THE SIGNIFICANCE OF CAP AND BASE RESTRAINT IN STRENGTH TESTS ON SOILS

A Report of an Investigation by

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under

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SUMMARY

The objective of this investigation was to determine the significance of the various effects of cap and base restraint in strength tests on soils. The normal caps and bases used in strength tests prevent lateral expansion of the top and bottom of test specimens. Previous studies have shown that this restraint causes nonuniform volume changes in drained tests, moisture migration in undrained tests, and, in rapidly conducted tests, nonuniformities in pore-water pressure in undrained clay specimens.

Lubricated caps and bases were used to eliminate end restraint in undrained triaxial and plane strain tests on undisturbed saturated clay. The results of these tests were compared with the results of tests performed using normal caps and bases to assess the significance of cap and base restraint. These tests showed that the magnitude of the effects of cap and base restraint are not significant. The strength of specimens tested with normal caps or bases is typically about 5 percent greater than the strength of specimens tested with lubricated caps and bases, and the changes in pore-water pressures are also about 5 percent higher. In tests conducted slowly enough to permit 95 percent or greater equalization of nonuniform pore-water pressures, the values of the pore-pressure coefficient $\bar{A}$ were found to be the same with either type of cap and base.

The results of these tests are in substantial agreement with the results of undrained tests on clay and drained tests on sand which have been performed by other investigators. Only in cases where accurate measurement of volume changes are required in drained tests, or where moisture migration must be prevented in undrained tests, will lubricated caps and bases be necessary.

In conjunction with this investigation a procedure was developed for insuring the effectiveness of lubrication in eliminating cap and base restraint. The same techniques may also be used to calculate the frictional forces between plane strain specimens and their end plates.

FOREWARD

The work described in this report was performed under Contract No. DA-22-079-CIVENG-62-47, "Shear Properties of Undisturbed Weak Clays," between the U. S. Army Engineer Waterways Experiment Station and the University of California.

The general objective of this research, which was begun in February, 1962, is to investigate the influence of pore-water pressure on the strength characteristics of undisturbed weak clays. Work on this project is conducted under the supervision of H. Bolton Seed, Professor of Civil Engineering, J. M. Duncan, Assistant Professor of Civil Engineering, and C. K. Chan, Associate Research Engineer. The project is administered by the Office of Research Services of the College of Engineering.

The phase of the investigation described in this report was performed by P. Dunlop and G. A. Ross, Research Assistants, and the report was prepared by J. M. Duncan and H. Bolton Seed. This is the fifth report on investigations performed under this contract. The previous reports are "The Effects of Sampling and Disturbance on the Strength of Soft Clays," Report No. TE 64-1, February, 1964; "The Effect of Anisotropy and Reorientation of Principal Stresses on the Shear Strength of Saturated Clay," Report No. TE 65-3, (Contract Report No. 3-132) November, 1965; "Errors in Strength Tests and Recommended Corrections," Report No. TE 64-4, (Contract Report No. 3-133) November, 1965; and "The Effects of Temperature Changes During Undrained Tests," Report No. TE 65-10 (Contract Report No. 3-134) November, 1965.

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LIST OF SYMBOLS

ENGLISH LETTERS

A	pore pressure coefficient (= $\Delta u/(\Delta\sigma_1 - \Delta\sigma_3)$)
$\overline{A}$	pore pressure coefficient (= $A \cdot B$)
A_s	specimen area
a_t	true area of contact
B	pore pressure coefficient (= $\Delta u/\Delta\sigma_3$)
b	one-half width of strip
C-U	Consolidated Undrained test
c_u	$\frac{1}{2}(\sigma_1 - \sigma_3)_f$
F_{ep}	frictional force on an end plate
F_n	normal force
F_t	tangential force
f	subscript indicating failure, or normal force per unit length
H	height
HPS	Horizontal Plane Strain
HPS-L	Horizontal Plane Strain with lubricated cap and base
h	theoretical thickness of grease between two surfaces
i	as a subscript, indicates initial value
K_o	coefficient of earth pressure at rest
L.L.	Liquid Limit
N.C.	Normally Consolidated
OCR	Overconsolidation Ratio
P.L.	Plastic Limit
p	major principal stress during consolidation
p_c	chamber pressure
p_d	diaphragm pressure
r	radius
t	time
t_{50}	time for 50% consolidation
t_d	time for dissipation of excess pore-water pressure
t_f	time to failure

U-U	Unconsolidated Undrained test
u	pore pressure
VPS	Vertical Plane Strain
VPS-L	Vertical Plane Strain with lubricated cap and base
w_c	water content at the center of a specimen
w_{tb}	water content at the top and bottom of a specimen

GREEK LETTERS

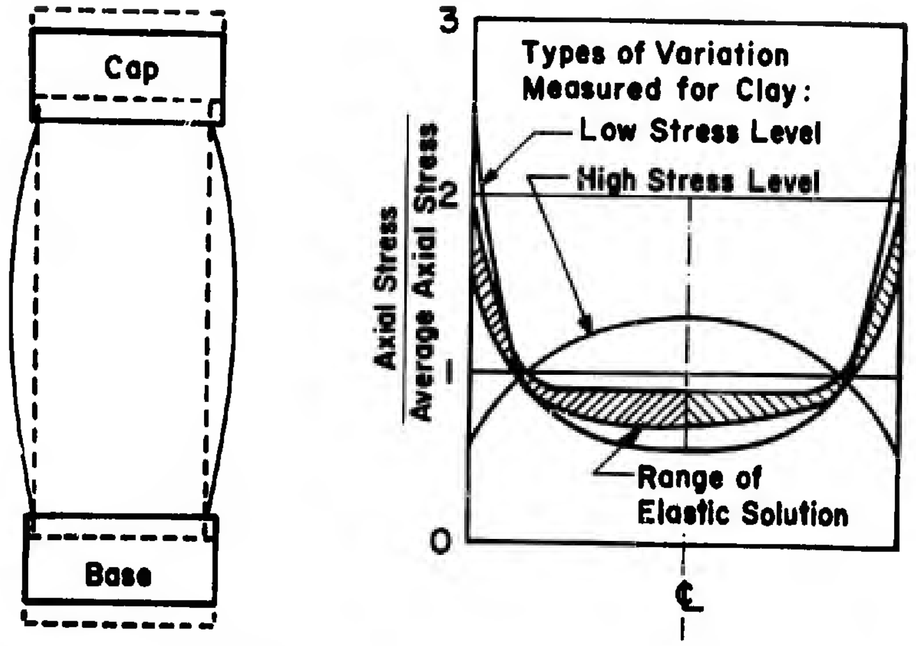
Δ	a prescript indicating a change in the quantity appended, or a correction to the stress in a specimen
$\Delta\sigma_{aep}$	correction to axial stress for end plate friction
ε_a	axial strain
ε_v	volumetric strain
μ_e	effective coefficient of friction
ν	viscosity
σ	normal stress, prime indicates effective stress
σ_a	axial stress
σ_ℓ	lateral stress
$\sigma_1,\sigma_2,\sigma_3$	major, intermediate and minor principal stresses
$(\sigma_1-\sigma_3)$	deviator stress
σ_y	yield value of normal stress
τ	shear stress
τ_y	yield value of shear stress
ϕ'	angle of inclination of a strength envelope plotted in terms of effective stress

NONUNIFORMITIES CAUSED BY CAP AND BASE RESTRAINT

The caps and bases commonly used in triaxial and plane strain tests on soils cause nonuniform deformation of the test specimens. Friction between a soil specimen and its cap and base prevents lateral expansion at the top and bottom with the result that the specimen bulges during compression.

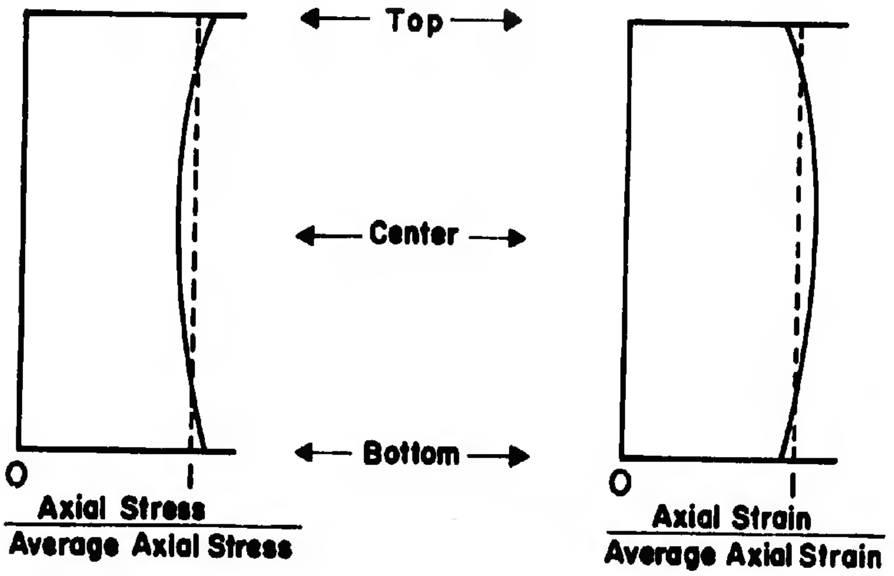
Cap and base friction, and the resultant bulging deformation shown in Fig. 1a, result in nonuniform stresses and strains in the test specimen. Analyses of the stresses in triaxial specimens, based on the theory of elasticity, have been made by Filon (1902), Pickett (1944), D'Appolonia and Newmark (1951) and by Balla (1960). These analyses show that the axial stress at the top or bottom varies from a minimum at the center of a specimen to a maximum at the edge as shown in Fig. 1b; at midheight of a specimen with a height-to-diameter ratio of two or more, the axial stress is essentially uniform. A stress distribution similar to the elastic distribution has been measured at low stress levels in large-diameter triaxial tests on sand (Shockley and Ahlvin, 1960). Barden and McDermott (1965) measured the axial stress near the center and near the edge of the bottom of an unconfined clay specimen; at low stress levels they also found that distribution of axial stress conformed to the elastic distribution, but at higher stress levels the variation reversed, with the maximum axial stress at the center and the minimum at the edge, as shown in Fig. 1b.

Because bulging deformation causes variation in the cross-sectional area of a test specimen, the average value of the axial stress also varies over the height of the specimen, from a maximum at the top and bottom to a minimum at the center. The axial strain values also vary over the height, in roughly the reverse manner from the average axial stress as a result of the larger constraint near top and bottom. Qualitative variations of the axial stress and strain over the height of a specimen are shown in Fig. 1c and 1c. It may be noted that the values of axial stress and axial strain over the center section of a sufficiently



Bulging Deformation of Compression Specimen
(a)

Radial Stress Variations at Top and Bottom
(b)



Longitudinal Stress Variation
(c)

Longitudinal Strain Variation
(d)

FIG. 1.– NON–UNIFORMITIES IN COMPRESSION TEST SPECIMENS DUE TO CAP AND BASE FRICTION

long test specimen would not be significantly influenced by cap and base restraint. Thus the relationship between stress and strain for the soil tested would be closely approximated by the stress and strain values determined for this section. Because the value of axial stress at midheight is smaller than the average value for the specimen as a whole and the value of axial strain is larger, the stress-strain curve derived using the average values will be steeper than the correct stress-strain curve, as shown in Fig. 2

Evidence of nonuniform volumetric strains within test specimens is provided by measurements of volume changes during shear. Shockley and Ahlvin (1960) have reported measurements of volume changes in triaxial specimens of sand during drained tests. Two different techniques for determining volume changes indicated that the volume of all specimens tested increased at the center; at the top and bottom the volume of the sand either decreased or increased less than at the center, depending on test pressure and initial density. Similar behavior has been observed by Blight (1963) during the later stages of a drained triaxial test on heavily overconsolidated clay; during the early stages of the same test, however, the relationship was reversed, with the volume decreasing at the center of the segmented sample and increasing at the top and bottom.

Even in undrained tests, wherein the overall volume change is zero, volume increase in one portion of a specimen may occur if accompanied by volume decrease in another portion. Such volume changes may be studied by measuring the water content of various segments of a specimen after test. The results of such determinations on various types of soil are summarized in Table 1. These data show that moisture tends to migrate from the top and bottom toward the center in specimens of compacted clay, overconsolidated clay, or remoulded clays which exhibit decrease in pore-water pressure or relatively small increases in pore-water pressure during undrained shear. For normally consolidated or very lightly overconsolidated clays, in which large increases in pore-water pressure would occur during shear, the moisture migration is from the center toward the top and bottom. This latter tendency has been observed in San Francisco Bay Mud in about two-thirds of the tests where

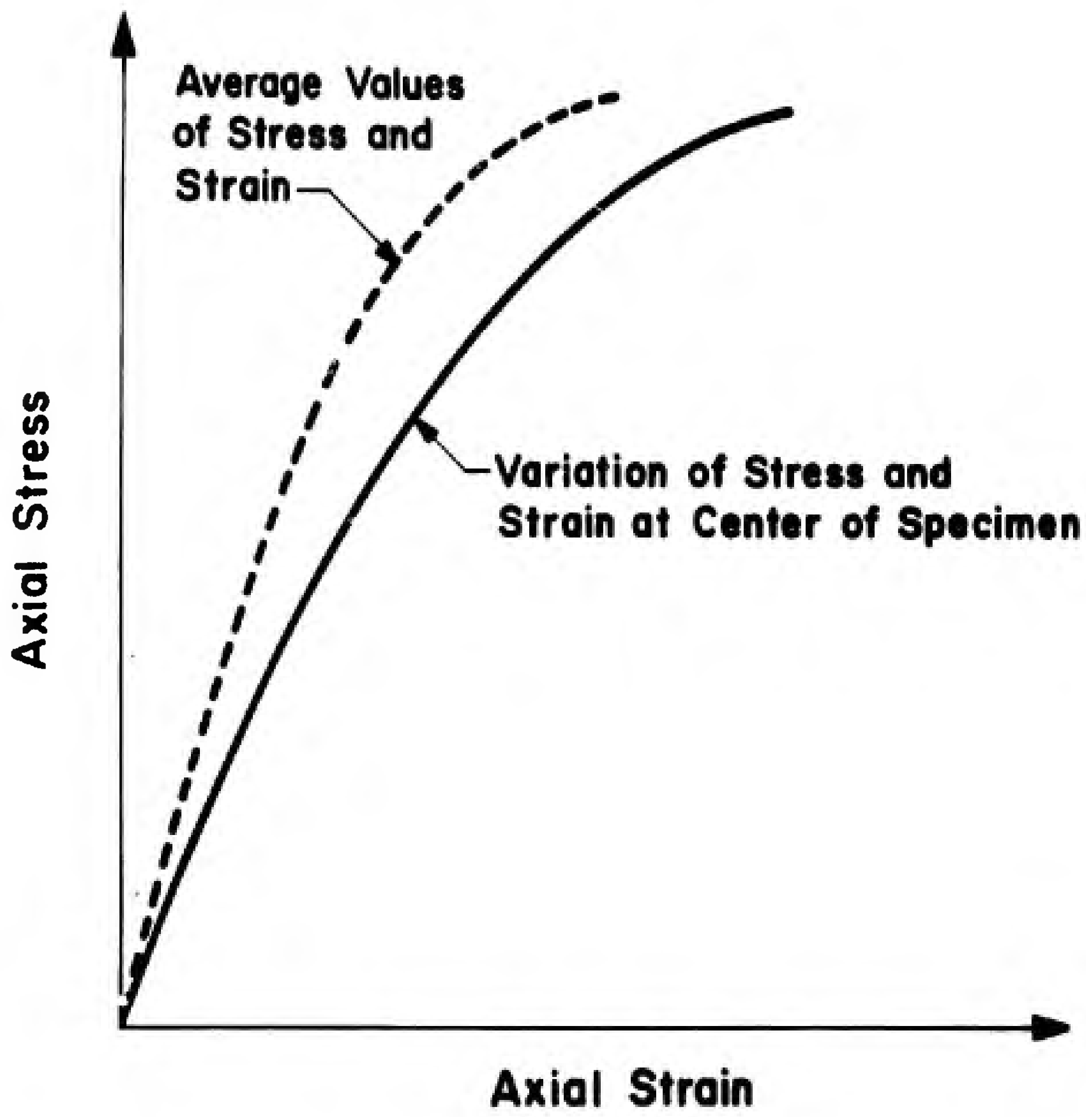


FIG.2- STRESS-STRAIN RELATIONSHIPS FOR COMPRESSION TEST SPECIMENS

TABLE 1. - REDISTRIBUTION OF WATER CONTENT IN CLAY SPECIMENS DURING UNDRAINED TESTS

Reference	Type of Test	Type of Soil	Water Content Distribution
Bishop, Blight and Donald (1960)	C-U	Compacted clay shale	$w_c > w_{tb}$
	C-U	Remoulded clay shale	$w_c > w_{tb}$
Casagrande and Poulos (1964)	C-U	Compacted clay	$w_c > w_{tb}$
	U-U	Compacted clay	$w_c > w_{tb}$
Rowe and Barden (1964)	C-U	Remoulded clay	$w_c > w_{tb}$
Barden and McDermott (1965)	C-U	Compacted clay	$w_c > w_{tb}$
Olson (1960)	C-U	Sedimented illite (OCR > 8)	$w_c > w_{tb}$
Whitman, Ladd and da Cruz (1960)	C-U	Remoulded Vicksburg buckshot clay (OCR > 3)	$w_c > w_{tb}$
Taylor and Clough (1951)	C-U	Undisturbed Boston blue clay (N.C.)	$w_c < w_{tb}$
Simons (1960)	C-U	Undisturbed sensitive clay (N.C.)	$w_c < w_{tb}$
Olson (1960)	C-U	Sedimented illite (OCR < 2)	$w_c < w_{tb}$
Whitman, Ladd and da Cruz (1960)	C-U	Remoulded Vicksburg buckshot clay (OCR < 2)	$w_c < w_{tb}$

w_c = water content at center after testing

w_{tb} = water content at top and bottom after testing water content distribution was examined after testing. Natural variations in the water content may amount to as much as 5 percent over small distances, however, making moisture migration studies difficult with Bay Mud.

Bishop, Blight, and Donald (1960) have suggested that the direction of moisture migration might be related to the value of the pore pressure coefficient A as follows. According to the definition of this coefficient, (Skemption, 1954), the pore-water pressures in an undrained test specimen may be expressed as

$$\Delta u = B[\Delta\sigma_3 + A\,(\Delta\sigma_1 - \Delta\sigma_3)] \tag{1}$$

which may also be written

$$\Delta u = B\Delta\sigma_1 + B[(A-1)(\Delta\sigma_1 - \Delta\sigma_3)] \tag{2}$$

Bulging causes the axial stress near the cap and base to be higher than that near the center with the result that the first term on the right-hand side of Eq. 2 will be larger for the top and bottom of a soil specimen than for the center, i.e. as a result of bulging, pore-water pressures tend to be larger at the top and bottom than at the center. Cap and base restraint causes an increase in confinement ($\Delta\sigma_3$) and a reduction in deviator stress ($\Delta\sigma_1 - \Delta\sigma_3$) with the result that when the value of (A-1) is negative the second term on the right-hand of Eq. 2 will be more negative for the center of a soil specimen than for the top and bottom, i.e., for values of $A < 1$, pore-water pressures tend to be larger at the top and bottom than at the center, as a result of cap and base restraint. For values of $A > 1$, pore-water pressures tend to be larger at the center than at the top and bottom as a result of end restraint. These conclusions may be summarized as shown in Table 2.

