , and the increase in inner radial stress $\Delta\sigma_{ri}$, a consistent pattern of variation in other of the test parameters e.g. the volumetric strain $(\Delta V/V)_s$

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2) ε_θ and ε_r as well as ε_z and $(\Delta V/V)$ have been expressed as absolute strains in this study. The use of natural strains instead of absolute strains as deformation parameters is of little significance for the purpose of this study.

3) Mathematical theory of inequality of the strains ε_θ , ε_r with volumetric change in right cylinder specimen is given in:

JAMAL, A.K., 1966. The Distribution of Radial Stress in the Triaxial Strength Test of a Cohesionless, Granular Soil. Thesis submitted to Cornell University, USA, in September 1966, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

or the axial strain ε_z , could not be discerned in the present series of hollow cylinder experiments with constant pressure or constant volume condition of the inner chamber. It was also not possible to relate the hollow specimen consolidation parameters to the corresponding solid specimen parameters. A clearer picture of the consolidation test parameters is, in this respect, difficult to form because of the previous stress history of the in-situ extracted samples as well as the random variations in their natural properties.

Undrained Axial Compression Tests. Results of the axial compression tests on solid cylinder specimens are presented in Figs. 9 and 10. These are notable chiefly for the differences in pore-water pressure variations in the test specimens with 35 mm and 60 mm diameter, as reflected by the effective radial stress σ'_{ro} . The maximum deviator stress $\sigma'_{z\ ext}$, was approximately equal for the two test cylinders. Also the stress ratio (σ'_z / σ'_{ro}) variations show similar characteristics.

It can be seen from Figs. 11 and 12 for the hollow cylinder compression tests, that the deviator stress $\sigma'_{z\ ext}$ is somewhat higher when the inner chamber volume was held constant during axial compression in comparison to the case when the inner chamber pressure was held constant. However, this difference is attributed to the randomness of the in-situ extracted samples. An examination of all of the hollow cylinder test results did not reveal any consistent variation in the $\sigma'_{z\ ext}$ values for either the drained or the undrained inner chamber condition. In comparison with the solid cylinders, especially the 60 mm test specimens, the maximum deviator stress $\sigma'_{z\ ext}$, for the hollow cylinders was consistently higher. The differences, however, are considered to be only marginal.

For all clay cylinders, the principal stress ratios expressed as (σ'_z / σ'_r) or ($\sigma'_z / \sigma'_\theta$) increased with the increasing axial deformation. A maximum value of the stress ratios was not reached for any of the tests. If the stress ratios in the individual test specimens at the maximum $\sigma'_{z\ ext}$ condition are arbitrarily compared, it is observed that the (σ'_z / σ'_{ro}) values for the solid cylinder specimens are approximately equal. The solid cylinder (σ'_z / σ'_{ro}) ratios tend to be higher than the (σ'_z / σ'_r) values for the hollow cylinders. However, the hollow cylinder strength as expressed by ($\sigma'_z / \sigma'_\theta$) is greater than the solid cylinder strength as expressed by the stress ratio (σ'_z / σ'_{ro}).

