EFFECTIVE STRESS RESPONSE OF CLAY TO UNDRAINED CYCLIC LOADING

by

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ABSTRACT

No information exists in the current soil mechanics literature on the behaviour of saturated clays under slow cyclic reversal in stress and strain, that will allow an effective stress interpretation of their undrained response. This study fills such a gap in our knowledge of clay behaviour.

The undrained response of normally consolidated Cloverdale clay to slow constant stress amplitude cyclic reversal in stress and strain follows two distinct patterns. Under low cyclic stress levels (less than half the undrained strength), residual strain and pore water pressure development with loading cycles tends toward equilibrium. Under high cyclic stress levels (higher than half the undrained strength), strains at peak of cyclic stress eventually accumulate at an accelerated rate per cycle. A single threshold principal effective stress ratio signals the onset of strain acceleration for all cyclic stress levels. A step increase in cyclic stress level may shift the clay response from equilibrium type into instability type within the same cyclic loading event.

During cyclic loading the effective stress states for a given number of cycles form a collapsing stable state boundary surface common to all cyclic stress levels. The relationship between principal effective stress ratio and strain at peak of cyclic stress depends on both cyclic stress level and loading phase. Cyclic stress level also affects the correlation between cumulative hysteretic work and residual pore water pressure. However, damping ratio remains essentially constant for all cyclic stress levels. Upon cyclic instability, the clay fails on the same effective stress strength failure envelope as under monotonic loading.

Undrained cyclic loading clay response depends on the initial loading direction. Cyclic loading initiated in the direction opposite to natural clay deposition is more damaging than loading initially congruent with natural direction of material deposition.

Constant stress ratio amplitude cyclic reversal in stress and strain results in limited strain and pore water pressure development with loading cycles. The collapsing stable state boundary surface found for constant stress amplitude cyclic loading is however also a bounding effective stress state for constant stress ratio cyclic loading.

Postcyclic undrained monotonic loading results in strength and stiffness degradation directly related to the maximum strain developed during cyclic loading and to the effective stress stability threshold found for constant stress amplitude cyclic loading. A unique relationship exists between normalized undrained strength and overconsolidation ratio regardless of the type of overconsolidation history, provided that the overconsolidation ratio is defined with respect to the equivalent consolidation stress.

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B	Skempton's parameter
E_{50}	secant modulus at half peak deviatoric stress
ϵ_a	axial strain
ϵ_c	cyclic axial strain
ϵ_m	mean axial strain
ϵ_{max}	axial strain at peak of cyclic stress in compression
ϵ_{min}	axial strain at peak of cyclic stress in extension
ϵ_r	residual axial strain
f	frequency of cyclic loading
LL	liquid limit
N	number of cycles
PL	plastic limit
OCR	overconsolidation ratio
OCR_e	equivalent overconsolidation ratio
Su_c	reference undrained strength in compression
Su_{pc}	postcyclic undrained strength
σ_1	major principal total stress
σ_3	minor principal total stress
σ_1'	major principal effective stress
σ_3'	minor principal effective stress
σ_a	total axial stress

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σ_r	total radial stress
σ_a'	effective axial stress
σ_r'	effective radial stress
σ_c'	effective consolidation stress
σ_1'/σ_3'	principal effective stress ratio
σ_e'	equivalent effective consolidation stress
τ_{cy}	cyclic deviatoric stress
τ_{cy}/Su_c	cyclic stress level
u_b	pore pressure at base of specimen
u_m	mean pore pressure
u_r	residual pore pressure
u_s	secondary pore pressure

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INTRODUCTION

Engineering structures founded on clay deposits are often designed to withstand cyclic loads such as seismic ground motions or ocean waves. Typically, the loading period ranges from one second (seismic pulses) to twenty seconds (ocean waves). Due to the low permeability of clays, loading is considered to occur under undrained conditions. The soil properties needed for design are generally derived from undrained laboratory tests on clay specimens under controlled cyclic loading conditions.

The selection of the testing apparatus is based on the intent to simulate the loading conditions of typical soil elements in the clay foundation. Commonly, cyclic loading is carried out in the triaxial apparatus or the simple shear device with a constant cyclic stress amplitude using field loading frequency. A considerable amount of information exists from such fast cyclic loading tests on clays using both triaxial and simple shear apparatus (2, 73, 123). In the cyclic triaxial test, a cylindrical soil specimen is first consolidated under the desired effective stress, then the axial stress is increased or decreased while the confining total stress is maintained constant. The soil specimen is oriented so that the cyclic axial load acts perpendicular to the sedimented layers. In the cyclic simple shear test, the specimen is first consolidated under the desired vertical stress, then the cyclic loading is applied on the horizontal plane as a symmetrical loading pulse. The soil specimen is then oriented so that the cyclic horizontal load acts parallel to the sedimented layers.