Although values of the coefficient A are not known for all of the soils listed in Table 1, it seems likely on the basis of the descriptions that all of the soils characterized by moisture migration toward

TABLE 2. - EFFECTS OF BULGING AND END RESTRAINT ON PORE-WATER PRESSURES IN COMPRESSION SPECIMENS

Value of Pore Pressure Coefficient A	Effect of Bulging on Pore-water Pressure	Effect of End Restraint on Pore-water Pressure
$A < 1$	$\Delta u_{tb} > \Delta u_c$	$\Delta u_{tb} > \Delta u_c$
$A > 1$	$\Delta u_{tb} > \Delta u_c$	$\Delta u_{tb} < \Delta u_c$

Δu_{tb} = change in pore-water pressure at the end of a specimen

Δu_c = change in pore-water pressure at the center of a specimen the center would also be characterized by smaller values of A than those in which moisture migrated away from the center. Thus the hypothesis proposed by Bishop, Blight and Donald (1960) is in qualitative agreement with the data in Table 1, and is a useful concept for assessing the effects of cap and base restraint on pore-water pressures and moisture migration.

For overconsolidated clays and for compacted or remoulded clays characterized by small values of the coefficient A, pore-water pressures would be expected to be larger at the top and bottom than at the center of the test specimen. For normally consolidated clays or any other clay characterized by high values of A, pore-water pressures would be expected to be larger at the center. In tests of sufficiently long duration, pore-water pressures will be effectively equalized at failure. However, because the water content of the central, relatively unrestrained section will have changed during the course of pore pressure equalization, it is possible that the equilibrium value of pore-water pressure may be influenced by cap and base restraint.

In view of the adverse effects of cap and base restraint on strength test results, it is desirable to examine the magnitudes of these effects to determine their significance. This may be done by comparing the results of tests with and without restraint. With this objective in mind, the following section is devoted to a discussion of techniques for minimizing cap and base restraint; subsequently the magnitudes of the effects of cap and base restraint in various types of tests are examined; finally, conclusions are drawn and recommendations are made with regard to desirable test procedures.

TECHNIQUES FOR REDUCING THE EFFECTS OF CAP AND BASE RESTRAINT

The influence of cap and base restraint on test results may be minimized in two distinct ways. The first technique is the one commonly used: an appropriate ratio of specimen height-to-width is selected so that the central zone of the specimen suffers negligible restraint. Taylor (1941) found that the strength of soil specimens decreased with increasing values of the height-to-width ratio, up to a ratio of 2 to 1; further increase in the value of the ratio resulted in no change in strength. This result has since been confirmed by Olson and Campbell (1964), and by Bishop and Green (1965), among others. This finding has led to the adoption of a standard height to diameter ratio of 2 or 2.5 to 1 for soil strength determination using triaxial compression test procedures. Thus it is apparent that conventional test technique with respect to specimen shape has been adopted with a view to minimizing the influence of cap and base restraint on the strength, and is therefore likely to be satisfactory in this regard, although it may be somewhat unsatisfactory with respect to some of the other effects of cap and base restraint.

The second technique for eliminating the effects of cap and base restraint involves provision of mechanisms at the cap and base to allow free expansion of the top and bottom of the specimen. Early attempts along this line included the use of segmented caps and bases, cone-shaped caps and bases, paraboloidal caps and bases, and rubber caps and bases. None of these techniques resulted in uniform specimen deformation however, (Rowe and Barden, 1964) and they were subsequently abandoned.

Along similar lines, Blight (1965) minimized the effects of end restraint by using a segmented soil specimen in which the top and bottom sections of the specimens were sealed separately from the center. Use of the same soil in the top and bottom sections as in the center resulted in small end restraint for the center portion of the specimen, and nearly uniform conditions within this zone. Thus pore-water pressures measured in the center portion of the specimen should be practically uninfluenced by restraint at the cap and base. Values of axial strain were computed from the axial deformation of the entire specimen, however, and would therefore be influenced by cap and base restraint to some extent.

Rowe and Barden (1964) have developed lubricated caps and bases which employ a layer of grease between the cap or base, which is highly polished, and a sheet of rubber in contact with the sample. This technique has proved to be reasonably convenient and effective in reducing end restraint. Lubricated caps and bases have also been used which employed more than one sheet of rubber, with grease at each interface (Lee and Seed, 1964; Bishop and Green, 1965). Schematic representations of lubricated bases appropriate for unconsolidated-undrained testing are shown in Fig. 3(a) and 3(b). Rowe and Barden found that it was not necessary for the cap and base to be of larger diameter than the specimen; slight protrusion of the specimen did not affect the test results for strains less than about 10 percent.

Because a porous stone having the same diameter as the base cannot be used in conjunction with lubricated end plates, new techniques have been developed for providing drainage in conjunction with lubricated caps and bases. Rowe and Barden (1964) have successfully employed a small porous disk in the center of the base as shown in Fig. 3(c), and filter paper strips communicating with a porous disk beneath the enlarged portion of the base as shown in Fig. 3(d). The type of base illustrated in Fig. 3(e) was used in conjunction with the plane strain tests described in the next section. Pore-pressure probes through the membranes, sealed with rubber cement or "O"-ring seals, have been used by Barden and McDermott (1965) and by Blight (1965) in conjunction with lubricated caps and bases. The response times of these devices appear to be fast enough for use in even rapidly conducted tests.

In the lubricated cap and base tests described in the next section, some difficulty was encountered in preventing specimens from slipping sideways during testing. This difficulty was overcome by using non-rotating caps in triaxial tests. For plane strain tests it was necessary to provide both non-rotating caps and stainless steel pins, 1/16 in. dia. by 1/2 in. long, near each end of the cap and base; these pins, pushed into the specimens during assembly, prevented the specimens

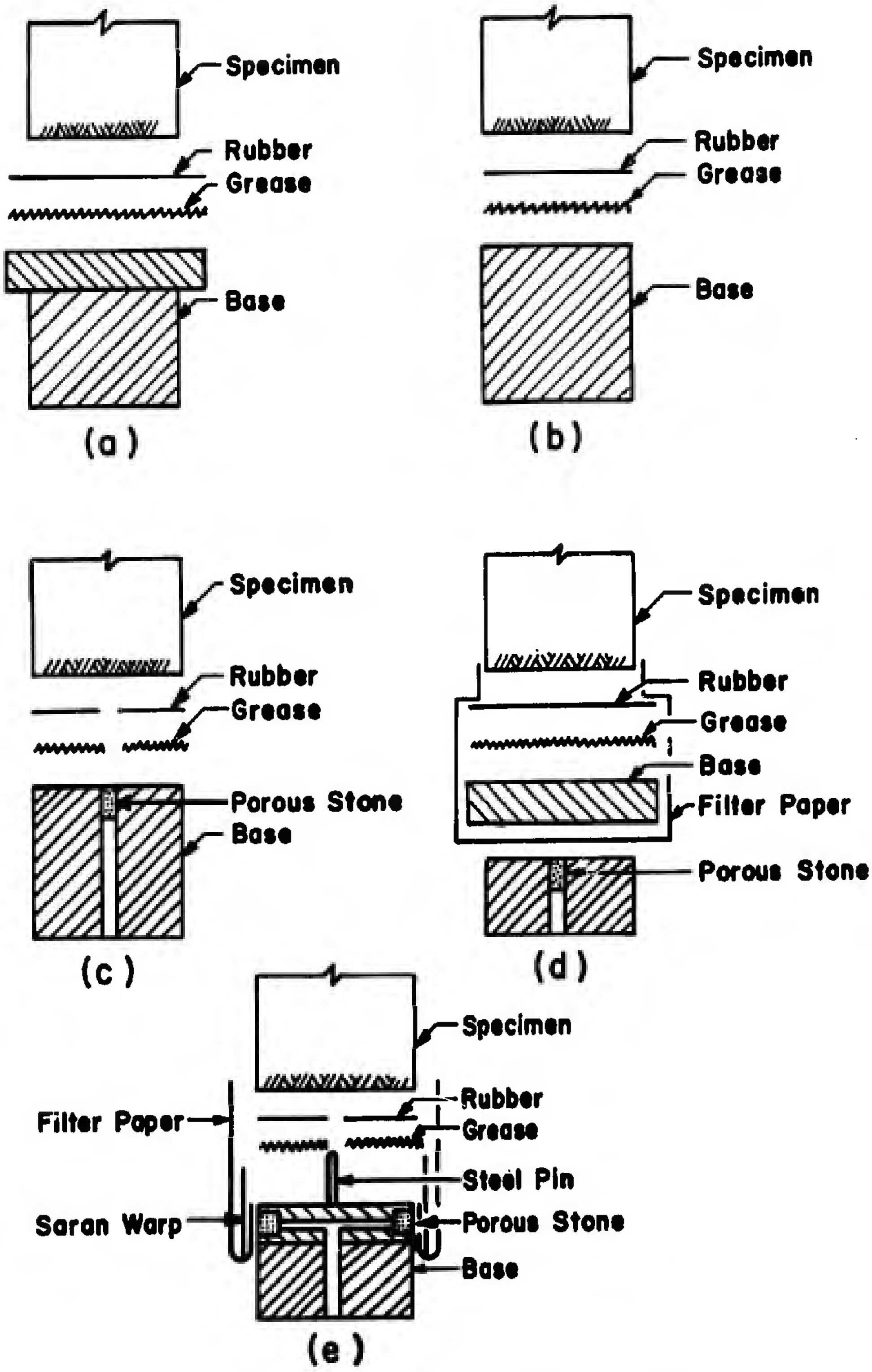


FIG 3.— LUBRICATED BASES FOR TRIAXIAL AND PLANE STRAIN TESTS

from sliding sideways during testing. In order to prevent the grease used for lubrication from plugging the filter paper drainage strips, it was found to be necessary to separate the filter paper from the grease with Saran wrap, as shown in Fig. 3(e).

The effectiveness of lubricated caps and bases in eliminating cap and base friction may be evaluated in two ways: Sliding block friction tests may be used to measure the coefficient of friction for rubber sliding on the base material (polished lucite or stainless steel) with a layer of grease in between. Alternatively, the effectiveness of lubricated caps and bases may be evaluated on the basis of the degree of bulging of the specimen during testing. Both of these techniques have been used by various investigators, with somewhat conflicting results. Rowe and Barden (1964) found the coefficient of friction for rubber-silicone grease-polished steel to be 1 degree or less, and found that practically no bulging occurred during testing using caps and bases of this type. Lee and Seed (1964) found that the coefficient of friction depends on the relationship between the soil particle size and the thickness of the rubber sheet, and on the amount of time between application of the normal load and measurement of the coefficient of friction. Sand specimens were found to undergo practically no bulging during tests with lubricated caps and bases, provided that the rubber sheet was sufficiently thick. Olson and Campbell (1964) and Casagrande and Poulos (1964) found lubricated caps and bases to be ineffective in reducing bulging of 1.4-in. diameter clay specimens during consolidated-undrained tests.

A study of the effectiveness of grease in reducing friction is described in the Appendix to this report. Grease reduces friction between smooth surfaces by carrying a portion of the normal load tending to force the surfaces into contact. Under the influence of the normal load, the effective coefficient of friction increases with time as the thickness of the grease separating the surface decreases. The theoretical thickness of grease after any value of time may be calculated if the size of the loaded area, the normal stress and the grease viscosity are known. Techniques for calculating the theoretical thickness of the grease are explained in the Appendix. Measurements of friction after various lengths of time have shown that a unique relationship exists between the theoretical thickness of grease and the effective coefficient of friction as shown in Fig. 4. This fact makes it possible to determine the effective coefficient of friction for lubricated caps and bases by calculating the theoretical thickness of grease and determining the friction coefficient from Fig. 4.

Examples of the variation of the effective coefficient of friction with time for lubricated caps and bases are shown in Fig. 5. It may be noted that 4-in. diameter specimens will be restrained by much smaller values of friction than will 1.4-in. diameter specimens. The effects of specimen size and test duration shown in Fig. 5 may explain why lubricated caps and bases have been found to be effective in some cases and ineffective in others. The relationship between theoretical thickness of grease and effective coefficient of friction may also be used for calculating the frictional force between a plane strain specimen and its end plates; the procedure by which this may be done is explained in detail in the Appendix.

TESTS WITH LUBRICATED CAPS AND BASES

Unconsolidated-undrained triaxial and plane strain tests, and consolidated-undrained plane strain tests have been performed on undisturbed San Francisco Bay Mud using lubricated and normal caps and bases. The results of these tests, as well as the results of similar tests which have been reported elsewhere, have been examined to determine the significance of errors resulting from cap and base restraint.

Tests on Undisturbed San Francisco Bay Mud

U-U Triaxial Tests. The analysis of lubrication previously described indicates that lubricated caps and bases should be very effective in reducing restraint in tests of short duration. Thus unconsolidated-undrained tests, which may be performed in a few minutes, provide a convenient means of evaluating the influence of

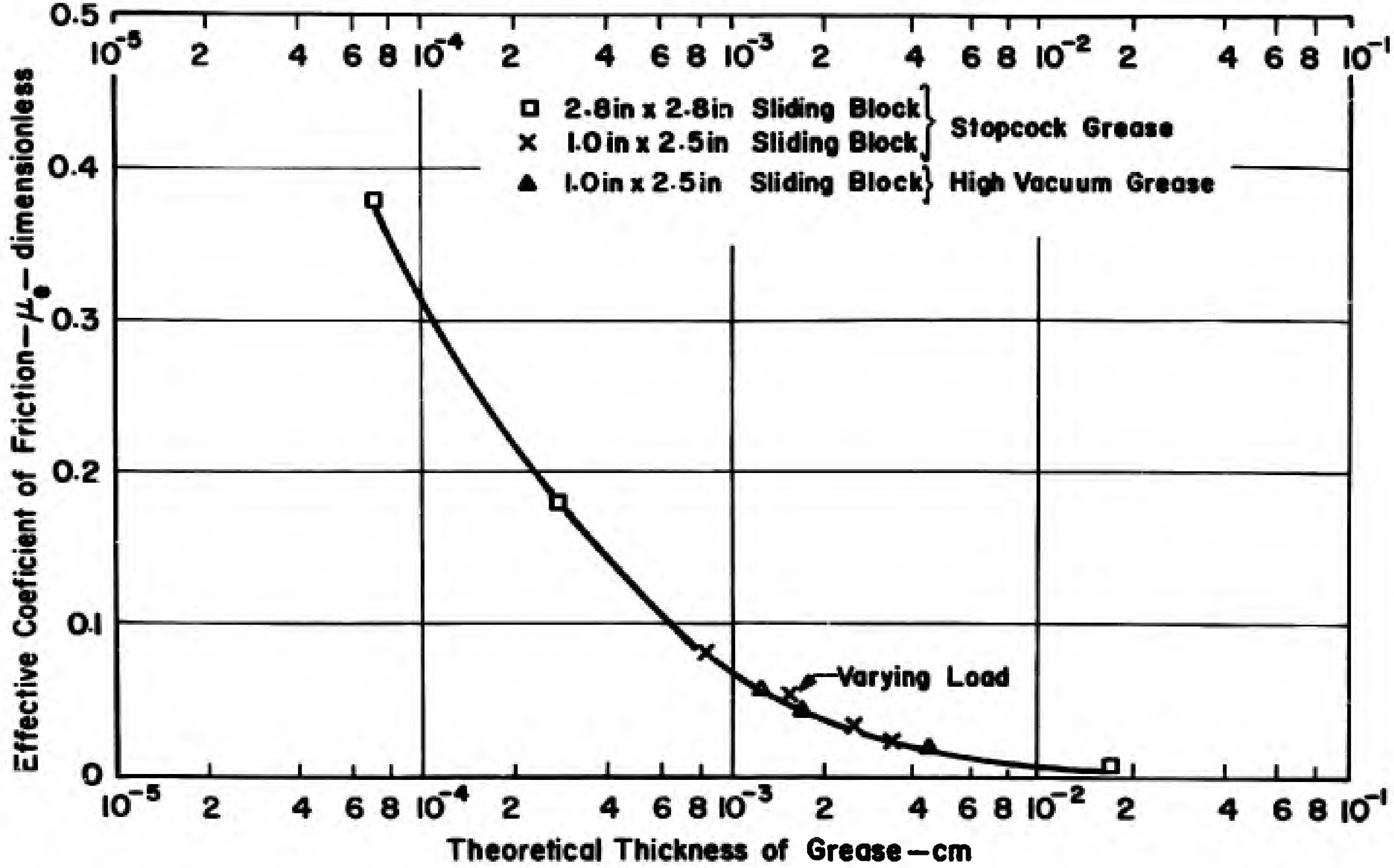


FIG.4.—RELATIONSHIP BETWEEN THE EFFECTIVE COEFICIENT OF FRICTION AND THE THEORETICAL THICKNESS OF GREASE BETWEEN POLISHED LUCITE AND RUBBER

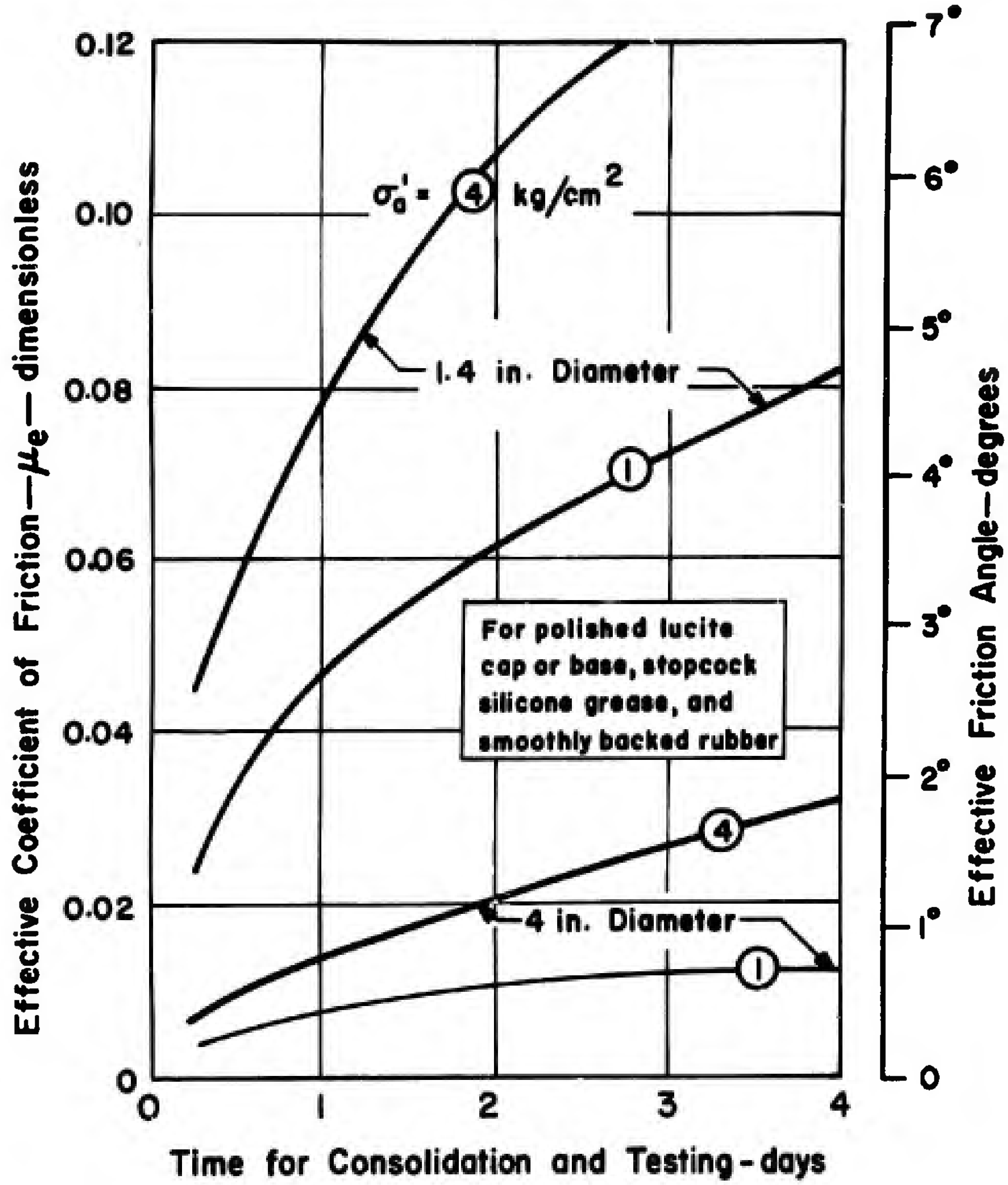


FIG.5.- VARIATION OF FRICTION WITH TIME FOR LUBRICATED CAPS AND BASES ON TRIAXIAL SPECIMENS

restraint on strength test results. By conducting U-U tests lasting varying periods of time, it is also possible to determine at what value of friction lubricated caps and bases become ineffective. Knowledge of the acceptable limiting value of friction coefficient, combined with the analytic techniques described in the Appendix, provides a means for determining the suitability of lubricated caps and bases for long-term tests.