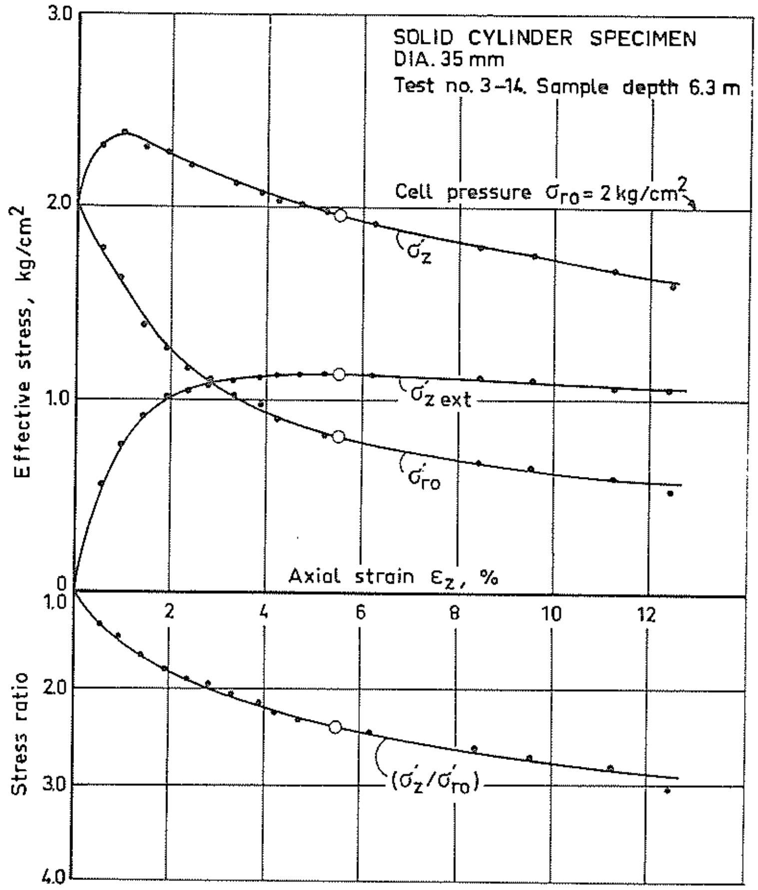

Fig. 9 Undrained axial compression test. Solid cylinder specimen dia. 35 mm

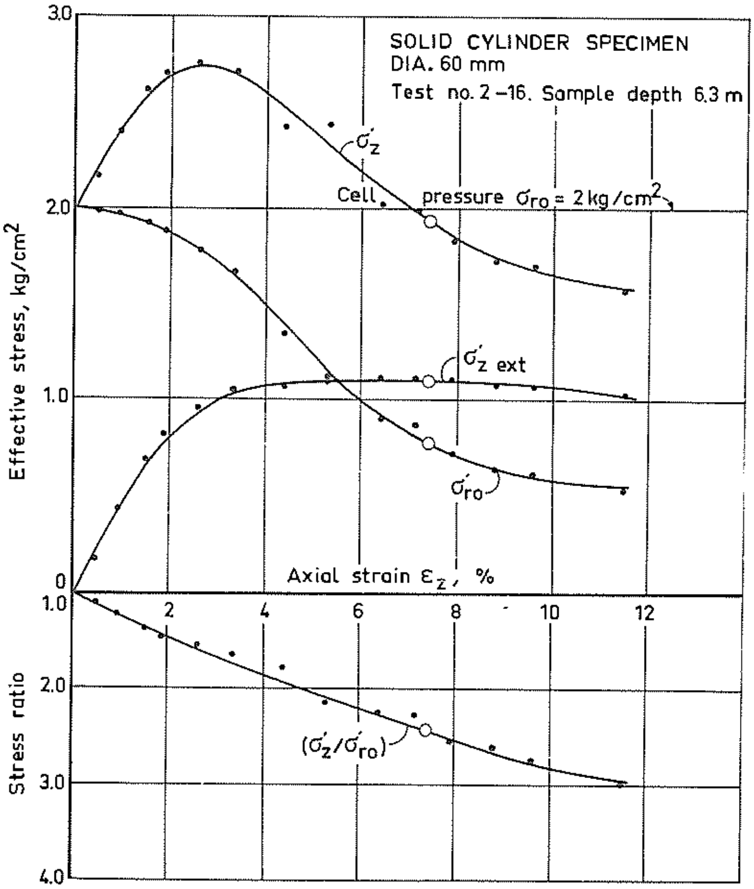

Fig. 10 Undrained axial compression test. Solid