INTRODUCTION

During undrained monotonic or cyclic loading, the behaviour of saturated clay is controlled by the effective stresses acting in the test element. In triaxial tests, reliable measurement of the excess pore water pressure generated during cyclic loading is necessary for the determination of the effective stress state within the specimen. The reliability of the pore water pressure measurement depends on the degree of end restraint imposed by the testing apparatus and the rate of loading applied (15, 17, 28, 35, 37, 42, 69, 100). The use of frictionless ends that promote uniform stresses has in general not been effective because of the long consolidation periods required in testing clays (3, 18, 40, 41, 87, 95). Even localized measurement of the pore water pressure within or along the specimen does not eliminate the nonuniform pore water pressure distribution during fast cyclic loading (20, 28, 37, 46, 47, 110, 111). For confident measurements of pore water pressure within the specimen, the frequency of cyclic loading must be sufficiently slow to allow the pore water pressure to equalize throughout the specimen.

Because of the significantly longer loading periods required, the response of clays to slow undrained cyclic loading has been examined on a limited scale (23, 96, 127). The few existing experimental studies have been confined to repeated triaxial compression tests (one-way cyclic loading). In one-way cyclic loading, the direction of the loading pulse coincides with the natural direction of material deposition. Reversal of the cyclic loading direction with respect to the direction of material deposition does not occur. It is well recognized from fast cyclic triaxial tests that cyclic stress reversal (two-way cyclic loading) has a more damaging effect on clay behaviour than cyclic loading without stress reversal (71, 73, 103, 113, 123). Paradoxically, there is no information available on the effective stress response of clays to slow cyclic reversal in stress and strain. Moreover, in fast two-way cyclic loading triaxial tests it is common to initiate cyclic loading in the direction of material deposition (compression pulse). Possible differences in behaviour on two-way cyclic loading initiated in the direction oppposite to the natural material deposition (extension pulse) have seldom been considered (71, 57).

Under one-way cyclic loading, some anomalies become apparent when comparing slow cyclic behaviour (96, 127) with fast cyclic behaviour (4,30, 74, 84) in terms of effective stresses for normally consolidated clays:

a) In slow cyclic tests, the development of residual pore water pressure with number of cycles occurs mostly in the first few cycles. In fast cyclic tests, the predominence of the initial loading cycles on the pore water pressure development with number of cycles is not apparent.

b) In slow cyclic tests below a given cyclic stress amplitude, the clay tends toward a nonfailure equilibrium condition characterized by no further development of strain and pore water pressure with further loading cycles. This equilibrium condition is not conclusively noted in fast cyclic tests.

c) The effective stress path followed during slow cyclic loading is bounded by the slow monotonic loading effective stress failure envelope. In fast cyclic loading the effective stress path travels beyond the slow monotonic loading effective stress failure envelope.

These anomalies clearly indicate that the interpretation of fast cyclic loading tests in terms of effective stresses may be questionable because of the unreliable pore water pressure measurement. These observed differences do not necessarily reflect the dependence of material behaviour on the frequency of cyclic loading.

During fast cyclic loading, the nonequalization of pore water pressure may lead to a nonuniform strain distribution within the specimen (15, 62, 78, 79, 101, 106). This nonuniform distribution of strain will be emphasized in the first few loading cycles where the rate of pore water pressure development per cycle is large. This aspect further points to the need for systematic studies based on slow cyclic tests in which pore water pressure and strain measurements would be reliable.

In fast cyclic loading tests on clay the residual strain has often been considered as the average between the maximum and the minimum strain developed in a cycle (2, 4, 9, 81, 123). In fact, the residual strain corresponds to the completion of the loading cycle when the deviatoric stress returns to zero. The residual strain corresponding to the completion of a loading cycle is the most relevant for design.

This thesis is concerned with the undrained response of a soft saturated natural clay to slow cyclic loading with stress and strain reversal. The effect of cyclic stress level on the development of strain and pore water pressure with number of cycles is studied in a series of cyclic compression-extension loading tests with constant deviatoric stress amplitude. A direct comparison is made between slow and fast cyclic response to point out the influence of a nonreliable pore water pressure measurement on the interpretation of test results.

The stress-strain response to slow cyclic loading is then examined and interpreted in terms of effective stresses. The effect of cyclic stress level on hysteretic work and damping ratio during cyclic loading is pointed out. The effect of the initial direction of cyclic loading on stress-strain response is studied by initiating cyclic loading both in the direction and opposite to the natural direction of material deposition under level ground (compression-extension versus extension-compression cyclic loading).

In most geological materials strain development is closely associated with change in principal effective stess ratio. The development of strains during constant stress amplitude cyclic loading is related to the corresponding variation in principal effective stress ratio. The relationship between effective stress ratio and strain development is further examined based on a series of slow cyclic loading tests with stress reversal under a constant amplitude of the principal effective stress ratio.

The effect of a step increase in cyclic stress level on the clay response is then determined in both constant stress amplitude and constant effective stress ratio amplitude cyclic loading. The observed behaviour is related to the behaviour under constant stress or effective stress ratio pulse.

The undrained postcyclic loading response of the clay is also examined in terms of the effect of prestrain and change in effective stress due to cyclic loading.