A series of U-U triaxial tests, lasting various periods of time, was conducted on specimens of undisturbed San Francisco Bay Mud. The specimens were assembled in triaxial compression cells using either lubricated or normal caps and bases. The cell pressures were applied for various periods of time before the specimens were loaded axially; the length of time from application of the first increment of deviator stress until failure was about eight minutes for all specimens.

Some of the first specimens tested with lubricated caps and bases slid sideways off the base at an early stage of the shear tests, and it was necessary to use non-rotating caps to prevent this. The deformed shape of each specimen was carefully noted during testing, both visually and by means of paper girth gages stuck to the specimens with silicone grease. Specimens tested with normal caps and bases deformed by bulging at the center, as shown in Fig. 6(a); whereas most specimens tested with lubricated caps and bases deformed either uniformly or by spreading at the top or bottom or both, as shown in Figs. 6(b), (c), (d) and (e). Failure planes developed in specimens tested with both types of cap and base; formation of multiple failure planes was more common in specimens with lubricated caps and bases. In tests where the cell pressure was applied for a period of 10 days or more before testing, the lubricated caps and bases were ineffective, and the specimens bulged at the center. The paper girth gages were not sufficiently sensitive to provide accurate determination of the deformed shapes of the specimens, but they were more sensitive than visual observation, particularly at small values of strain.

During this test series it was observed that the longer a specimen

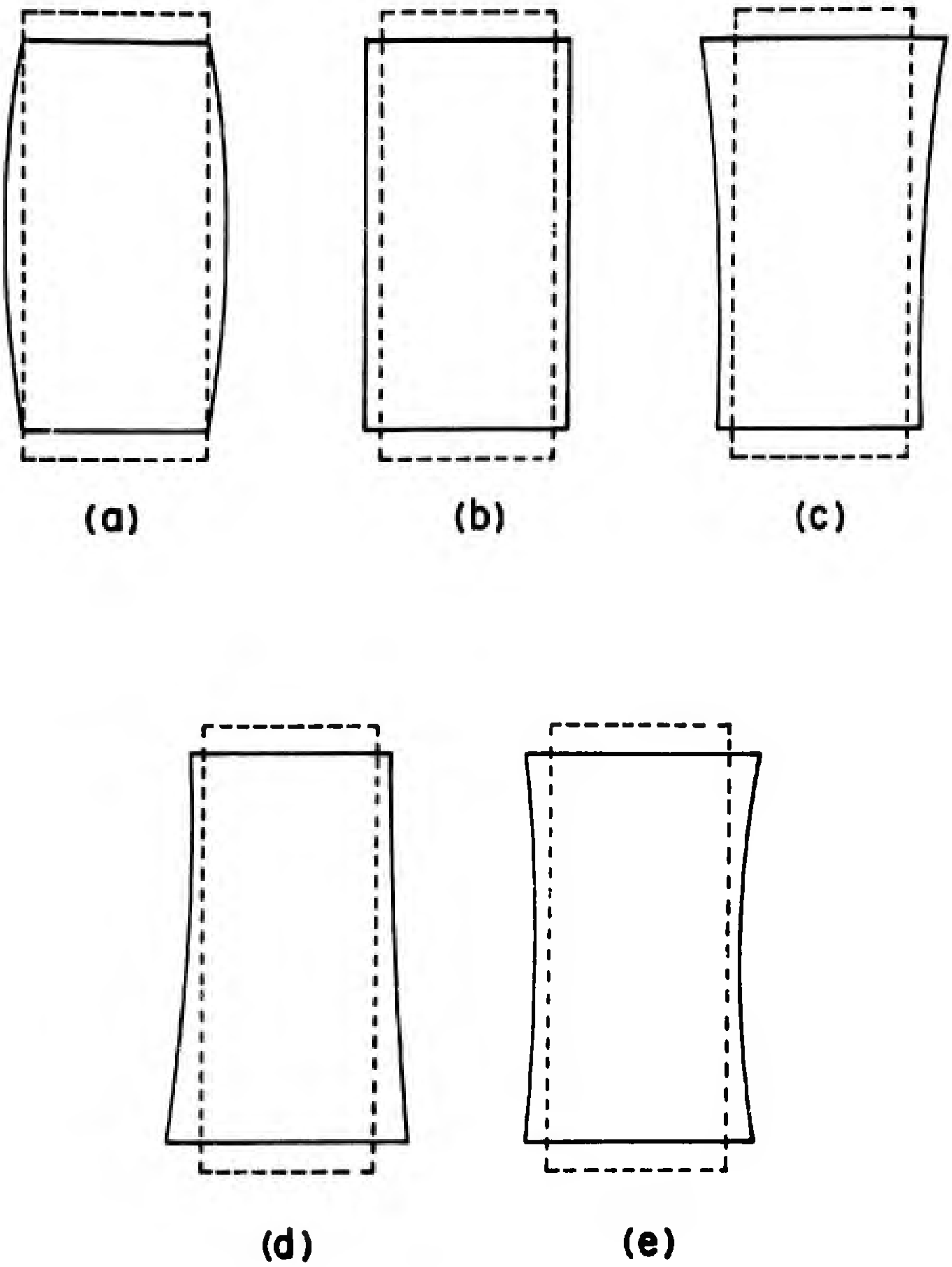


FIG.6.– TYPES OF SPECIMEN DEFORMATION

was subjected to pressure before testing, the larger was its strength. Therefore the stress-strain curves and strengths of specimens are only directly comparable if they were subjected to pressure for about the same length of time before testing. Stress-strain curves for specimens subjected to pressure for two hours or less are shown in Fig. 7. The amount of scatter in the test results, which is normal for U-U tests on undisturbed Bay Mud, makes evaluation of the influence of cap and base lubrication difficult. However, by comparing the average stress-strain curves for normal and for lubricated caps and bases as shown in Fig. 8, it may be seen that the stress-strain curves are somewhat steeper over most of their range and the strengths are somewhat higher for specimens tested with normal caps and bases. In these tests the difference in strength was found to be about 10 percent.

U-U Plane Strain Tests. Unconsolidated-undrained plane strain tests were also performed on undisturbed Bay Mud, using both normal and lubricated caps and bases. All of these tests were unconfined compression tests. No membranes were used, but a 0.010 in. thick piece of rubber and a layer of silicone grease was placed between each end of the specimen and the end plate. Test duration was about 15 minutes for all specimens.

Stress-strain curves for vertical specimens are shown in Fig. 9, and average stress-strain curves for vertical specimens tested with normal and with lubricated caps and bases are shown in Fig. 10. The comparison is similar to that for triaxial tests, the stress-strain curve being somewhat steeper and the strength being somewhat higher for specimens tested with normal caps and bases. The average difference in strength in these tests is about 5 percent. In addition it may be noted that the average strain at failure is about 2.5 percent for specimens tested with normal caps and bases, and about 3 percent for specimens tested with lubricated caps and bases.

U-U plane strain tests were also performed on undisturbed Bay Mud specimens trimmed horizontally. Stress-strain curves for these tests are shown in Fig. 11, and the average curves are shown in Fig. 12.

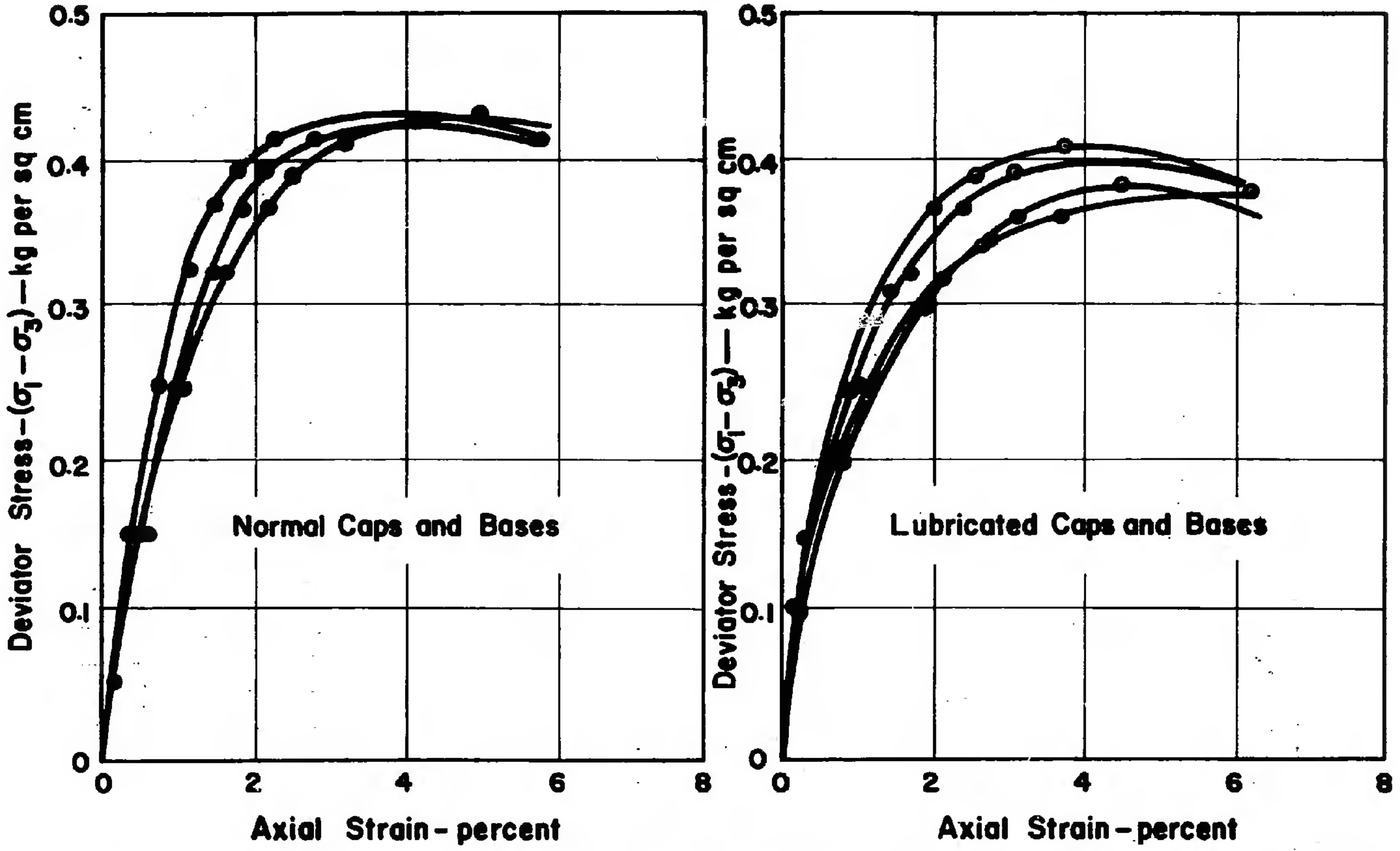


FIG.7.- STRESS-STRAIN CURVES FOR UNCONSOLIDATED-UNDRAINED TRIAXIAL TESTS ON VERTICAL SPECIMENS OF UNDISTURBED SAN FRANCISCO BAY MUD

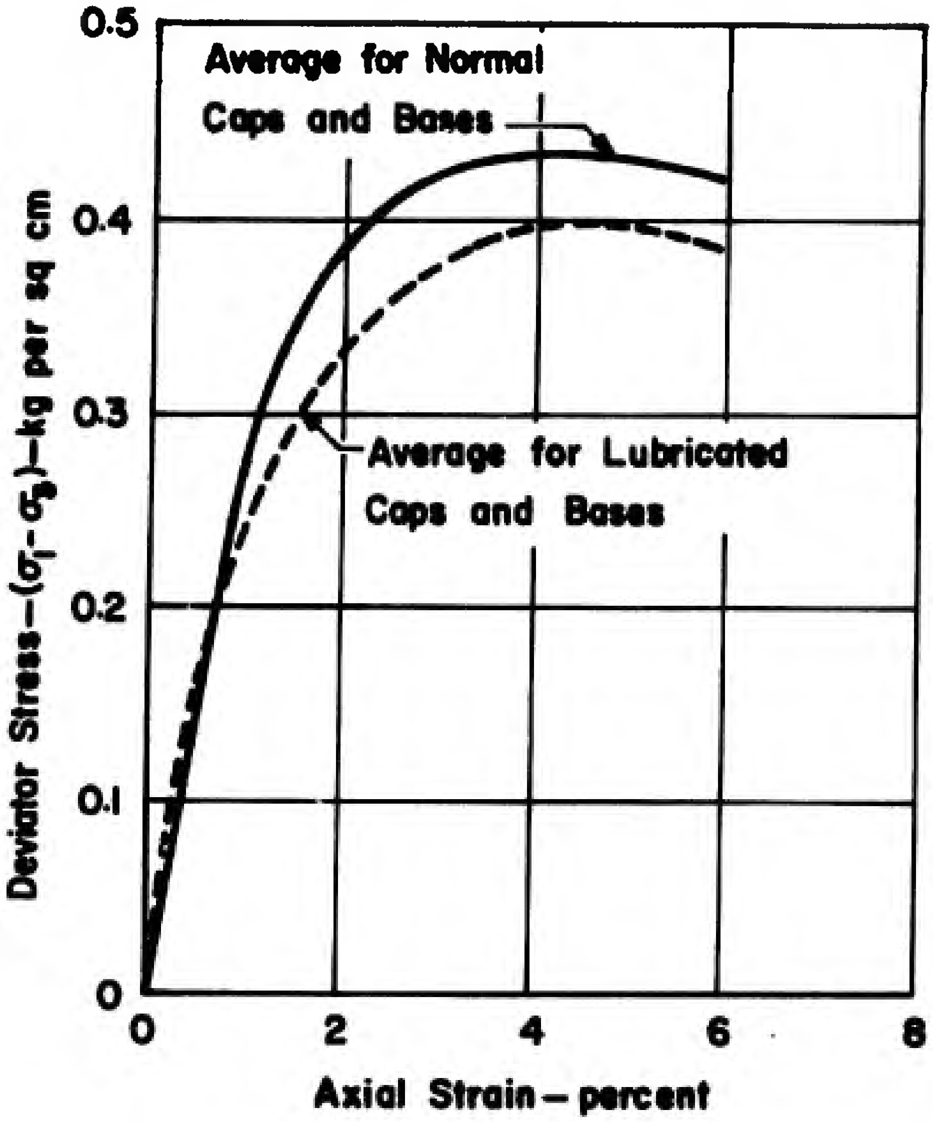


FIG.8.— COMPARISON OF STRESS-STRAIN CURVES FOR LUBRICATED AND NORMAL CAPS AND BASES IN UNCONSOLIDATED-UNDRAINED TRIAXIAL TESTS ON VERTICAL SPECIMENS OF UNDISTURBED SAN FRANCISCO BAY MUD

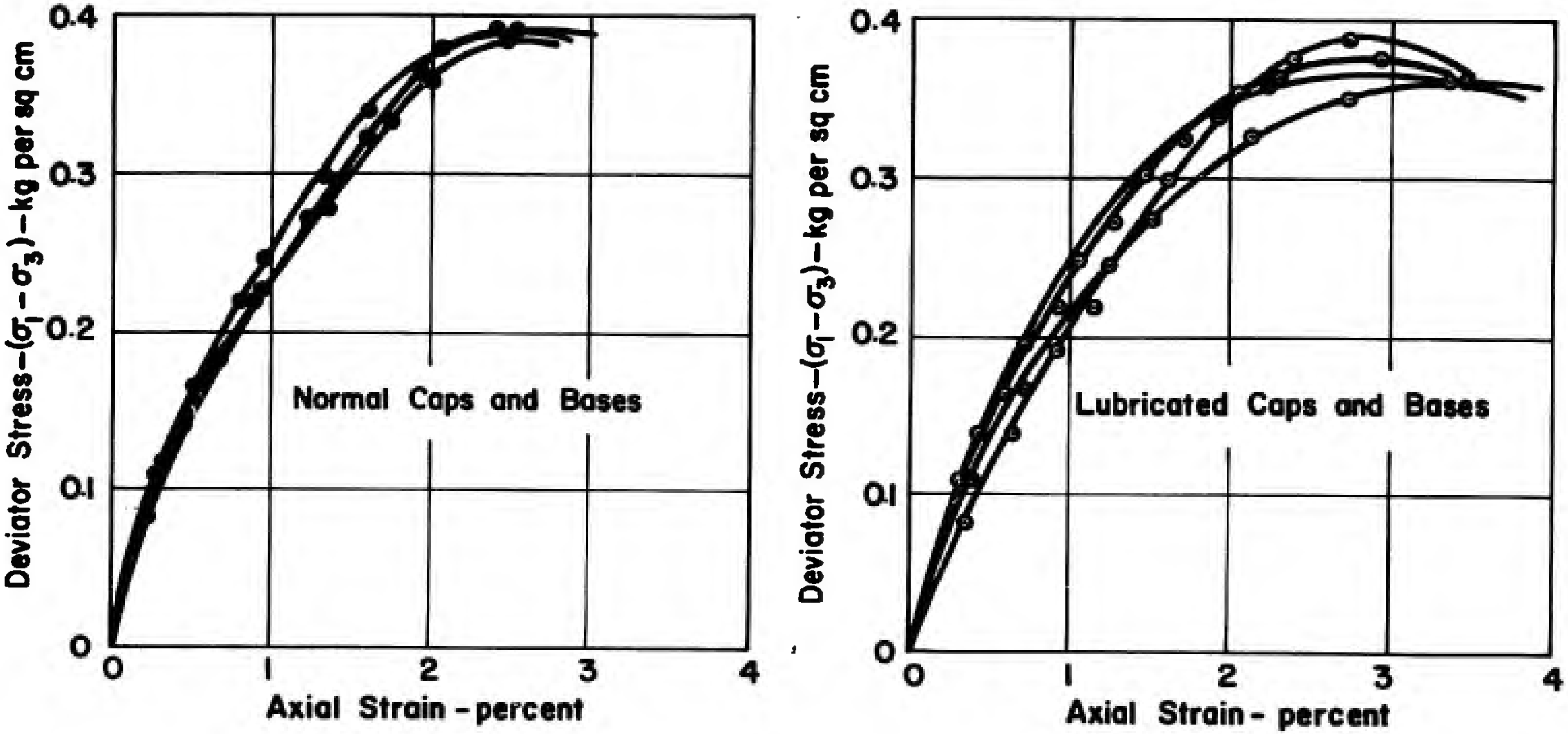


FIG.9. - STRESS-STRAIN CURVES FOR UNCONSOLIDATED-UNDRAINED PLANE STRAIN TESTS ON VERTICAL SPECIMENS OF UNDISTURBED SAN FRANCISCO BAY MUD