cylinder specimen dia. 60 mm

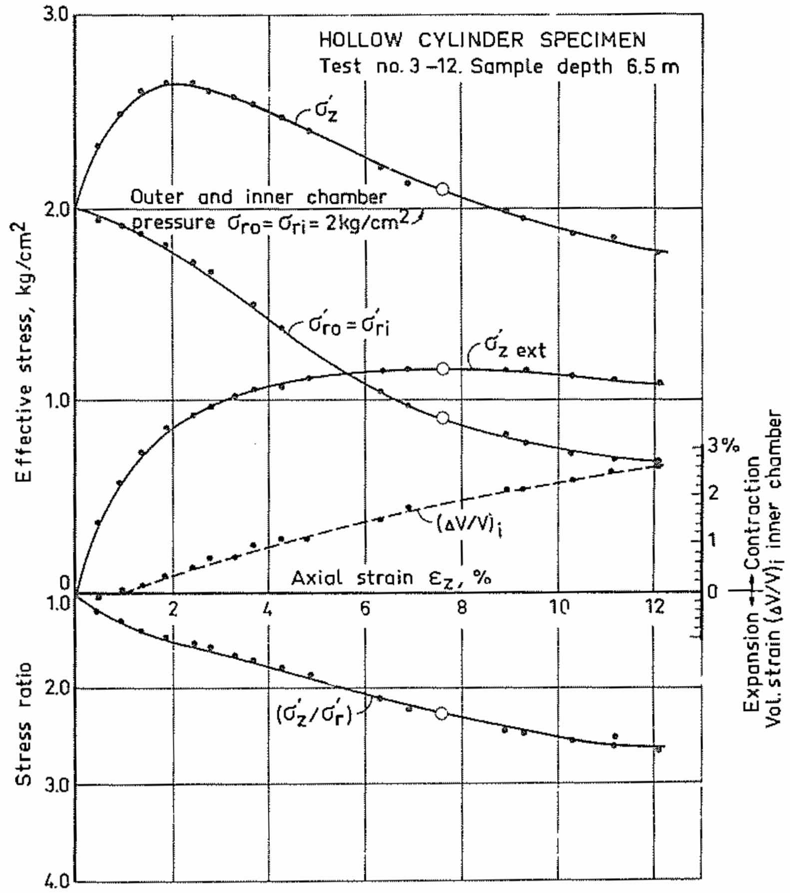

Fig. 11 Undrained axial compression test. Hollow cylinder specimen with drained inner chamber and $\sigma_{ro} = \sigma_{ri}$