LITERATURE SURVEY

There is a very limited amount of research reported on clays under slow undrained cyclic loading. The effective stress response of clay to slow cyclic reversal in stress and strain has not been studied. In particular, little attention has been given to the response of clay to two-way cyclic loading initiated in the direction of loading opposite to the natural direction of clay deposition in level ground (extension pulse). Such cyclic loading condition may result in a response different from that under cyclic loading initiated in the direction of natural clay deposition (compression pulse).

The following literature survey is considered under two sections. The first section describes the response of normally consolidated clays to slow undrained cyclic loading. This section includes only the experimental studies with a rate of loading sufficiently slow so that pore water pressure can be regarded as reliable. The second section deals with the response of normally consolidated clays to fast undrained cyclic loading. This section encompasses behaviour where pore water pressure measurements are considered unreliable because of the fast rates of loading used. The comparison between one-way cyclic loading (no stress reversal) and two-way cyclic loading (with stress reversal) will be discussed whenever attempted in the studies reported.

2.1 Preliminary considerations

2.1.1 Strain and pore water pressure development

Strain and pore water pressure development with number of cycles has often been reported in the literature in terms of mean and cyclic values as defined in figure 2.1 for one-way cyclic loading and in figure 2.2 for two-way cyclic loading. The mean strain is the average between the maximum and minimum strain within a cycle. The cyclic strain is half the difference between maximum and minimum strain within a cycle. The mean strain must be distinguished from the residual strain which should correspond to the strain remaining at the completion of the loading cycle when the deviatoric stress returns to zero. Similar definitions have been applied for mean, cyclic, and residual pore water pressure.

2.1.2 Cyclic stress level

The clay response to slow undrained monotonic compression loading is considered as a bench mark reference for both fast and slow cyclic loading tests. Conventionally, the cyclic stress level is expressed as the ratio of the cyclic deviatoric stress amplitude and the undrained strength under slow compression loading. Thus, the cyclic stress level is defined as :

$$\tau_{cy}/Su_c$$

in which :