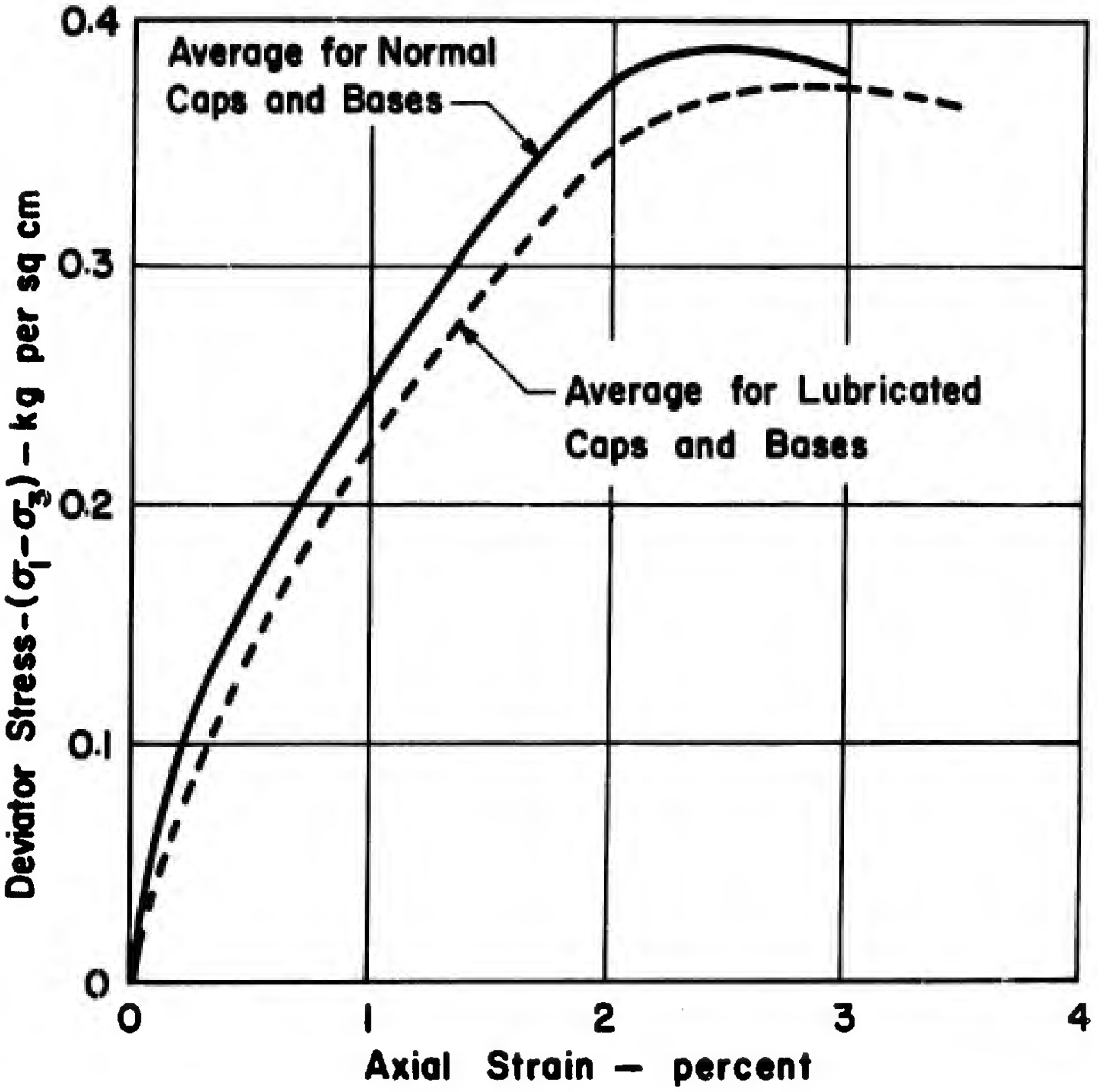


FIG.10.– COMPARISON OF STRESS–STRAIN CURVES FOR LUBRICATED AND NORMAL CAPS AND BASES IN UNCONSOLIDATED-UNDRAINED PLANE STRAIN TESTS ON VERTICAL SPECIMENS OF UNDISTURBED SAN FRANCISCO BAY MUD

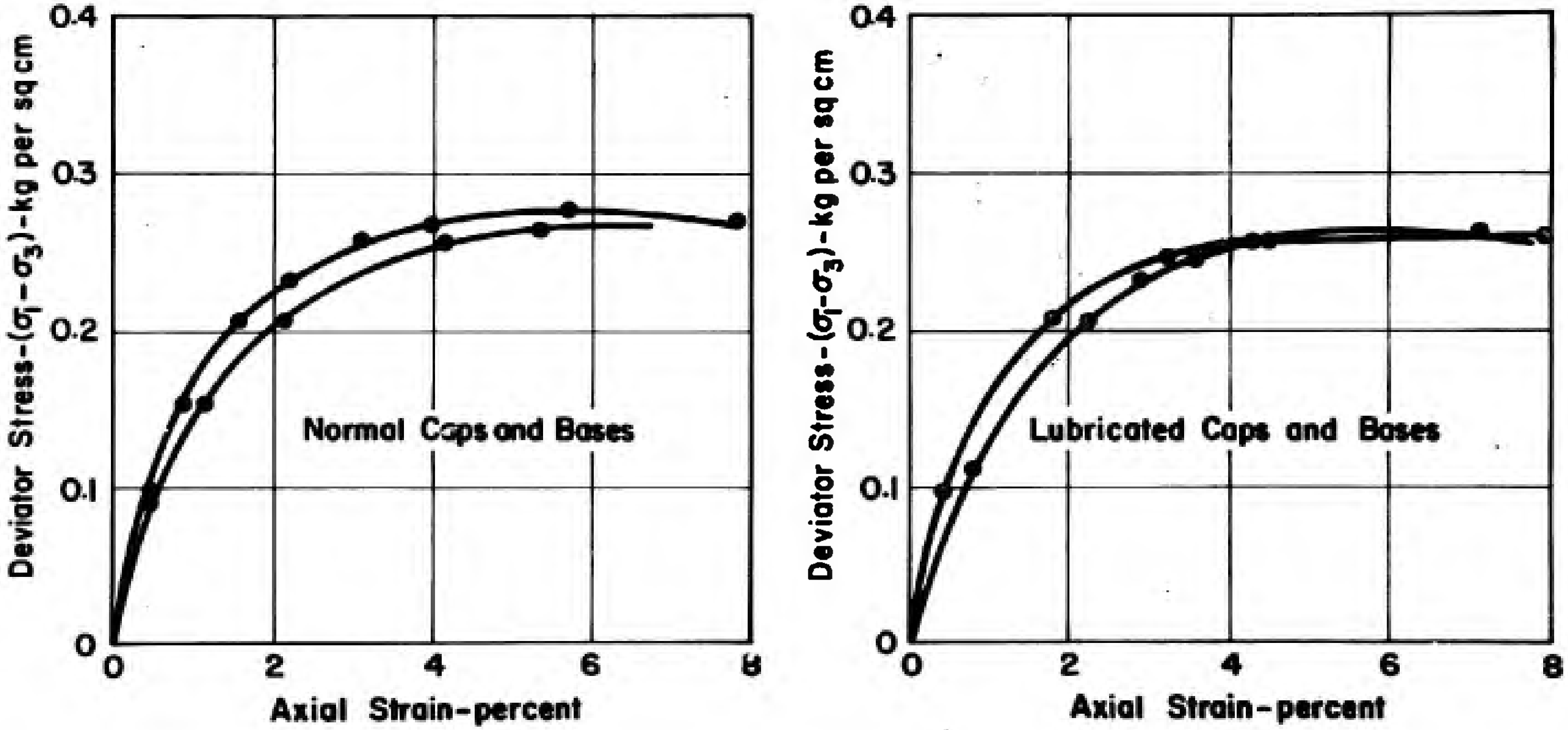


FIG.11.— STRESS-STRAIN CURVES FOR UNCONSOLIDATED-UNDRAINED PLANE STRAIN TESTS ON HORIZONTAL SPECIMENS OF UNDISTURBED SAN FRANCISCO BAY MUD

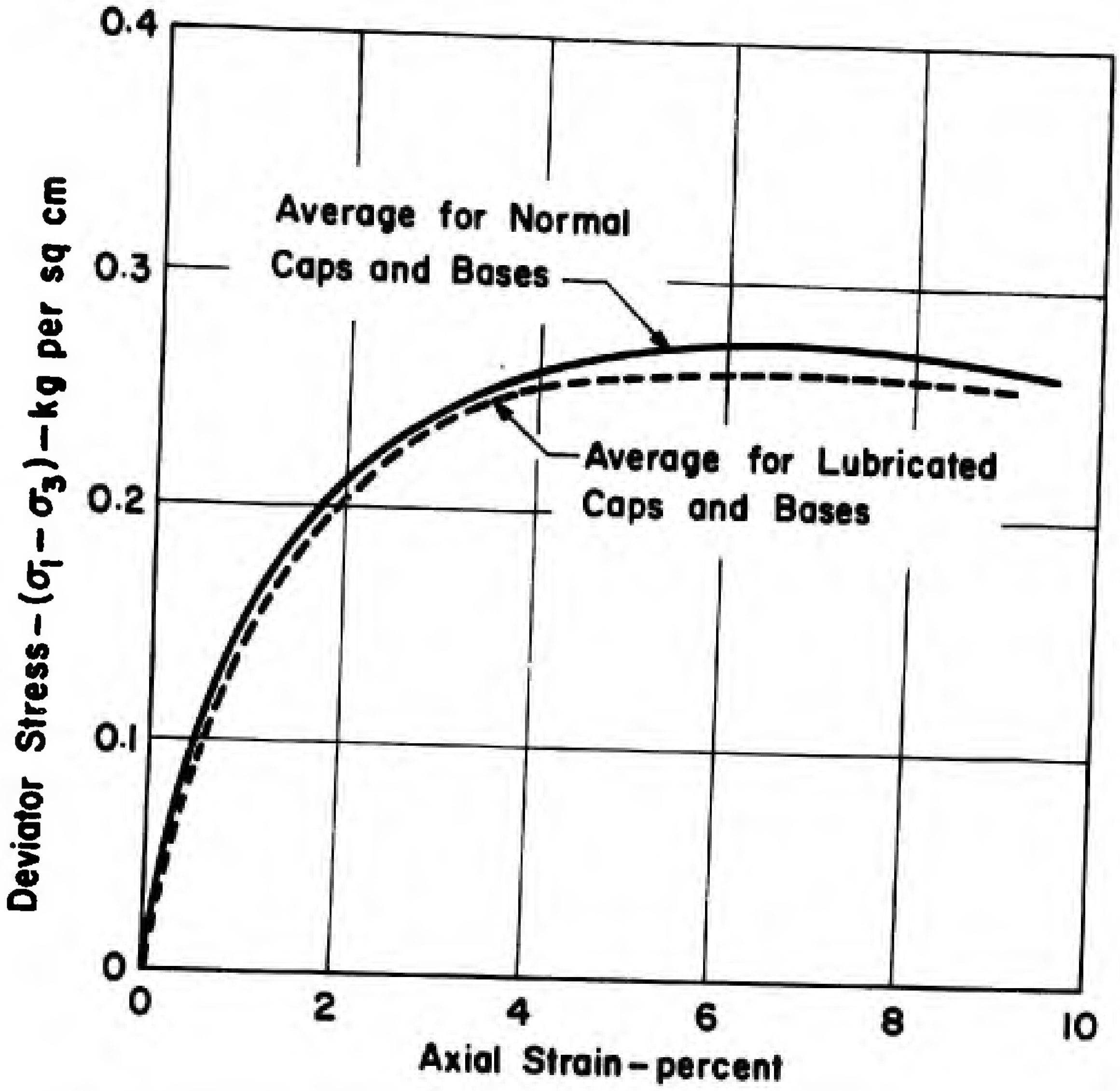
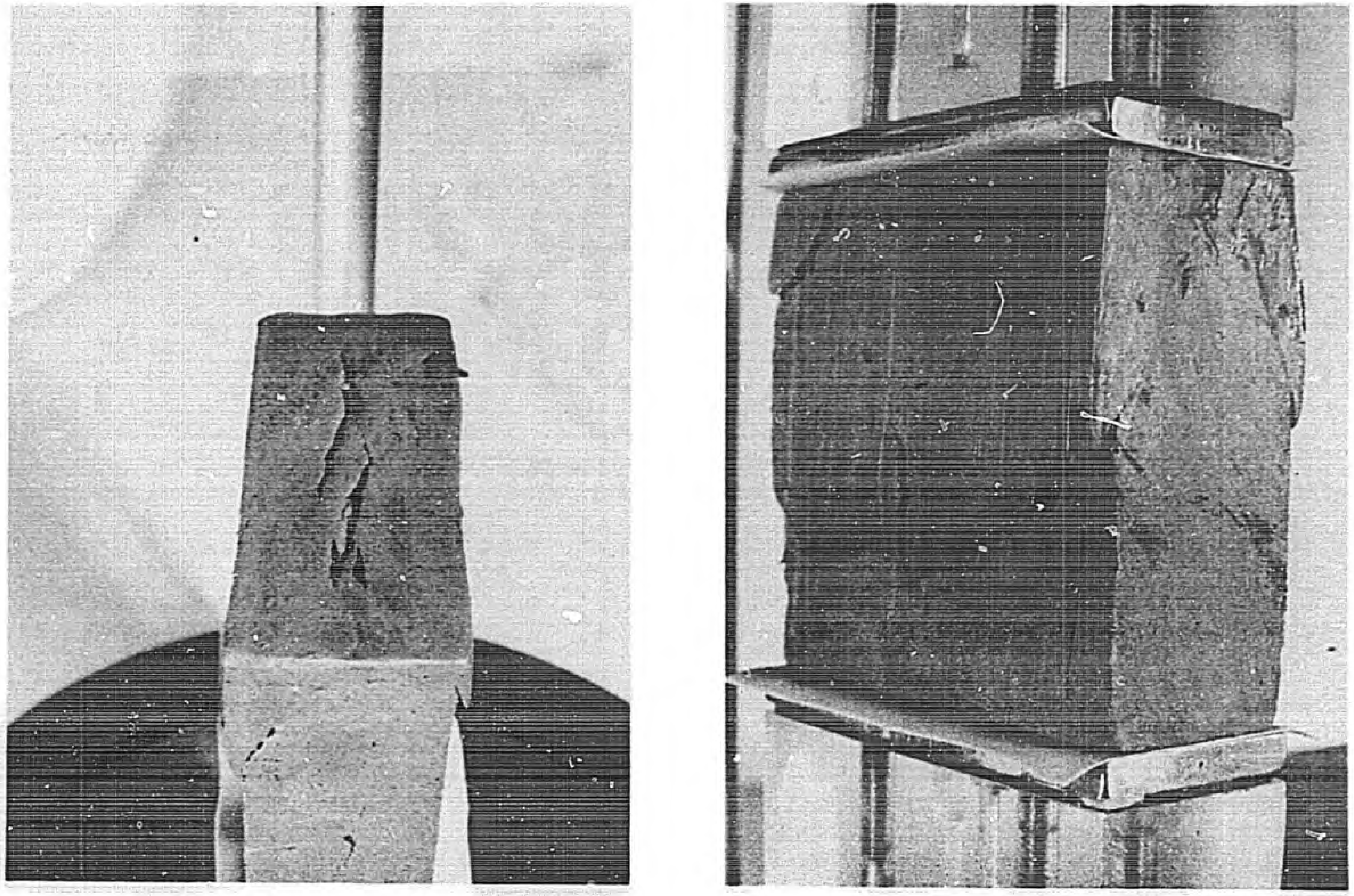


FIG.12.– COMPARISON OF STRESS–STRAIN CURVES FOR LUBRICATED AND NORMAL CAPS AND BASES IN UNCONSOLIDATED–UNDRAINED PLANE STRAIN TESTS ON HORIZONTAL SPECIMENS OF UNDISTURBED SAN FRANCISCO BAY MUD

Although the strength of the horizontal specimens are smaller than those for vertical specimens, and the strains at failure are larger, the relative positions of the stress-strain curves and the relative values of strength for normal and for lubricated caps and bases are similar to those for vertical triaxial and plane strain specimens. The strength of specimens tested with normal caps and bases is about 5 percent higher than the strength of those tested with lubricated caps and bases. Because the stress-strain curves are so flat near the peaks, it is difficult to discern any difference in the values of strain at failure.

Inspection of the plane strain specimens after the tests had been performed and the apparatus had been disassembled showed that several specimens tested with lubricated caps and bases had apparently begun to split vertically. Longitudinal cracks in the top and bottom extending from end to end of some specimens, were associated with the intersection of the failure planes with the cap and base as shown in Fig. 13(a). It could not be determined whether the formation of these cracks constituted the failure mechanism, or if the cracks developed during the deformations following failure. Development of more than one failure plane, as shown in Fig. 13(b), was common in tests where lubricated caps and bases were used. Specimens tested with normal caps and bases typically failed on a single well-defined failure plane which did not intersect the cap or base.