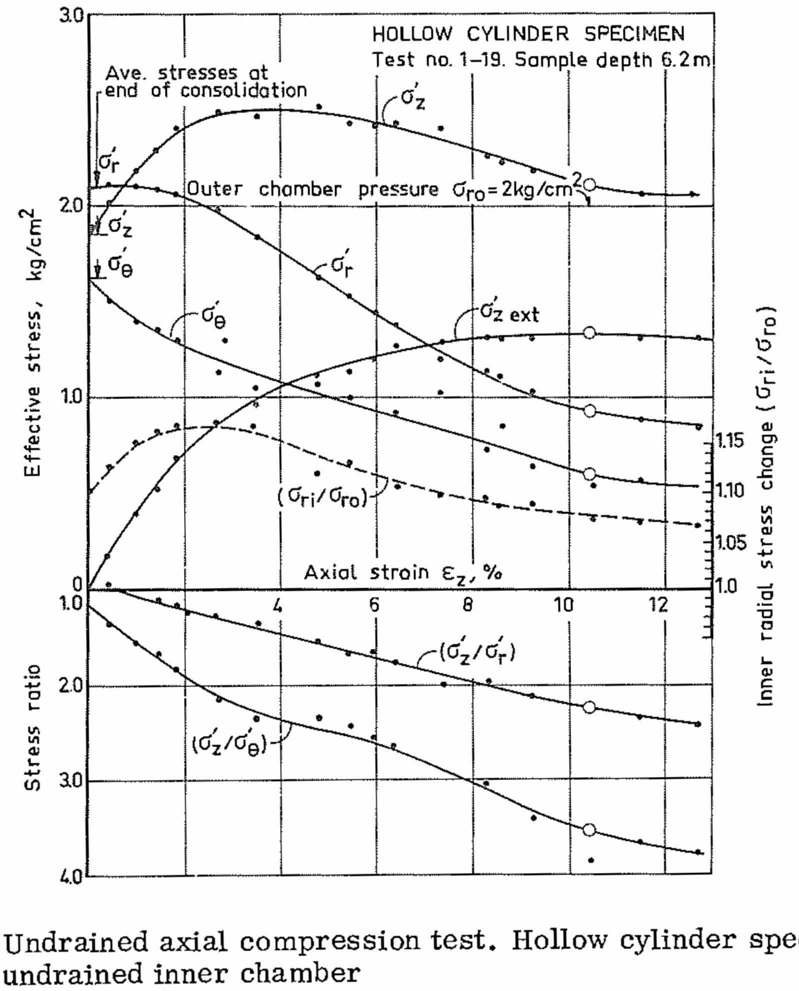

Fig. 12 Undrained axial compression test. Hollow cylinder specimen with undrained inner chamber

The radial stress σ_{ri} at the inside face of all hollow cylinder specimens which were subjected to axial compression with constant volume of the inner chamber, increased during the initial test stages and later decreased as shown by the variation of the total stress ratio σ_{ri}/σ_{ro} in Fig. 12. The initial value of σ_{ri}/σ_{ro} corresponds to the stress condition in the test specimen at the end of consolidation. For the hollow cylinder test with a drained inner chamber and constant chamber pressures $\sigma_{ro} = \sigma_{ri}$, a volume decrease in the inner chamber occured for all of the tests, as exemplified by the plot of $(\Delta V/V)_i$ in Fig. 11.

4 SUMMARY

From the presented experimental results, it is shown that during consolidation of the hollow cylinder clay specimen under an all-round pressure, the radial strain ε_r was much larger than the circumferential strain ε_θ. The radial effective stress σ'_r in the cylinder wall was found to be greater than the circumferential effective stress σ'_θ during axial compression of the hollow cylinder under undrained condition. The deviator stress $\sigma'_{z\ ext}$ at failure for the hollow cylinders was marginally higher than the maximum deviator stress for the solid samples with 35 mm or 60 mm diameter. The deformation characteristics of solid cylinders as expressed by the pore-water pressure changes during axial compression in the undrained state, were dissimilar for the test cylinders with 35 mm and 60 mm diameter in spite of similarity of the test boundary conditions.

ACKNOWLEDGEMENTS

The work reported herein was done in 1966-67 when the Author was employed at the Swedish Geotechnical Institute. Part of the Author's funds during this period were provided by a grant from the Swedish National Council for Building Research. To both these institutions, the Author expresses his sincere gratitude.

Acknowledgement is made of the assistance at the design of the test apparatus provided by Mr A. Hallén, Mechanical Department of the Institute.

APPENDIX

Formulae for Strain and Stress Computations in Hollow Cylinder Specimen.

Compressive strains and stresses are reckoned positive in the following equations. All stresses are assumed to be effective stresses unless specified otherwise.

Axial Strain ε_z - is computed as the ratio[4] of the change in cylinder height Δh to the initial height h of the specimen, thus

$$\varepsilon_z = \frac{\Delta h}{h} \tag{1}$$

For the consolidation phase of test, h corresponds to the cylinder height after trimming of the sample, while for the axial compression test h corresponds to the specimen height at the end of consolidation.

Volumetric Strains $(\Delta V/V)_i$, $(\Delta V/V)_s$ - The volumetric change in the inside chamber $(\Delta V)_i$ and the clay cylinder $(\Delta V)_s$ are expressed as the volumetric strains $(\Delta V/V)_i$ and $(\Delta V/V)_s$ referenced respectively to the volume of the inside chamber V_i and the clay cylinder V_s. For the consolidation test, V_i and V_s correspond to the specimen volume after trimming the sample.