τ_{cy} = cyclic shear stress amplitude = $(\sigma_1 - \sigma_3)/2$

Su_c = undrained strength in slow compression

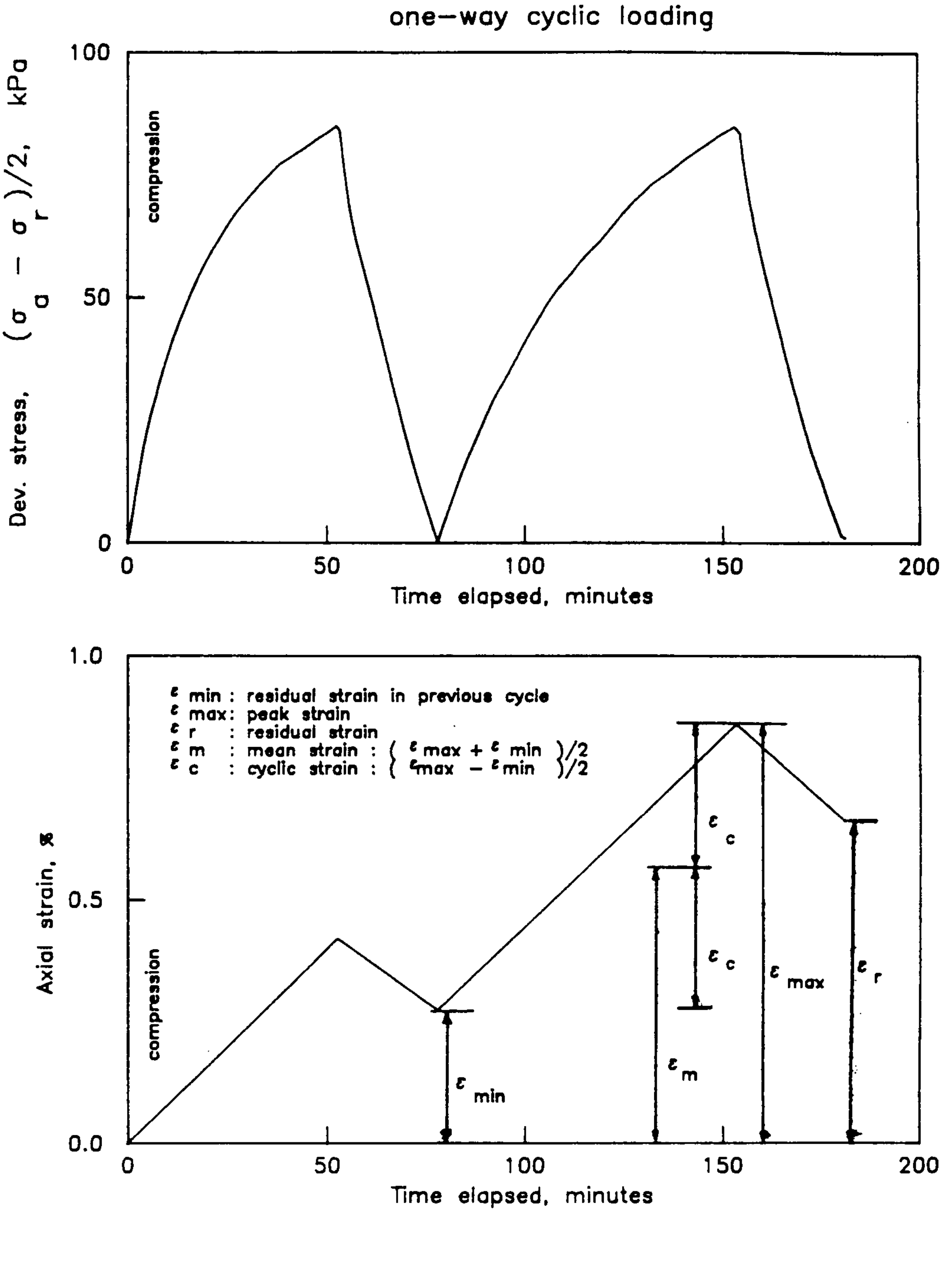


Fig 2.1 Definition of terms for axial strain development during one-way cyclic loading.

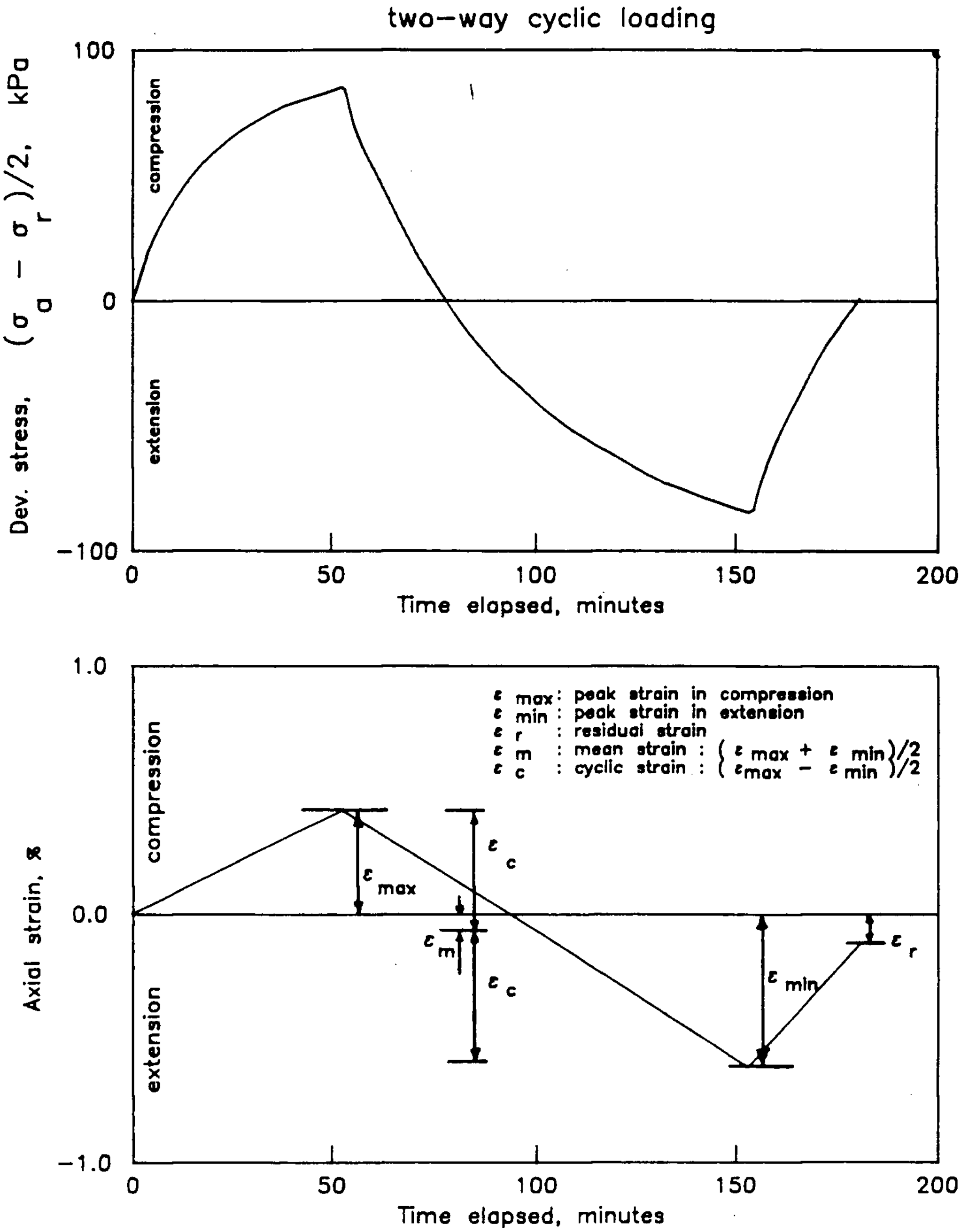


Fig 2.2 Definition of terms for axial strain development during two-way cyclic loading.