Effectiveness of Lubrication. Because lubricated caps and bases have been found by Olson and Campbell (1964) and by Casagrande and Poulos (1964) to be ineffective in eliminating bulging during consolidated-undrained tests, the results of the unconsolidated-undrained triaxial tests described previously were examined to determine the limiting value of cap and base friction which results in negligible restraint. The values of deviator stress at failure in these tests were plotted against the logarithms of the durations (time under pressure in the triaxial cell plus test time), for both lubricated and normal caps and bases, as shown in Fig. 14. With either type of cap and base, the undrained strength increases with increasing value of the length of time the



(a) (b)

FIG.13.– PHOTOGRAPHS OF VERTICAL PLANE STRAIN SPECIMENS OF SAN FRANCISCO BAY MUD AFTER UNCONSOLIDATED–UNDRAINED TESTS WITH LUBRICATED CAPS AND BASES

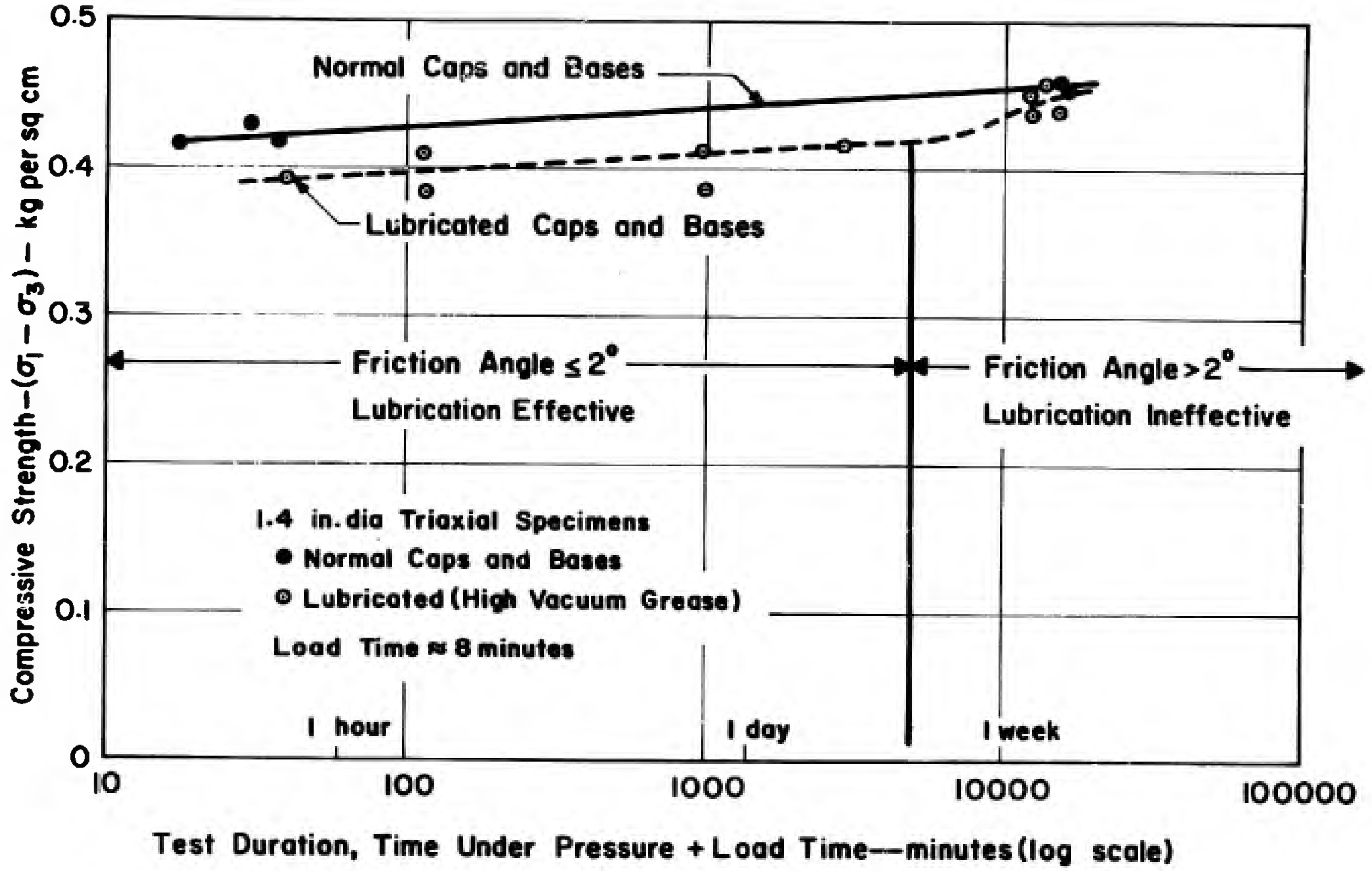


FIG.14.— EFFECT OF TIME BETWEEN CELL PRESSURE APPLICATION AND FAILURE ON THE UNCONSOLIDATED-UNDRAINED STRENGTH OF UNDISTURBED SAN FRANCISCO BAY MUD

specimens were allowed to remain under pressure, the strengths of specimens tested with lubricated caps and bases being some 5 percent lower in tests of relatively short duration. For tests lasting longer than about 5000 minutes the difference in strength begins to decrease due to the decreasing effectiveness of the lubrication, and for tests lasting 15,000 minutes there is very little difference in strength. Using the techniques discussed previously, values of the effective coefficient of friction may be determined from a knowledge of test duration, specimen size, grease viscosity and effective axial stress in the specimen, along with Fig. 4 which relates theoretical thickness of grease to effective coefficient of friction. Taking a test duration of 5000 minutes as the longest in which the lubrication was fully effective in reducing restraint and the other values pertinent to these tests (1.4 in. dia. specimens, grease viscosity 0.23 kg. sec. cm^{-2}, effective axial stress = 0.35 kg/cm^2), it was calculated that the theoretical thickness of grease would be 2.2 x 10^{-3} cm, which corresponds to an effective friction angle of 2°. It was therefore concluded that for cap and base lubrication to be effective, the friction angle should be less than 2°.

So far as it is possible to determine, a 2° limit on effective friction angle appears to be consistent with the experience of other investigators who attempted to use lubricated caps and bases for reducing end restraint. Olson and Campbell (1964) and Casagrande and Poulos (1964) have noted that lubricated caps and bases did not reduce bulging in their tests. Olson and Campbell used silicone oil, which probably has very low viscosity compared to silicone greases, and would therefore be squeezed out relatively quickly with a resulting rapid increase in friction. Casagrande and Poulos used silicone grease for lubrication of 1.4-in. dia. specimens in which the effective axial stresses were relatively high and were applied for about eight hours. Using typical values for the viscosity of silicone grease, it has been estimated that the effective friction angle in these tests would have been 3° or more. It may also be significant that the caps and bases used were tapered about 1° toward the center; such a taper would tend to restrict spreading of the end of the specimen. Most of the other investigations performed using lubricated caps and bases have been conducted on sands or on clays using 4 in. dia. specimens. With these larger specimens, three to four days would be required for the effective friction angle to increase to 2° if the effective axial stress was 4 kg/cm^2 and stopcock silicone grease was used for lubrication, as shown in Fig. 5. Apparently none of the tests was of such long duration, and lubrication was therefore effective.

C-U Plane Strain Tests. In order to determine the influence of cap and base restraint in the changes in pore-water pressure during undrained plane strain tests, a series of consolidated-undrained plane strain tests was conducted using lubricated and normal caps and bases.

Although it was desired to perform the consolidated-undrained plane strain tests using techniques which had been established previously (Duncan and Seed, 1965), it was found that this would not be possible; the relatively long consolidation period employed in previous tests would allow too much reduction in grease thickness and increase in friction. It was considered that the shortest feasible consolidation period would be 48 hours, with another 4 to 6 hours for strength testing. Friction values were calculated for tests of 54 hours total duration, using high vacuum silicone grease for cap and base lubrication and specimens of the same size used previously. The results of these calculations, shown in Fig. 15, indicate that 1.6 kg/cm^2 is the upper limit of effective axial stress during consolidation which will result in effective friction angles less than 2° in VPS tests. Accordingly, both VPS and HPS tests were performed using lubricated caps and bases with values of the major principal stress during consolidation nominally 0.8 and 1.6 kg/cm^2.

Test specimens were consolidated anisotropically, using a single increment for load application, and were allowed to consolidate for 48 hours before testing. In order to determine if the change in consolidation procedure from the incremental application of

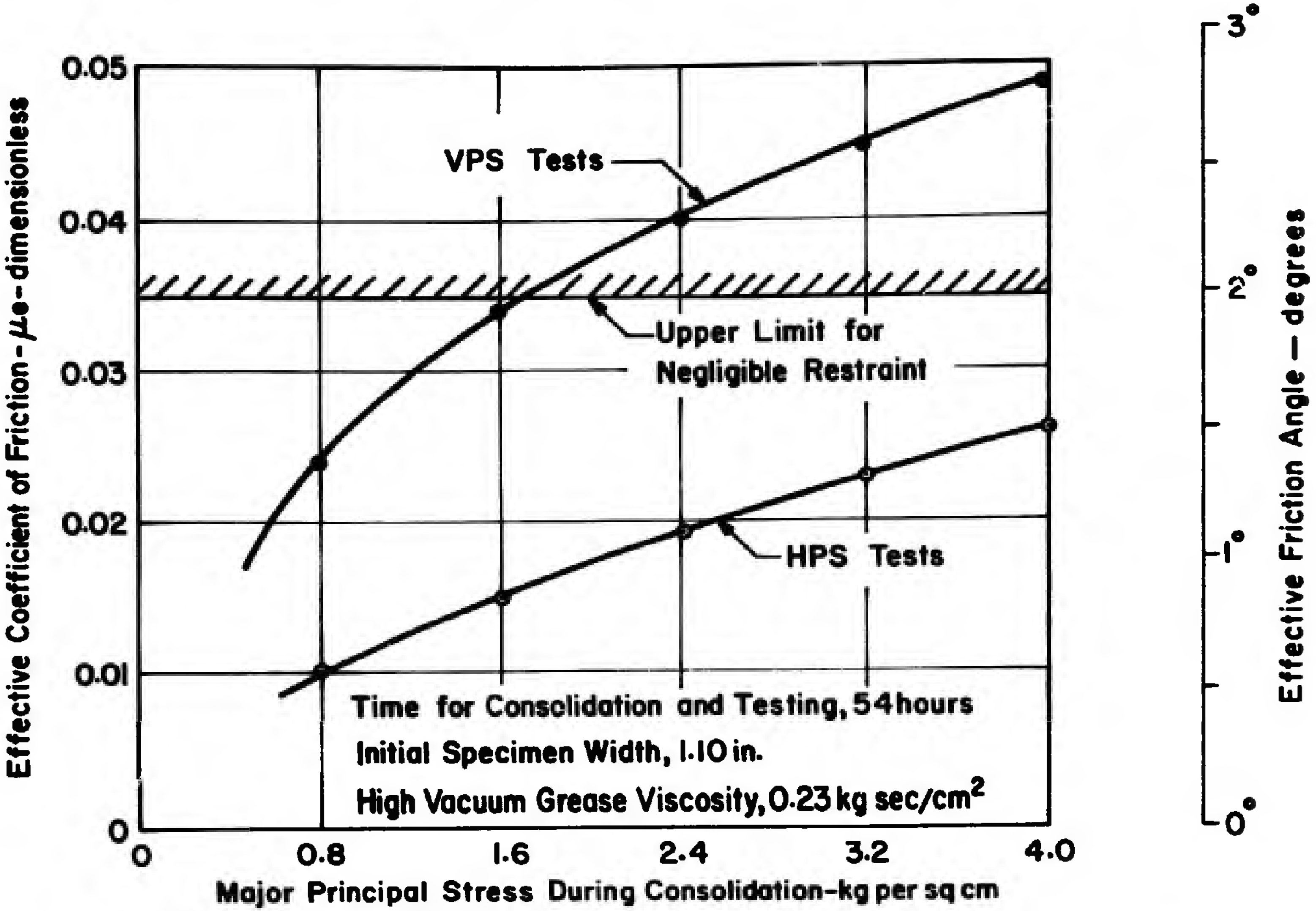


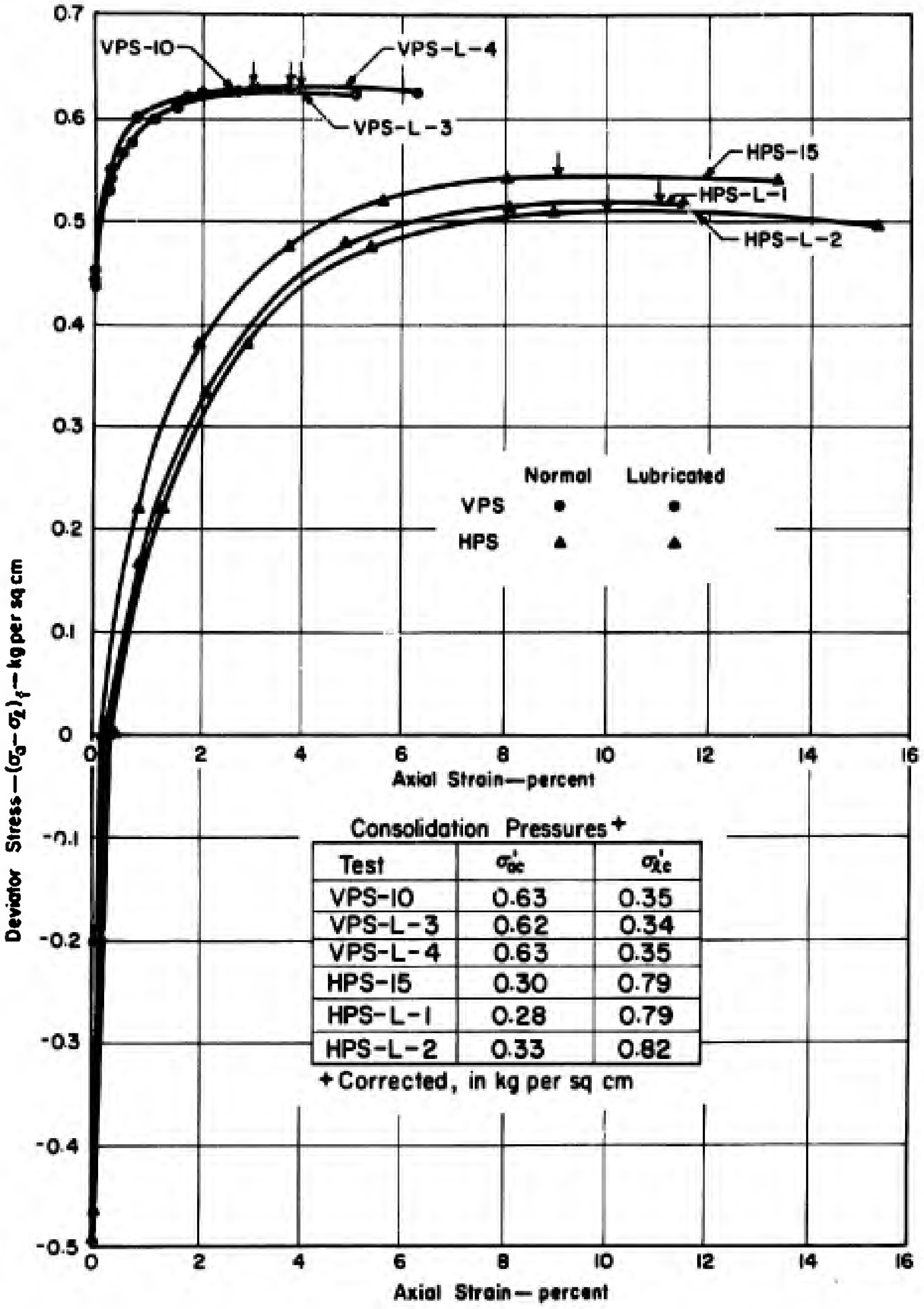
FIG.15.– CALCULATED VALUES OF FRICTION FOR PLANE STRAIN TESTS

consolidation stresses used in previous studies had an appreciable effect on the test results, tests were also performed using the single increment consolidation procedure with normal caps and bases. Except for this change in consolidation procedure, the procedure was the same as that used previously for HPS and VPS tests (Duncan and Seed, 1965).

The results of these consolidated-undrained plane strain tests are summarized in Table 3. Stress-strain curves for the undrained strength tests are shown in Figs. 16 and 17. Each of the two figures shows stress-strain curves for specimens consolidated to approximately equal consolidation pressures. The values of deviator stress shown in these figures have not been corrected for the loads carried by piston friction, filter paper drains, rubber membranes nor end plate friction; the required corrections would be the same for specimens with either type of cap and base, however. The consolidation pressures tabulated in Figs. 16 and 17 have been corrected, as have the data in Table 3.

Stress-Strain Relationships. The stress strain curves for specimens tested with normal caps and bases are again somewhat steeper with somewhat higher strengths than those for specimens tested with lubricated caps and bases; the difference in strength amounts to as much as 6 percent. There does not seem to be any consistent effect on the values of strain at failure. Observations of specimen deformations during testing, as well as the relative positions of the stress-strain curves, indicated that the lubricated caps and bases were effective in eliminating restraint.

Pore Pressure Changes. The changes in pore-water pressure with axial strain for these plane strain tests are shown in Fig. 18. It may be noted that the values of changes in pore-water pressure are typically slightly smaller for specimens tested with lubricated caps and bases, the difference in values being as large as 7 percent in some cases. (The values measured in a single test, VPS-L-2, contradict the trend and are not believed to be representative). Because lubricated caps and bases have similar effects on changes in deviator stress and pore-water pressures, the values of the pore pressure coefficient $\overline{A}$

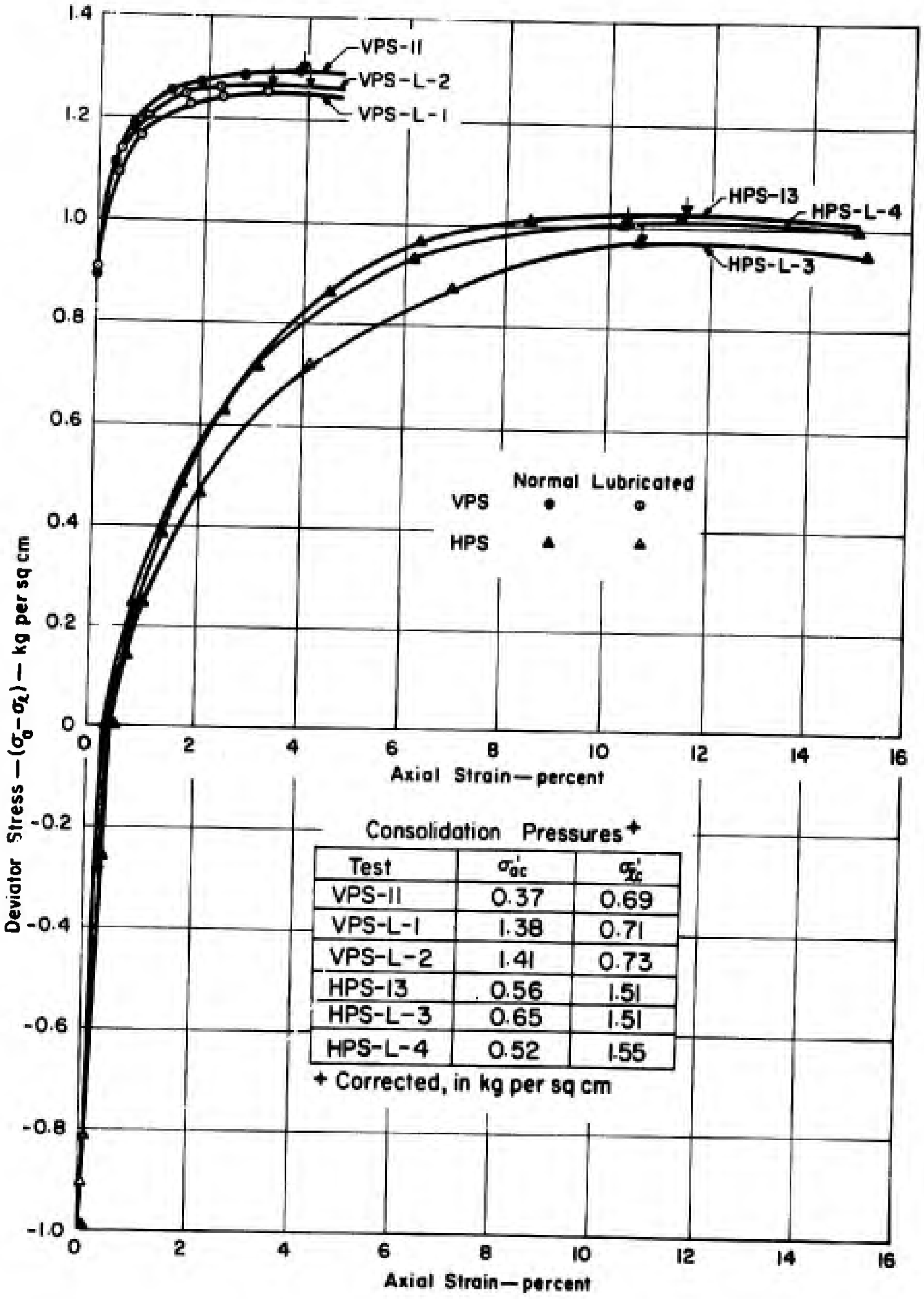


Consolidation Pressures+

Test	σ'_{ac}	$\sigma'_{\ell c}$
VPS-10	0.63	0.35
VPS-L-3	0.62	0.34
VPS-L-4	0.63	0.35
HPS-15	0.30	0.79
HPS-L-1	0.28	0.79
HPS-L-2	0.33	0.82