The volumetric strain $(\Delta V/V)_i$ in the hollow cylinder during axial compression, corresponds to the volume of inner chamber at the end of consolidation.

Boundary Strains $\varepsilon_{\theta i} = \varepsilon_{ri}$ and $\varepsilon_{\theta o} = \varepsilon_{ro}$ - The boundary strain $\varepsilon_{\theta i} = \varepsilon_{ri}$ at the inner circumferential plane of hollow cylinder is computed from the known volumetric strain $(\Delta V/V)_i$ and the compatibility relationship, assuming small strains as

$$\left(\frac{\Delta V}{V}\right)_i = \varepsilon_z + 2\varepsilon_{\theta i} = \varepsilon_z + 2\varepsilon_{ri} \tag{2}$$

4) See foot-note 2 on page 14

Similarly the outer boundary strain $\varepsilon_{\theta o} = \varepsilon_{ro}$ is computed from

$$\left(\frac{\Delta V}{V}\right)_o = \varepsilon_z + 2\varepsilon_{\theta o} = \varepsilon_z + 2\varepsilon_{ro} \tag{3}$$

where $(\Delta V/V)_o$ is the volumetric strain for the clay cylinder and the inner chamber, thus

$$\left(\frac{\Delta V}{V}\right)_o = \frac{\Delta V_s + \Delta V_i}{V_s + V_i} \tag{4}$$

<u>Radial Strain ε_r</u> - is computed from the known boundary strains $\varepsilon_{\theta i} = \varepsilon_{ri}$ and $\varepsilon_{\theta o} = \varepsilon_{ro}$ and is expressed as the unit change in the finite cylinder thickness ($r_o - r_i$), thus

$$\varepsilon_r = \frac{\varepsilon_{\theta o} r_o - \varepsilon_{\theta i} r_i}{r_o - r_i} \tag{5}$$

where r_o and r_i are the outside and inside radii respectively, of the test cylinder.

<u>Circumferential Strain ε_θ</u> - is calculated from the volume compatibility relationship written as

$$\left(\frac{\Delta V}{V}\right)_s = \varepsilon_z + \varepsilon_r + \varepsilon_\theta \tag{6}$$

where ($\Delta V/V$)$_s$ is the clay cylinder strain and the strains ε_z and ε_r are computed from Eqs. 1 and 5, respectively.

<u>Axial Stress σ'_z</u> - In the absence of an externally applied axial load, the axial stress $\sigma'_{z\ int}$ due to unequal chamber pressures in the hollow cylinder is calculated from the requirement of equilibrium as,

$$\sigma'_{z\ int} = \frac{\sigma'_{ro} r_o^2 - \sigma'_{ri} r_i^2}{r_o^2 - r_i^2} \tag{7}$$

where σ'_{ro} and σ'_{ri} are the outside and inside chamber pressures, respectively. The externally applied axial load P causes a deviator stress $\sigma'_{z\ ext}$ to act upon the test specimen given by

$$\sigma'_{z\ ext} = \frac{P}{A_s} \tag{8}$$

where A_s is the current cross-sectional area of the test cylinder. The average axial stress σ_z' is then given by

$$\sigma_z' = \sigma_{z\ ext}' + \sigma_{z\ int}' = \frac{P}{A_s} + \frac{\sigma_{ro}' r_o^2 - \sigma_{ri}' r_i^2}{r_o^2 - r_i^2} \tag{9}$$

<u>Radial Stress σ_r'</u> - is taken as the mean of the known outer and inner boundary radial stresses as

$$\sigma_r' = \frac{\sigma_{ro}' + \sigma_{ri}'}{2} \tag{10}$$

<u>Circumferential Stress σ_θ'</u> - is computed from the requirement of equilibrium in the lateral direction of the test cylinder and is given by

$$\sigma_\theta' = \frac{\sigma_{ro}' r_o - \sigma_{ri}' r_i}{r_o - r_i} \tag{11}$$

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