2.1.3 Clays studied by previous investigators

Various cohesive soils have been studied by previous investigators under undrained cyclic loading as indicated on the standard plasticity chart in figure 2.3. These soils vary in properties from silts and sensitive clays of low plasticity (plasticity index less than 15 percent) to soft clays and loams of high plasticity (plasticity index higher than 40 percent). Very few cohesive soils were studied under slow undrained cyclic loading particularly in the medium plasticity range (plasticity index between 15 and 40 percent). The few slow cyclic studies reported have been limited to one-way cyclic compression loading only. The effective stress interpretation based on such limited observations cannot be extrapolated to other types of clays and certainly not to cyclic loading conditions where stress reversal occurs.

2.2 Slow undrained one-way cyclic loading

All slow cyclic loading tests reported by previous investigators were performed under strain controlled loading conditions as shown on table 2.1. A constant rate of strain sufficiently slow was selected to minimize the degree of pore water pressure nonequalization within the specimen due to end restraint effects.

The effect of end restraint on the axial strain measurement during slow undrained one-way cyclic loading was examined by Kraft (62). Axial strains based

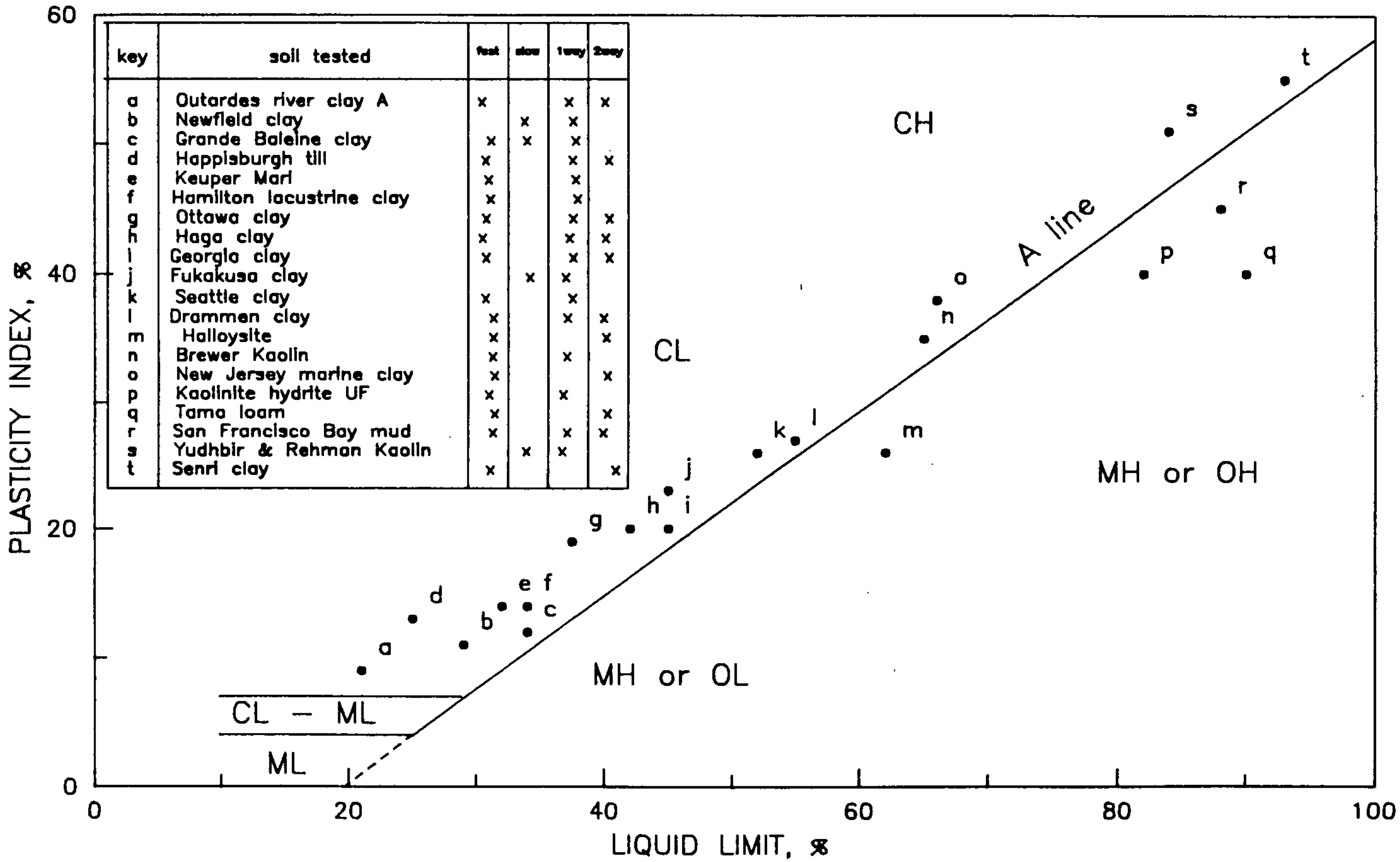


Fig 2.3 Classification on the standard plasticity chart of the cohesive soils tested by previous investigators in undrained cyclic loading.