+Corrected, in kg per sq cm

FIG.16.— STRESS-STRAIN CURVES FOR CONSOLIDATED-UNDRAINED PLANE STRAIN TESTS ON UNDISTURBED SAN FRANCISCO BAY MUD



Consolidation Pressures +

Test	σ'_{ac}	$\sigma'_{\ell c}$
VPS-11	0.37	0.69
VPS-L-1	1.38	0.71
VPS-L-2	1.41	0.73
HPS-13	0.56	1.51
HPS-L-3	0.65	1.51
HPS-L-4	0.52	1.55

+ Corrected, in kg per sq cm

FIG. 17. — STRESS-STRAIN CURVES FOR CONSOLIDATED-UNDRAINED PLANE STRAIN TESTS ON UNDISTURBED SAN FRANCISCO BAY MUD

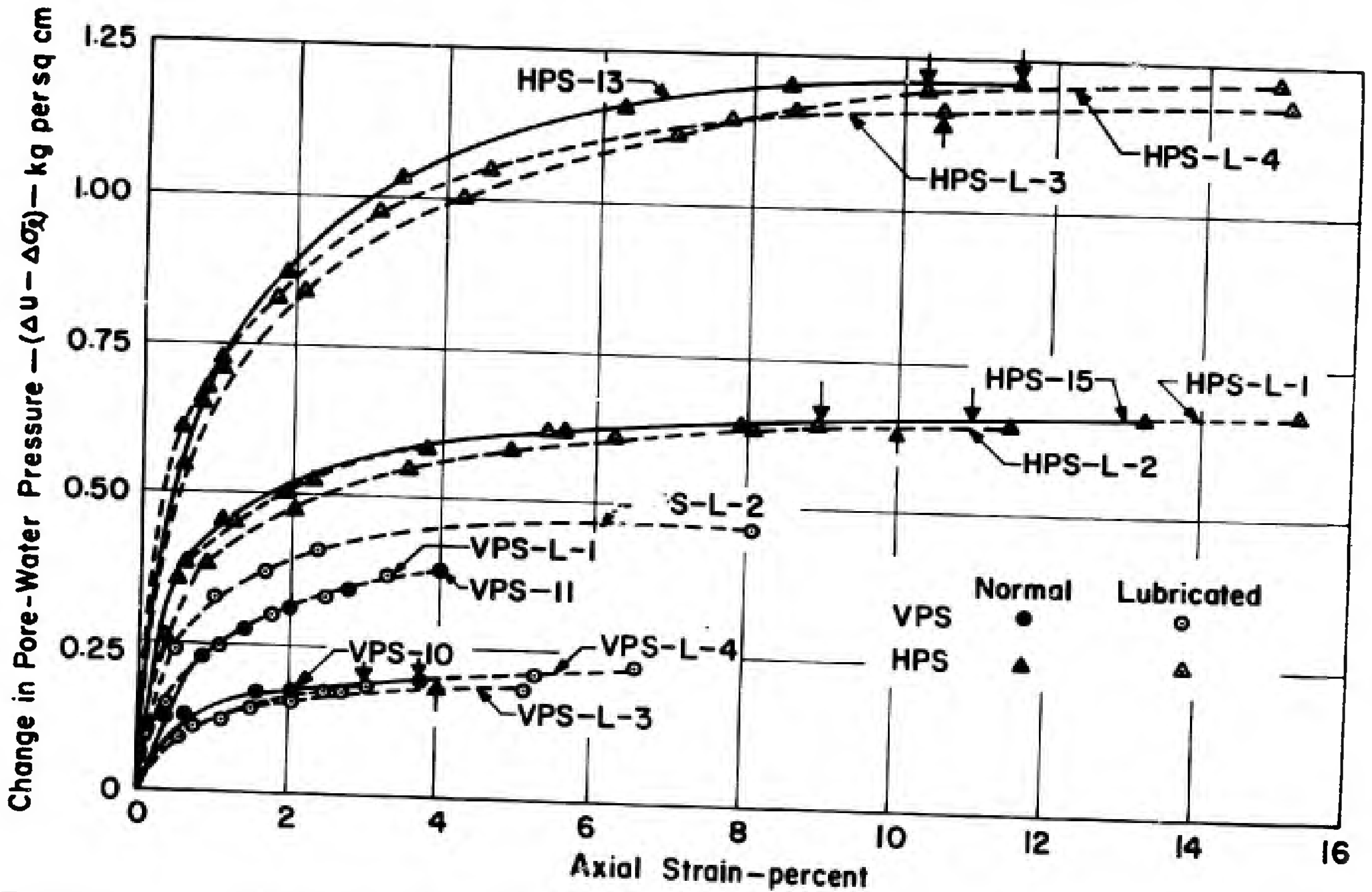


FIG. 18. — VARIATION OF CHANGES IN PORE-WATER PRESSURE WITH AXIAL STRAIN FOR CONSOLIDATED-UNDRAINED PLANE STRAIN TESTS ON UNDISTURBED SAN FRANCISCO BAY MUD.

TABLE 3. - SUMMARY OF RESULTS OF "IN-SITU" PLANE STRAIN TESTS ON UNDISTURBED SAN FRANCISCO BAY MUD.

Specimen	Cap and Base	Depth (feet)	Initial w/c (percent)	σ'_{ac} (kg/cm^2)	$\sigma'_{\ell c}$ (kg/cm^2)	$\left(\frac{\sigma'_3}{\sigma'_1}\right)_c$	Consol. w/c (percent)	ε_v (percent)	$(\sigma_a-\sigma_\ell)_f$ (kg/cm^2)	$(\Delta\sigma_a-\Delta\sigma_\ell)_f$ (kg/cm^2)
VPS-10	Normal	16.0	90.8	0.63	0.35	0.55	79.2	8.8	0.46	0.18
VPS-L-3	Lubricated	16.0	87.7	0.62	0.34	0.55	79.4	8.3	0.46	0.18
VPS-L-4	Lubricated	17.0	89.0	0.63	0.35	0.56	79.0	8.3	0.45	0.17
VPS-11	Normal	16.0	88.9	1.37	0.69	0.49	63.6	19.5	1.07	0.39
VPS-L-1	Lubricated	17.5	86.0	1.38	0.71	0.51	61.8	17.7	1.03	0.36
VPS-L-2	Lubricated	--	91.5	1.41	0.73	0.52	66.8	23.5	1.02	0.34
HPS-15	Normal	15.5	91.0	0.30	0.79	0.38	77.6	8.7	0.38	0.87
HPS-L-1	Lubricated	18.5	91.5	0.28	0.79	0.36	80.0	8.6	0.36	0.87
HPS-L-2	Lubricated	16.5	90.2	0.33	0.82	0.40	80.5	8.7	0.38	0.83
HPS-13	Normal	--	94.5	0.56	1.51	0.37	69.5	21.5	0.82	1.77
HPS-L-3	Lubricated	15.5	86.0	0.65	1.51	0.43	64.0	18.3	0.76	1.73
HPS-L-4	Lubricated	16.0	92.6	0.52	1.55	0.34	68.8	18.0	0.80	1.83

TABLE 3. - Continued

Specimen	Cap and Base	$(\Delta u - \Delta\sigma_\ell)_f$ (kg/cm^2)	$\overline{A}_f$	$\left(\frac{\sigma'_1}{\sigma'_3}\right)_f$	ϵ_{af} (percent)	Time to Failure (hours)	σ'_{1f} (kg/cm^2)	σ'_{3f} (kg/cm^2)	$\frac{(\sigma_1-\sigma_3)_f}{2}$ (kg/cm^2)	$\frac{(\sigma'_1+\sigma'_3)_f}{2}$ (kg/cm^2)
VPS-10	Normal	0.19	0.95	3.90	3.8	4.25	0.62	0.16	0.23	0.39
VPS-L-3	Lubricated	0.17	1.06	3.71	4.0	4.00	0.63	0.17	0.23	0.40
VPS-L-4	Lubricated	0.185	1.09	3.66	4.0	4.00	0.62	0.17	0.23	0.40
VPS-11	Normal	0.38	0.98	4.45	3.9	4.25	1.38	0.31	0.54	0.85
VPS-L-1	Lubricated	0.37	1.03	4.03	3.8	4.00	1.37	0.34	0.52	0.86
VPS-L-2	Lubricated	0.41	1.20	4.10	4.0	4.00	1.35	0.33	0.51	0.84
HPS-15	Normal	0.67	0.77	3.92	9.0	4.00	0.51	0.13	0.19	0.32
HPS-L-1	Lubricated	0.67	0.77	4.00	10.0	3.75	0.48	0.12	0.18	0.30
HPS-L-2	Lubricated	0.66	0.79	3.14	11.0	4.25	0.50	0.16	0.17	0.33
HPS-13	Normal	1.20	0.68	3.64	11.5	4.25	1.13	0.31	0.42	0.72
HPS-L-3	Lubricated	1.15	0.67	3.12	10.6	4.25	1.12	0.36	0.38	0.74
HPS-L-4	Lubricated	1.23	0.68	3.51	10.3	4.25	1.12	0.32	0.40	0.72

($\overline{A}$ = B · A) are very nearly the same for either type of cap and base. The variations of the values of $\overline{A}$ with axial strain, shown in Fig. 19, show no consistent influence of the type of cap and base. The values of $\overline{A}$ at failure shown in Fig. 20, as well as the variation with the axial strain shown in Fig. 19, indicate negligible influence of cap and base restraint on the values of $\overline{A}$. It thus appears that the use of the normal type of cap and base does not result in erroneous values of $\overline{A}$ for normally consolidated, undisturbed clays like San Francisco Bay Mud, when the tests are performed slowly enough so that nonuniformities in pore-water pressure are essentially equalized at failure.

The average values of $\overline{A}_f$ from previous tests (Duncan and Seed, 1965) where a longer consolidation period was employed, also shown in Fig. 20, agree quite well with the more recent tests, indicating negligible effect of altering the consolidation procedure. This would be expected because in both series of tests the specimens were allowed to consolidate for the same length of time (about 30 t_{50}) under the final increment of consolidation pressure.

c_u/p Values. The variations of undrained strength with consolidation pressure are shown in Fig. 21; the strengths of specimens tested with lubricated caps and based (indicated by the open symbols) are generally somewhat lower than those for specimens tested with normal caps and bases. The value of the ratio c_u/p for the VPS tests is consistent with that established in earlier tests, but the value for HPS tests is some 10 percent lower than that established previously. Inspection of the data from the earlier series of tests (Duncan and Seed, 1965, p. 82) shows that the value of the ratio c_u/p for tests where the major principal effective stress during consolidation was 0.8 or 1.6 kg per sq cm were also somewhat lower than the average value of c_u/p for all tests, as shown in Fig. 21.

Strength Parameters. Variations of maximum shear stress with average effective normal stress for the VPS and HPS tests are shown in Fig. 22. The value of ϕ' for undisturbed San Francisco Bay Mud appears to be about 2 degrees less for specimens tested with lubricated caps

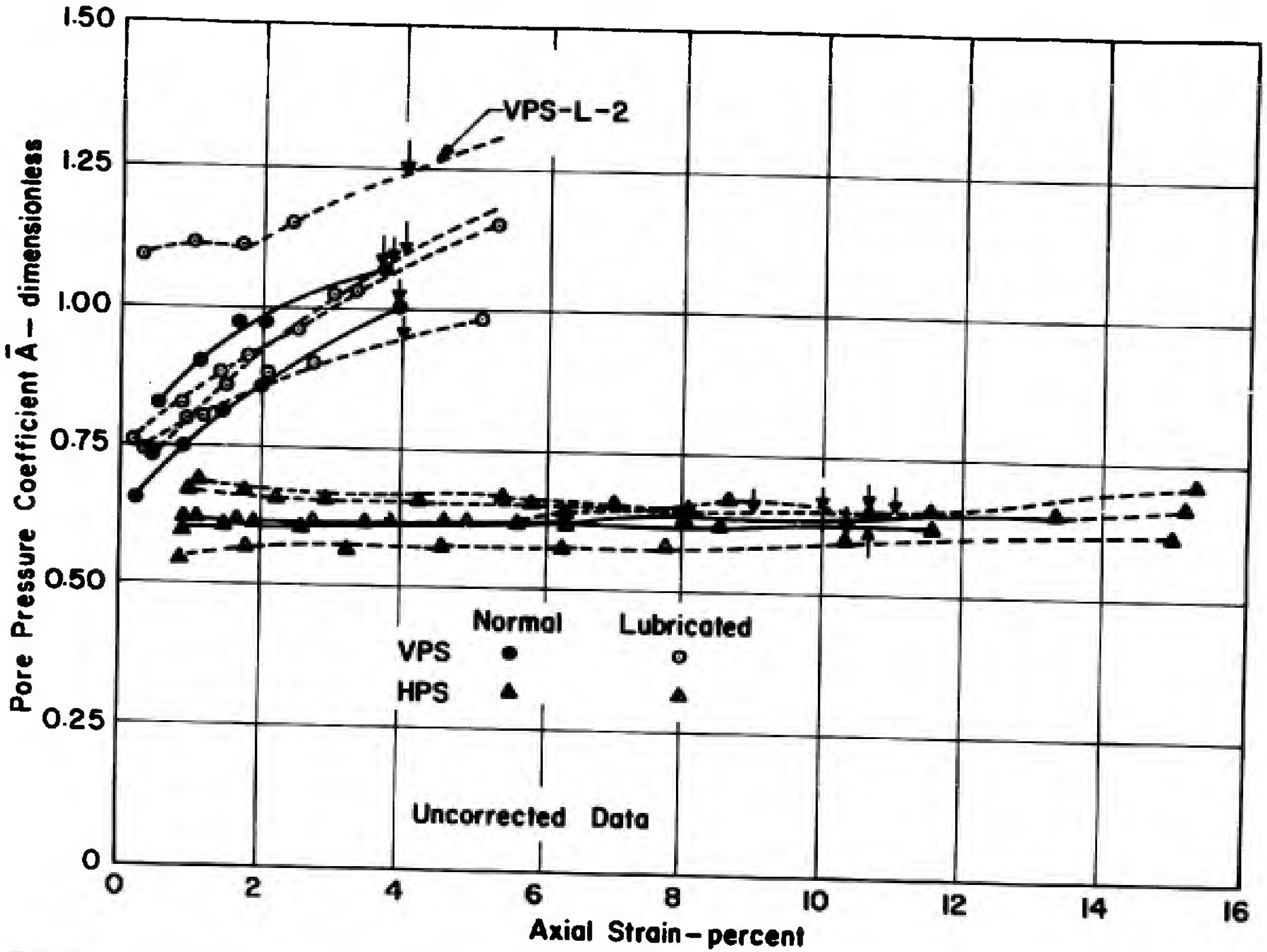


FIG.19. — VARIATION OF THE VALUE OF THE PORE PRESSURE COEFFICIENT $\bar{A}$ WITH AXIAL STRAIN IN CONSOLIDATED–UNDRAINED PLANE STRAIN TESTS ON UNDISTURBED SAN FRANCISCO BAY MUD

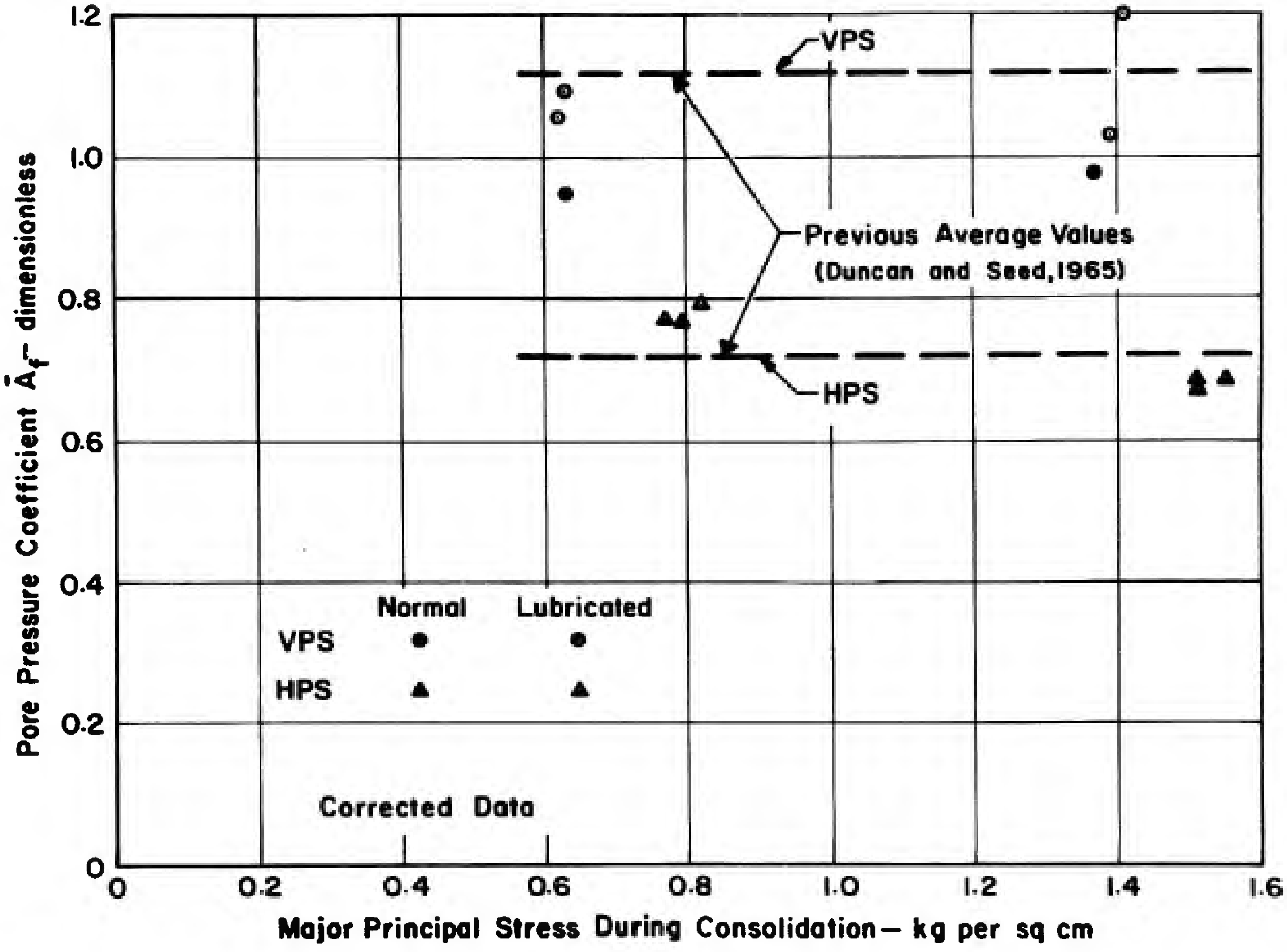


FIG. 20.- VARIATION OF VALUES OF $\bar{A}_f$ WITH CONSOLIDATION PRESSURE IN PLANE STRAIN TESTS ON UNDISTURBED SAN FRANCISCO BAY MUD