Table 2.1 - Clays Tested in Slow Undrained Cyclic Loading by Previous Investigators

Material Tested	Reference Authors	LL (%)	PL (%)	%<2μ (%)	Sample Condition	Mode of Loading	Strain Rate (%/hr)	Number of Cycles
Newfield clay	Sangrey, Henkel & Esrig	27-31	17-19	32	Undisturbed	one-way	1.3 & 0.5	12
Grande Baleine clay Sensitivity=300	Lefebvre, Leboeuf & Demers	34	22	59	Undisturbed	one-way	1.0	220
Fukakusa clay	Akai,Ohnishi Yamanaka, Nakagawa	45	22	24	Remoulded	one-way	7.2 & 3.6	30
Kaolin	Yedhbir & Rehman	84	33	84	Remoulded	one-way	1.0	50

on measured boundary displacements were compared to axial strains measured along various gage lengths across the midheight of remolded triaxial clay specimens. The two types of strain measurement resulted in a different clay stress-strain response. Average axial strains were generally smaller than the central gage length axial strains. The difference became more pronounced as axial deformations increased. Thus slow rates of strain do not entirely eliminate the end restraint effects on the clay response. The end restraint effect can only be aggravated by faster rates of loading. It is generally believed that slow rates of loading would minimize the nonuniformity of axial strains. In this literature survey, all axial strains are expressed in terms of overall axial deformations along the specimen bearing in mind that some degree of strain nonuniformity will exist due to end restraint.

2.2.1 Cyclic loading with constant stress amplitude

During one-way cyclic loading of normally consolidated clays under a constant cyclic stress level, strain development with number of cycles is associated with the generation of positive pore water pressure. This behaviour is shown in figure 2.4 for normally consolidated Newfield clay (96, 98). Pore water pressure development per cycle is maximum in the first loading cycle and decreases gradually with subsequent cycles. The pattern of strain development with number of cycles depends on the cyclic stress level. Above a given cyclic stress level, called the critical level of repeated loading (70, 96, 98), both peak and residual strains increase with cycles of loading. The critical level of repeated loading (CLRL) was 0.67 for normally consolidated Newfield clay.

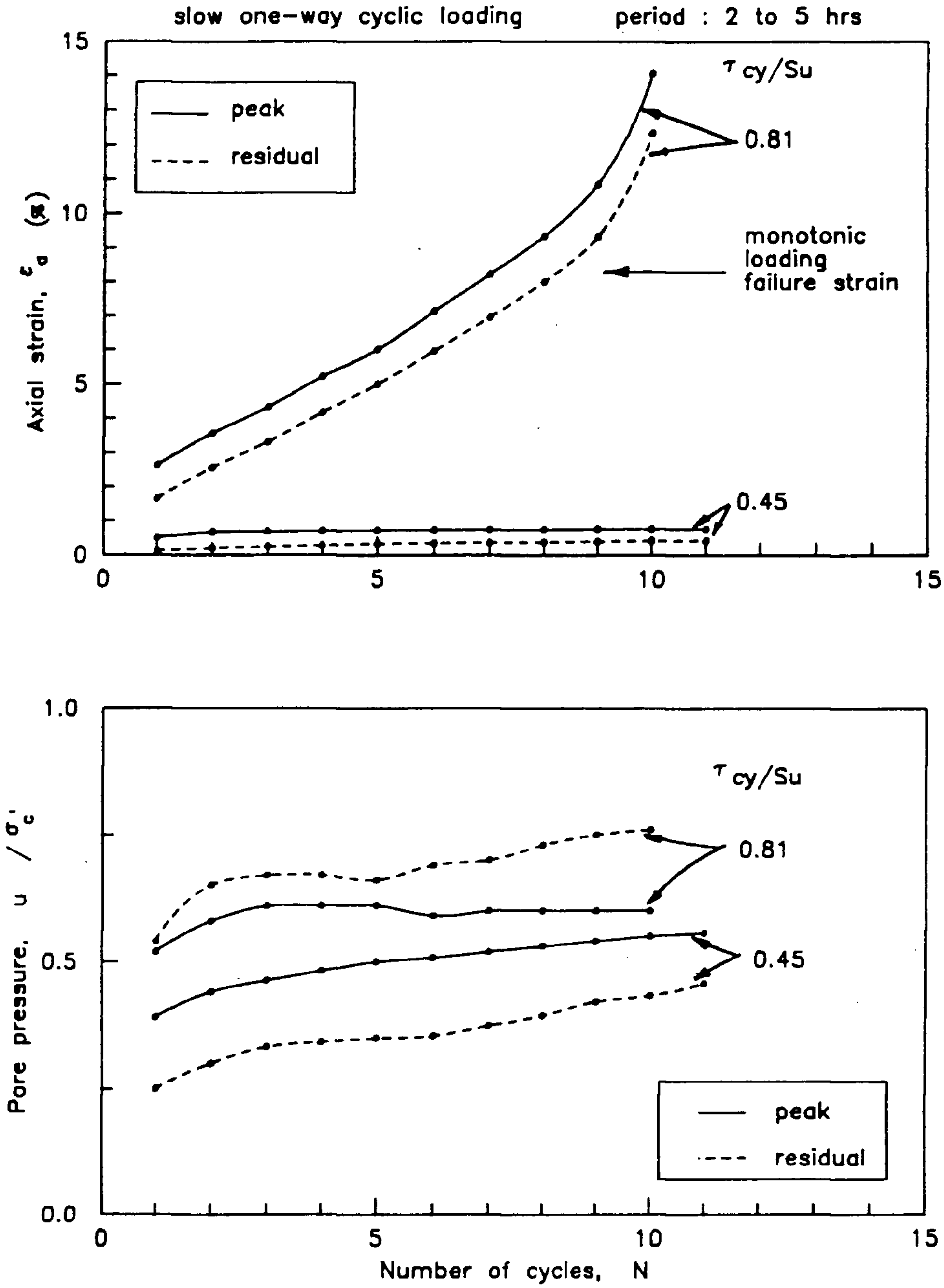


Fig 2.4 Development of axial strain and pore pressure with number of cycles during one-way undrained cyclic loading of normally consolidated Newfield clay (data from Sangrey, 1968).

When the accumulated peak strain during cyclic loading becomes equal to or larger than the monotonic loading failure strain (at peak deviatoric stress) the clay specimen is considered to have failed. The number of cycles required to reach failure decreases with increasing cyclic stress level. Below the CLRL, strain development with number of cycles tends toward a nonfailure equilibrium condition. Correspondingly, both peak and residual pore pressures tend toward an equilibrium plateau. However, figure 2.4 shows that neither peak nor residual pore pressures reach a true equilibrium value with loading cycles. Nonetheless, the peak pore water pressure when the strain approaches nonfailure equilibrium was found to increase linearly with cyclic stress level. This linear relationship is referred to as equilibrium line and forms an inclined straight line on the effective stress path space as shown in figure 2.5.

For cyclic stress levels higher than the CLRL, the effective stress path was bounded by the slow monotonic loading failure envelope defined at maximum principal effective stress ratio. The intersection of the cyclic effective stress path with the monotonic loading failure envelope corresponds with the occurrence of failure based on strain development with number of cycles. Therefore failure under undrained cyclic loading is also regarded as the intersection of the cyclic effective stress path with the monotonic loading failure envelope. The 'upward hook' in the effective stress path followed by normally consolidated Newfield clay when approaching the failure envelope is rather typical of the behaviour of sand (123). This similarity is due to the high silt content of Newfield clay (plasticity index less than 10 percent). In contrast, both remolded Kaolin clay with a plasticity index equal 50 percent (127) and undisturbed Grande Baleine clay with a plasticity index