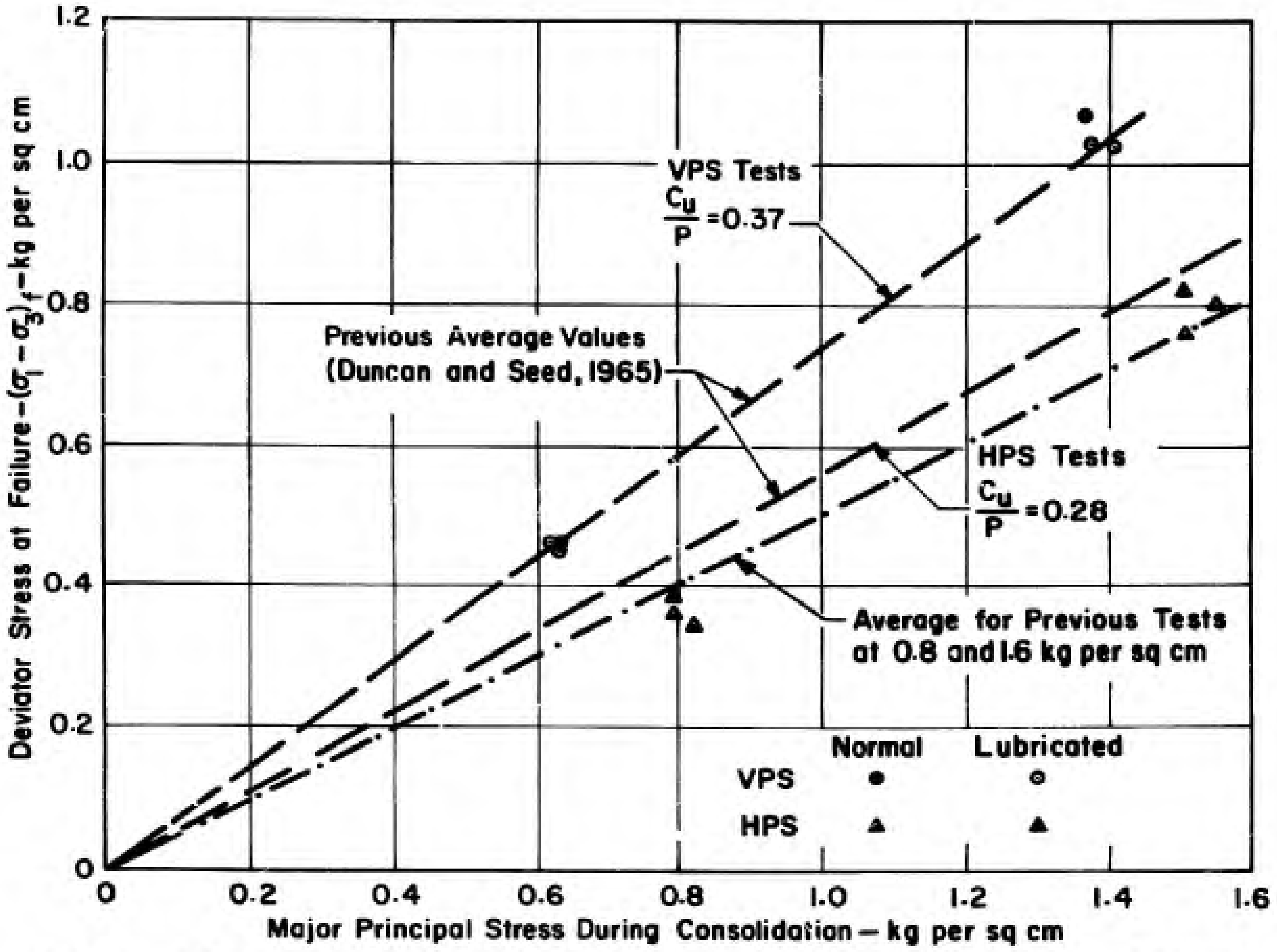


FIG.21. – VARIATION OF UNDRAINED STRENGTH WITH CONSOLIDATION PRESSURE IN PLANE STRAIN TESTS ON UNDISTURBED SAN FRANCISCO BAY MUD

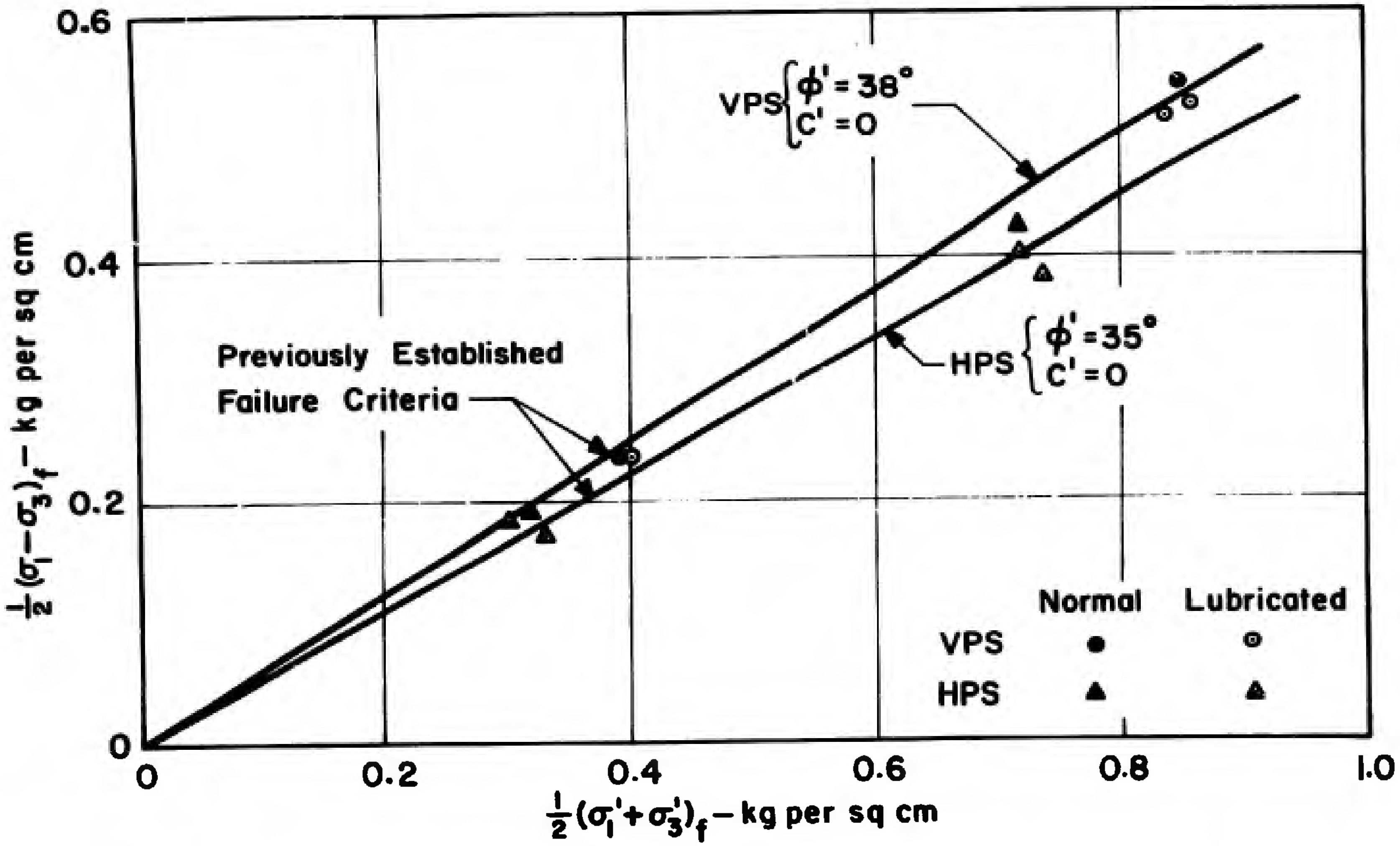


FIG.22.— EFFECTIVE STRESS STRENGTH PARAMETERS FOR UNDRAINED PLANE STRAIN TESTS ON UNDISTURBED SAN FRANCISCO BAY MUD

and bases. This amount of reduction is consistent with the fact that the values of strength are slightly lower when frictionless caps and bases are used, but the values of $\overline{A}_f$ are about the same.

Tests on Other Soils

Various investigators have evaluated the influence of cap and base restraint by testing different soils with lubricated and with normal caps and bases. Their findings are summarized in the following sections.

Undrained tests on clay. Rowe and Barden (1964) performed unconsolidated-undrained tests on remoulded, reconsolidated weathered shale (L.L. 57, P.L. 21). Large block samples were consolidated one-dimensionally from the liquid limit, and 1-1/2 in. by 3 in. test specimens were obtained from the blocks using thin-wall sampling tubes. The high initial degree of saturation of the specimens made pore-pressure measurements possible without first consolidating and back pressuring. Typical variations of change in pore-water pressure (measured at the base) with time for these tests are shown in Fig. 23. The value of $\overline{A}$ for the soil tested in this manner is approximately 0.25. The change in pore-water pressures were initially higher near the ends in the tests with normal caps and bases, as would be expected on the basis of the hypothesis by Bishop, Blight and Donald (1960) which was discussed previously. It should be noted that the values of pore-water pressure have essentially equalized after 3 to 4 minutes in tests with lubricated caps and bases, whereas a longer period of time is required for equalization with normal caps and bases. On the basis of the results shown it appears that the equilibrium values would be nearly the same for any of the three types of cap and base. The undrained compressive strengths of specimens tested with any type of cap and base were all 11 to 12 lb per sq in, and the strains at failure were all about 15 percent.

Barden and McDermott (1965) performed unconsolidated-undrained tests on compacted clay and consolidated-undrained tests on remoulded clay. In tests on both types of soil pore-water pressures were measured using probes through the membrane at various heights, as well as a disc

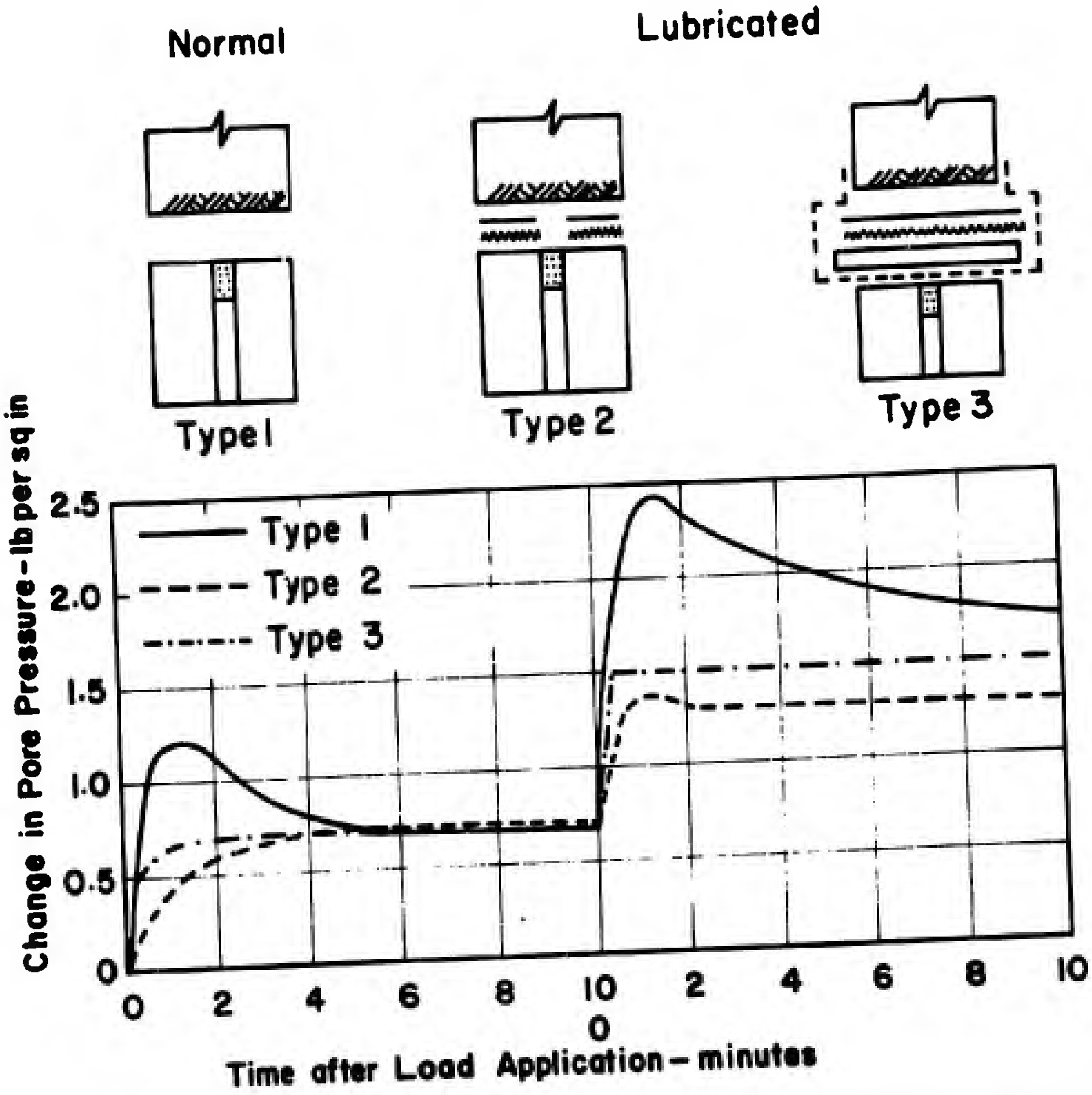


FIG.23.- VARIATIONS OF PORE WATER PRESSURE WITH TIME (AFTER ROWE AND BARDEN, 1964)

in the center of the base. Most tests were conducted at very high rates of strain and large nonuniformities in pore pressure were found in specimens tested with normal caps and bases. Pore-water pressures were nearly equalized at 10 percent strain in a test conducted with normal cap and base at a rate calculated to give 95 percent equalization at that value of strain, even though the height to diameter ratio of the specimen was 1 to 1. Pore-water pressures measured in a consolidated-undrained test on a specimen 8 in. high by 4 in. diameter, of normally consolidated clay, using normal caps and bases and a strain rate calculated to give 95 percent equalization at 10 percent strain, were in nearly exact agreement with pore-water pressures measured in a test on a 4 in. by 4 in. specimen, using lubricated cap and base and a strain rate 25 times as fast. From these results the following conclusions may be drawn: (1) Significant non-uniformities in pore-water pressure at failure may be avoided simply by conducting tests at normal rates, (2) it appears that if specimens with 2 or 2.5 to 1 height to diameter ratios are used, the equilibrium values of pore-water pressure will not be appreciably influenced by cap and base restraint, even though moisture migration occurs during the tests.

<u>Drained tests on sand</u>. Rowe and Barden (1964) investigated the influence of cap and base restraint on the drained strength and volume change characteristics of saturated Mersey sand. They found that the strength was about 10 percent less and the volumetric strains at failure somewhat larger when lubricated caps and bases were used. Lee and Seed (1964) found that the drained strength of saturated Sacramento River sand at low confining pressure was reduced about 5 percent and the tendency to dilate was increased by the use of lubricated caps and bases. In tests conducted at higher confining pressures, where the volume of the specimens decreased during shear, the strength was virtually the same with either type of cap and base, and the amount of decrease in volume was larger for specimens tested with normal caps and bases. Both Rowe and Barden, and Lee and Seed found that the stress-strain curves were somewhat steeper for specimens tested with normal

caps and bases. Bishop and Green (1965) found that cap and base restraint increased the strength of saturated Ham River sand; the influence of restraint decreased rapidly with increasing values of the height to diameter ratio, however, and at a ratio of 2 to 1 there was virtually no influence of end restraint on strength. Axial specimen loads were measured by a load cell inside the pressure chamber, thus eliminating the possibility that different amounts of piston friction with different types of cap and base could be interpreted as differences in the strengths of the specimens. Smaller values of piston friction may result when lubricated caps and bases are used, since they would be expected to exert smaller lateral forces on the loading piston. With a sliding bushing, reduction in lateral force would result in reduction piston friction (Warlam, 1960). A careful analysis of the data obtained by Bishop and Green (1965) shows that the stress-strain curves were somewhat steeper and the strains at failure somewhat smaller for specimens tested with normal caps and bases. The amount of increase in volume was found to be smaller for specimens with normal caps and bases, and the difference between the volumetric strains of specimens tested with normal and with lubricated caps and bases increased with increasing axial strain.

CONCLUSION

The studies previously described indicate clearly the characteristics and the magnitudes of the various effects of cap and base restraint and the resulting bulging deformation of compression test specimens. On the basis of these studies it is possible to make a number of conclusions with regard to the significance of end restraint.

Cap and base restraint results in nonuniform volumetric strains within drained test specimens and moisture migration within undrained test specimens. Because volumetric strain and uniformity of water content are themselves rarely of direct interest, variations in these quantities will usually be unimportant unless they cause appreciable changes in strength, pore-water pressure or stress-strain behavior of the soils tested.

In both undrained tests on clay and drained tests on sand, cap and base restraint results in increased strength and increased initial slope of the stress-strain curve. For all of the tests reviewed the magnitude of the strength increase due to restraint varied between zero and 10 percent, the average for both sand and clay being about 5 percent. The value of the 50 percent secant modulus would be 5 to 10 percent larger as a result of end restraint. These effects would not ordinarily be considered significant, since they correspond to the usual limits of accuracy with which these quantities can be measured.

The influence of cap and base restraint on pore-water pressures in undrained tests depends largely on the rate at which the specimen is loaded. In rapidly conducted tests on clay, large nonuniformities have been shown to exist, and pore-water pressures measured at the bottom of a specimen in a rapid test could be considerably in error. In tests conducted at rates calculated to give 95 percent or better equalization of nonuniform pore-water pressures, however, the values of pore-water pressure at the base are in good agreement with values measured in tests using lubricated caps and bases, showing that the influence of moisture migration on the equilibrium pore pressure value is small.

Because gradients in pore-water pressure between the top and bottom of a specimen and the center are smaller when lubricated caps and bases are used, effective pore pressure equilibrium is reached more quickly. For example, if nonuniformities in pore-water pressure can be reduced by 90 percent through the use of lubricated caps and bases, the required degree of equalization could be reduced from 95 percent to 50 percent with no overall reduction in accuracy, and the required test duration would be reduced considerably. Cap and base restraint is not, however, the only cause of non-uniformities in pore-water pressure. Variations in density within compacted or undisturbed soil specimens may also cause nonuniformities in pore-water pressure which should be given ample time to equalize.

If testing with lubricated caps and bases involved no additional difficulties, their routine use would be desirable. Their use, however, requires additional time for assembly, and makes provision of efficient drainage more difficult and less certain. In long-term tests it may be necessary to alter test procedures (as in the case of the plane strain tests on San Francisco Bay Mud discussed previously), or to use specimens of a larger size in order to insure that the effective friction angle will not exceed 2 degrees at failure. In view of these complications posed by their use, it seems logical to employ lubricated caps and bases only when sufficient accuracy cannot be attained with normal techniques. On the basis of the studies discussed previously, it appears that the use of lubricated caps and bases is warranted only when it is necessary to measure volumetric strains in drained tests on sand with unusually high accuracy.

Whenever it is desired to use lubricated caps and bases, the test conditions should be examined to insure that the effective friction angle will be reduced to less than 2 degrees, in order that end restraint will be effectively eliminated. This may be done by means of the techniques explained in the Appendix. These techniques may also be used to derive corrections to the axial stress for friction between plane strain specimens and their end plates.

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APPENDIX A

THE MECHANISM OF LUBRICATION, AND FRICTION BETWEEN LUBRICATED SURFACES

Introduction

Lubrication with grease has been used to reduce cap and base restraint in compression tests, and to reduce frictional drag between plane strain specimens and their end plates. The technique proved to be effective in some cases and ineffective in others. The study described in this Appendix was undertaken to find a means of calculating the friction between lubricated surfaces. The techniques explained may be used to insure the effectiveness of lubricated caps and bases or to calculate the magnitudes of the frictional forces between plane strain specimens and their end plates.

Friction

Frictional resistance to sliding between surfaces is proportional to the normal force holding the surfaces together. Terzaghi (1925) outlined a simple mechanism to explain the proportionality of shear and normal force during sliding. He hypothesized that the true area of contact, a_t, between solids being pushed together was very small due to the fact that all surfaces are rough on the smallest scale, and only the highest bumps actually touch each other. He further suggested that the material in these bumps would flow when the true contact stress became equal to σ_y, the yield stress of the material. Since the true contact stress cannot increase above σ_y, the material will flow so that the true contact area, a_t, is just sufficient to satisfy the equation

$$A_t = \frac{F_n}{\sigma_y} \tag{3}$$

where F_n is the normal force holding the surfaces together. If the material in the bumps is assumed to behave plastically under shear stress also, then the material in the bumps will flow when the true shear stress reaches some value τ_y. The tangential force, F_t, required to cause slip between the surfaces would then be given by

$$F_t = a_t \cdot \tau_y = F_n \frac{\tau_y}{\sigma_y} \tag{4}$$

The "coefficient of friction" is thus the ratio τ_y/σ_y, and the "friction angle" is arctan τ_y/σ_y.

Lubrication

Bowden and Tabor (1950) describe two distinct types of lubrication: (1) Fluid lubrication occurs when the solid surfaces are prevented from touching by a layer of lubricant which supports all of the normal force. Since there is no solid-to-solid contact, there is no friction. Generally, ideal or perfect fluid lubrication can only occur under hydrodynamic conditions, when the slip velocity is large enough to form a wedge of lubricant capable of keeping the solid surfaces apart. The conditions necessary for this type of lubrication were analyzed by Reynolds (1886). (2) Boundary lubrication occurs when surface bumps are prevented from touching by a layer of lubricant only about one molecule in thickness. If the lubricant is an efficient boundary lubricant, the friction between bumps separated by the molecular layer will be much less than if the lubricant were not present.

According to Bowden and Tabor, silicone grease is a poor boundary lubricant. Therefore, the beneficial effect of silicone grease must be due primarily to fluid lubrication rather than boundary lubrication. Thus it would be expected that the effectiveness of the lubrication would depend on the thickness of grease between the surfaces and the extent to which solid-to-solid contact is developed.

Theoretical Thickness of Grease

The relationship between the thickness of grease between two surfaces, the normal load forcing the surfaces together, and time is simple if the surfaces are assumed to be completely smooth. Michell (1923) has shown that in the case of a smooth circular disk being forced towards another smooth surface with grease in between, the thickness of grease at any time is expressed by the relationship

$$h^2 = \frac{h_i^2}{1 + \frac{4}{3\pi} \frac{h_i^2 F_n t}{\nu r^4}} \qquad (5)$$

where h = thickness of grease at any time, t - (cm)

h_i = thickness of grease at time, t = 0 - (cm)

F_n = force pushing disc toward surface - (kg)

t = time - (sec)

ν = viscosity of grease - (kg-sec/cm^2) (ν = 0.1 kg-sec/cm^2 for Dow-Corning silicone stopcock grease and ν = 0.23 kg-sec/cm^2 for high-vacuum silicone grease).

and r = radius of disc - (cm).

In the case of an infinitely long strip, it may be shown that the corresponding relationship is expressed by the equation

$$h^2 = \frac{h_i^2}{1 + \frac{1}{4} \frac{h_i^2 f t}{\nu b^3}} \qquad (6)$$

where f = force per unit length pushing strip toward surface - (kg/cm)

and b = one-half the width of the strip - (cm).

In order to derive equations 3 and 4 it has been assumed that the surfaces are smooth and that they do not touch through the grease. These assumptions are not likely to be correct for small thicknesses, and for this reason the thickness of grease computed by equation 5 or 6 has been termed the "theoretical thickness." If the assumptions used in deriving these equations were true there would be no solid-to-solid contact and there could be no frictional resistance to movement. Experiments which are described in the next section show that, in fact, there is frictional resistance to movement. Although the assumptions on which equations 5 and 6 are based are incorrect, they have been found to be useful because an empirical correlation has been established between the theoretical thickness of grease and the effective coefficient of friction, μ_e.

Correlation Between Theoretical Thickness and Effective Coefficient of Friction

The coefficient of friction between polished lucite and rubber was measured using the device shown in Fig. A-1. Essentially the device is a smooth inclined plane covered with rubber which is coated with grease. A dial gage is arranged so that the tangent of the angle of inclination can be read directly to 0.0001. A polished lucite sliding block rests on the grease-coated rubber, and its movement can be noted by pushing the foot of another dial gage into contact with its lower end. The normal and shearing force are provided by a weighted yoke hanging from the block.

The first experiment was conducted primarily to investigate the rate of creep of the block at inclinations less than the one required to cause slip. The test lasted 96 days, during which period the tangent of the angle of inclination was increased by increments of 0.0025 to 0.0100 per day. The block finally slipped at an inclination equal to arctan 0.380. During the experiment the creep movement rate was fairly constant at about 0.0003 inches per day until the tangent of inclination was 0.23. The rate gradually increased from this time until, at the increment just before complete slip, it was 0.0026 inches per day.

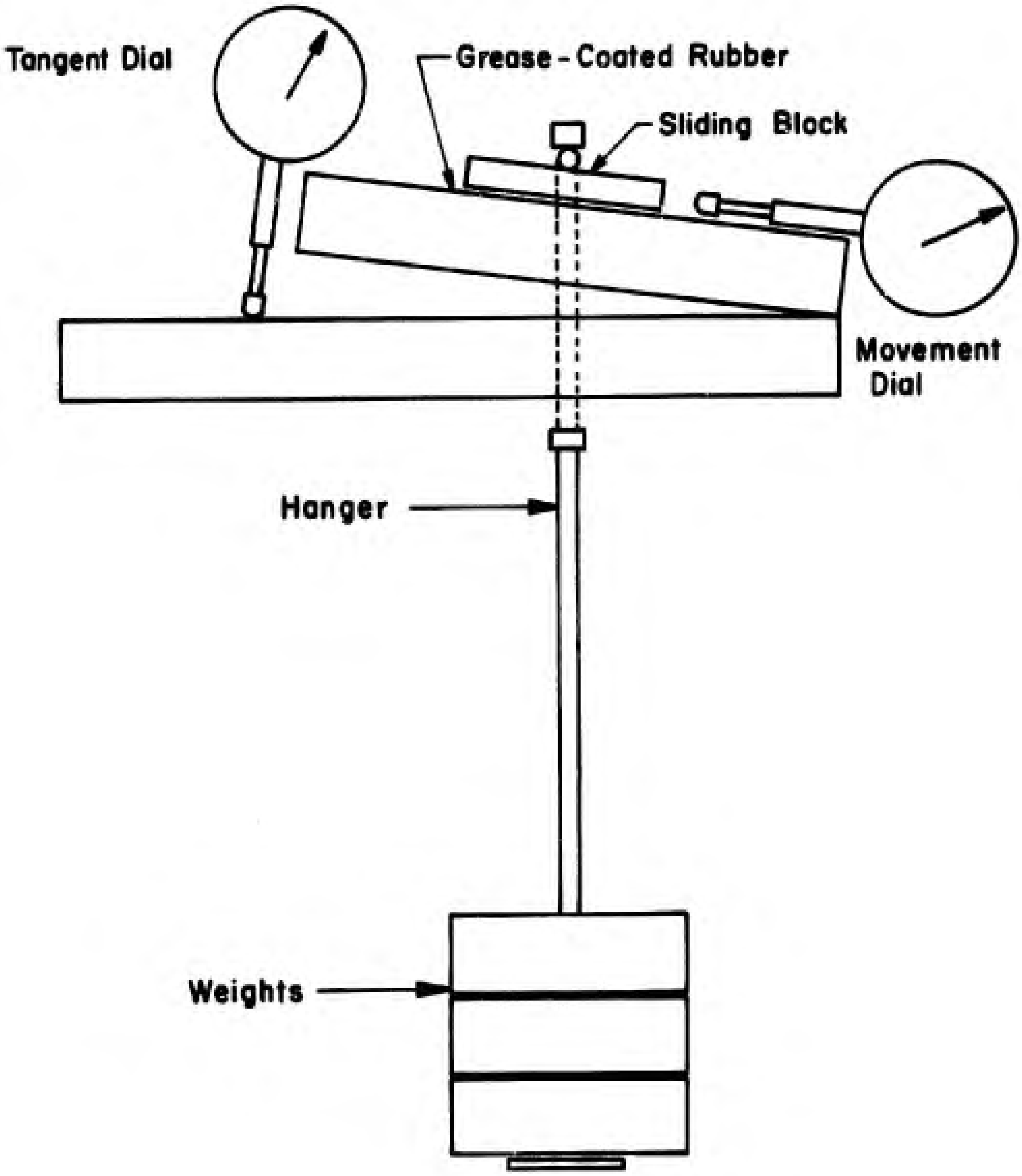

FIG.A-1. – SLIDING BLOCK FRICTION DEVICE.

Subsequent experiments were made by leaving the normal load (about 100 lbs.) in place for different lengths of time, and then increasing the inclination relatively quickly until slip occurred. There was never any problem in determining when slip occurred, because the sliding block accelerated rapidly once movement began. No creep rates were calculated for these tests. Two sliding blocks were used for the experiments; one was 2.80 inches square, the other was 1.00 inches by 2.50 inches.

To calculate the theoretical thickness of grease the square was treated as a circle of equal area, and the rectangle as an infinite strip. The initial thickness of grease was estimated by weighing the sliding blocks after coating with grease, but exact knowledge of the initial thickness is only important at short times. With the square block, for instance, the theoretical thickness calculated assuming $h_i = 0.1$ cm is only ten percent larger than the theoretical thickness calculated assuming $h_i = 0.01$ cm when $t = 24$ hours, for the normal force used.

The results of all tests are shown in Fig. 4. These tests lasted from 21 minutes to 96 days. The effective coefficient of friction shown is the tangent of the angle at which complete slip occurred. This correlation makes it possible to determine the effective coefficient of friction between polished lucite and smoothly backed rubber for any situation where the theoretical thickness of grease can be calculated.

In order to see if the relationship between the effective coefficient of friction and the theoretical thickness of grease applies only to tests where the normal load was constant, one test was run where the normal load varied with time. The 1.00 by 2.80 inch sliding block was used, and the loads were left in place (at zero inclination) for two to twenty hours over a five-day period. Each load was larger than the previous one, and the final load was 55 lb. This test, indicated by "varying load" in Figure 4, shows that the relationship between effective coefficient of friction and theoretical thickness is, for practical purposes, independent of the load-time history.

Application to Lubricated Caps and Bases

The correlation between theoretical thickness and effective coefficient of friction may be used to determine the effective frictional angle for lubricated caps and bases. The theoretical thickness of grease at the end of the test may be calculated using equation 5 (for triaxial specimens) or equation 6 (for plane strain specimens). Then the effective coefficient of friction may be determined from Fig. 4. Because the rubber was smoothly backed in the sliding block friction tests, the results shown in Fig. 4 should be directly applicable to tests on clay, which would also form a smooth backing. The results may not be directly applicable to tests on sand, however, unless the rubber is sufficiently thick compared to the grain size of the sand being tested.

The total axial stress in the specimen tends to force the grease to flow out from between the rubber and the cap or base, while the pore-water pressure in the specimen tends to restrict this flow, in much the same way as flow of water out of a consolidating soil specimen is restricted by back pressure. Therefore, in the case of triaxial specimens, the force F_n causing the extrusion of the grease is equal to the effective axial stress in the specimen multiplied by the specimen area. In the case of plane strain specimens, the force per unit length f causing extrusion of the grease is equal to the effective axial stress multiplied by the specimen width. Examples of friction angles calculated for lubricated caps and bases in triaxial and plane strain tests are shown in Figs. 5 and 15.

Application to Lubricated End Plates

The relationship between theoretical thickness of grease and effective coefficient of friction may also be used to determine the frictional forces between a plane strain specimen and its end plates. The longitudinal normal stress in a plane strain specimen (σ_2) tends to force the grease between the end plate and membrane to flow out, while the chamber pressure tends to prevent the grease from flowing out. Therefore, the force per unit length tending to cause extrusion of the grease is equal to the product $(\sigma_2' + u - p_c)2b$, where σ_2' is the effective lateral stress, u is the pore-water pressure, p_c is the chamber pressure and 2b is the specimen width.

The force tending to cause extrusion of the grease decreases with time during anisotropic consolidation of a plane strain specimen as the excess pore-water pressure decreases. During dissipation the excess pore-water pressure decreases to the back pressure p_b and the quality $(\sigma_2' + u - p_c)$ decreases to zero since the chamber pressure is equal to $(\sigma_2' + p_b)$. Thus at the beginning of consolidation, the force per unit length, f, tending to cause extrusion of the grease is $f_i = (\sigma_{2i}' + u_i - p_c)$. Within the time t_d required for the excess pore-water pressure to dissipate, the value of f decreases from f_i to zero. The decrease of f with time is non-linear and may be conveniently approximated by a second-degree parabola. For f decreasing parabolically from f_i to zero within the time period t_d, the theoretical thickness after dissipation can be shown to be given by

$$h_c^2 = \frac{h_i^2}{1 + \frac{h_i^2}{12} \frac{f_i \; t_d}{\nu b^3}} \tag{7}$$

where h_c = theoretical thickness of grease after consolidation - (cm).

During shear the total longitudinal stress increases, and at failure is equal to $(\sigma_{2f}' + u_f)$. Thus at failure the force per unit length tending to cause extrusion of the grease is $f_f = (\sigma_{2f}' + u_f - p_c)2b$. The increase of the total longitudinal stress with time may conveniently be approximated as linear for purposes of computing the decrease in theoretical thickness. If f increases from zero to f_f in time t_f (the time to failure), the theoretical thickness of grease at failure can be shown to be given by

$$h_f^2 = \frac{h_c^2}{1 + \frac{h_c^2 \, f_f \, t_f}{8 \; \nu b^3}} \tag{8}$$

where h_f = theoretical thickness of grease at failure - (cm).

The value of σ_2' has been found to be very nearly equal to $K_o\sigma_1'$ at any stage of a consolidated-undrained plane strain test on clay (Wade, 1963), and this fact makes computation of the decrease in theoretical thickness with time quite simple. In computing the frictional drag on plane strain specimens in a recent series of plane strain tests (Duncan and Seed, 1965) the initial value of the force per unit length tending to cause decrease in the thickness of grease during consolidation was computed using the expression

$$f_i = (K_o\sigma_{1i}' + u_i - p_c) \tag{9}$$

where σ_{1i}' = major principal effective stress at the beginning of consolidation - (kg/cm^2)

and u_i = pore-water pressure at the beginning of consolidation - (kg/cm^2)

When several load increments were used for consolidation, the theoretical thickness after each increment was calculated, using the theoretical thickness after the previous increment as the value of h_i. The thickness prior to the first increment was taken as 0.03 cm based on measurements of the average initial thickness measured in connection with the sliding block friction tests.

For computing the theoretical thickness of grease at failure, the final value of the force per unit length tending to cause decrease of thickness of the grease was computed from the expresion

$$f_f = (K_o\sigma_{1f}' + u_f - p_c) \tag{10}$$

where σ_{1f}' = major principal effective stress at failure - (kg/cm^2)

and u_f = pore-water pressure at failure - (kg/cm^2).

In computing the values of theoretical thickness for the plane strain tests on San Francisco Bay Mud, the value of K_o was taken as 0.45, based on measurements of the force required to maintain the height of HPS specimens constant during consolidation. The value of t_d was taken as four hours, the average length of time required to reach the end of primary consolidation, and the value of t_f was taken as the length of the undrained test.

After computing the values of theoretical thickness at failure, the value of the effective coefficient of friction was determined from Fig. 4. The frictional force exerted on each end of the specimen by the end plates was computed using the expression

$$F_t = \mu_e \cdot f_f \cdot H \qquad (11)$$

where F_t = frictional drag on each end of the plane strain specimen - (kg)

μ_e = effective coefficient of friction

f_f = force per unit length as given by equation 10 - (kg/cm)

and H = specimen height - (cm).

It should be noted that with floating end plates, which are free to move with respect to the top and bottom of the specimen, one half of F_t will act upward on the upper half of the specimen, and one half will act downward on the lower half of the specimen. Thus the axial force carried by each end plate is

$$F_{ep} = \frac{1}{2} F_t \qquad (12)$$

where F_{ep} = axial force carried by friction with one end plate - (kg).

Because two end plates are used, the necessary correction to the axial stress for end plate friction is

$$\Delta\sigma_{aep} = \frac{2 F_{ep}}{A_s} = \frac{F_t}{A_s}$$

where $\Delta\sigma_{aep}$ = correction to the axial stress for end plate friction - (kg/cm^2)

and A_s = cross-sectional area of the specimen at failure - (cm^2).

Because the cell pressure is equal to $(K_o\sigma_1' + p_b)$, the force per unit length f is zero at the end of consolidation, and the frictional drag is equal to zero after consolidation.

Values of end plate friction computed using the techniques explained in the previous pages are listed in Table 4; the upper values are the calculated frictional forces, and the values in parentheses are the corresponding corrections to the axial stress. It may be noted that the required corrections for end plate friction increase with increasing consolidation pressure; for specimens consolidated to $\sigma_{1c}' = 4$ kg per sq cm, the corrections to the axial stress amount to about 0.2% of the deviator stress at failure in VPS tests, and about 2% of the deviator stress at failure in HPS tests. Thus it might be reasonable to neglect corrections for end plate friction if, as in this case, they are found to be of small significance.

In order to check the computational procedure outlined previously, the frictional drag was measured during an HPS test on a specimen consolidated to 3.2 kg/cm^2 using a pair of small hydraulic load cells. The measured value, 0.95 kg, agrees very well with the computed value shown in Table 4, 1.01 kg. It should be noted that the load cells prevented downward movement of the end plates, so that the frictional force was double the value for floating end plates.

TABLE 4. - CALCULATED FRICTIONAL FORCE BETWEEN END PLATES AND MEMBRANE IN PLANE STRAIN TESTS, AND THE CORRESPONDING CORRECTIONS TO THE AXIAL STRESS AT FAILURE.

Major Principal Stress During Consolidation (kg/cm^2)	Calculated Frictional Force - (kg) (Correction to Axial Stress - (kg/cm^2))	
	VPS Tests	HPS Tests
0.8	0.031 (-0.001)	0.104 (-0.005)
3.2	0.127 (-0.005)	*1.01 (-0.059)
4.0	0.138 (-0.006)	0.830 (-0.050)

*This value is twice the value given by the expression for F_t, because the end plates were prevented from moving down by the load cells used to measure the frictional force.

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The objective of this investigation was to determine the significance of the various effects of cap and base restraint in strength tests on soils. The normal caps and bases used in strength tests prevent lateral expansion of the top and bottom of test specimens. Previous studies have shown that this restraint causes nonuniform volume changes in drained tests, moisture migration in undrained tests, and, in rapidly conducted tests, nonuniformities in pore-water pressure in undrained clay specimens. Lubricated caps and bases were used to eliminate end restraint in undrained triaxial and plane strain tests on undisturbed saturated clay. The results of these tests were compared with the results of tests performed using normal caps and bases to assess the significance of cap and base restraint. These tests showed that the magnitude of the effects of cap and base restraint are not significant. ~~The results~~ of these tests are in substantial agreement with the results of undrained tests on clay and drained tests on sand which have been performed by other investigators. Only in cases where accurate measurement of volume changes are required in drained tests, or where moisture migration must be prevented in undrained tests, will lubricated caps and bases be necessary. In conjunction with this investigation a procedure was developed for insuring the effectiveness of lubrication in eliminating cap and base restraint. The same techniques may also be used to calculate the frictional forces between plane strain specimens and their end plates.

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