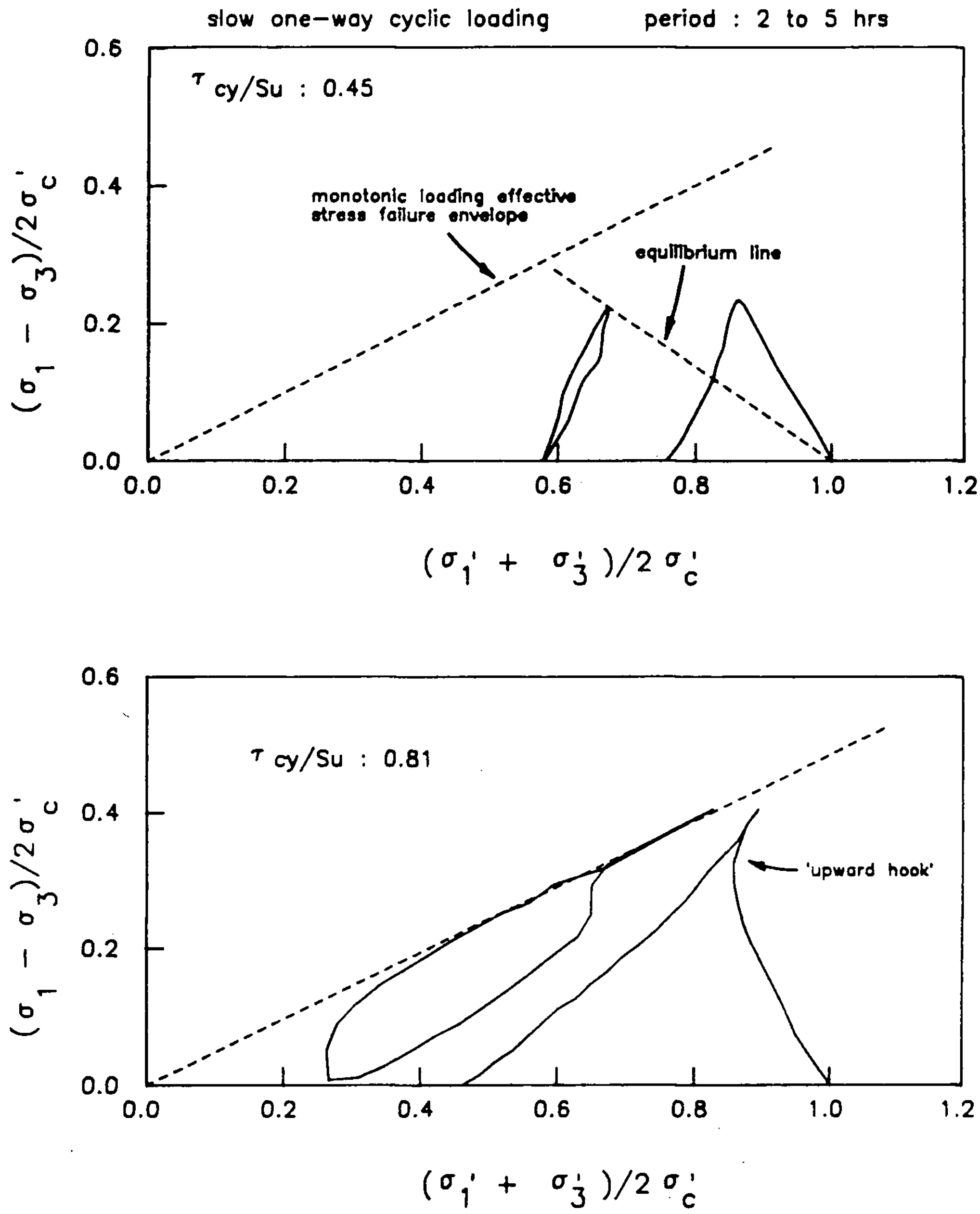


Fig 2.5 Effective stress path followed by normally consolidated Newfield clay during slow one-way undrained cyclic loading. (data from Sangrey, 1968)

equal 12 percent and a sensitivity higher than 300 (74, 75) exhibit the elliptic effective stress path typical of soft clays under undrained monotonic loading. Therefore cyclic behaviour of Newfield clay may not be typical of all clays. Nonetheless, both remolded Kaolin clay and Grande Baleine clay conformed with Newfield clay in terms of the existence of a CLRL below which nonfailure equilibrium conditions would prevail. However, a higher value of CLRL was noted for remolded Kaolin (0.92) and a slightly lower value was found for Grande baleine clay (0.62). The CLRL appears then to increase with higher plasticity index but remains virtually unaffected by an increase in clay sensitivity.

Since a constant rate of strain is used in slow cyclic tests, the loading period increases with each cycle as larger strains develop. Therefore the loading cycles are not strictly equivalent. For Newfield clay the period of loading typically increased from 2 to 5 hours. It is believed that such a variation in the cyclic loading period would not affect the clay response. The time-dependent response of clays during undrained loading is generally affected by variations in the rate of strain. Since the rate of strain is maintained constant during slow cyclic loading, the clay response should be independent of the loading period.

The observations based on slow cyclic loading tests are limited to the maximum number of cycles applied in the experiments (see table 2.1). They cannot be extrapolated to a larger number of cycles. In particular, the observation of an apparent nonfailure equilibrium condition in the laboratory may not necessarily hold for a significantly larger number of cycles such as encountered under wave loading conditions.

2.2.2 Cyclic loading with constant stress ratio amplitude

In addition to cyclic loading with a constant cyclic stress amplitude, some clays have been subjected to slow cyclic loading with a cyclic stress amplitude gradually decreasing with each cycle (1, 96). The decrease in cyclic stress level was such that the principal effective stress ratio σ_1'/σ_3' at the peak point was maintained constant. Undrained one-way cyclic loading with a constant amplitude of the principal effective stress ratio resulted in limited strain and pore water pressure development with number of cycles for both Newfield clay (96) and Fukakusa clay (1). The accumulated strain and pore water pressure, both at peak and residual points, reached an equilibrium plateau in the first few loading cycles. The equilibrium in strain and pore water pressure development may simply result from the decrease of the cyclic stress level toward the critical level of repeated loading. Such a response also supports the existence of a privileged relationship between principal effective stress ratio and strains at the peak point of each cycle. Results of constant strain amplitude undrained one-way cyclic loading on Fukakusa clay tend to confirm this privileged relationship (1). In this type of tests, the pore water pressure development with number of cycles, both at peak and residual points, also reached an equilibrium plateau after few loading cycles and the principal effective stress ratio varied within a fixed amplitude. Further support of the particular relationship between principal effective stress ratio and peak strains is found in the contours of equal peak strains for Newfield clay (96) under constant cyclic stress amplitudes. The strain contours formed a fan of inclined straight lines converging toward the origin of the effective stress path space; thereby, corresponding to constant principal effective stress ratios.

From the foregoing very limited data, the following observations can be made regarding slow undrained cyclic loading behaviour of normally consolidated clays:

1. No information exists on the behaviour of clays under slow strain controlled two-way cyclic loading.

For slow one-way cyclic compression loading of clays:

2. A given cyclic stress level, called the critical level of repeated loading (CLRL), exists below which strain and pore water pressure with cycles of loading appear to diminish progressively and above which strain accumulates with cycles of loading until an accelerating rate per cycle develops.
3. The onset of accelerated rate of strain development per cycle corresponds with the intersection of the cyclic effective stress path with themonotonic loading failure envelope.
4. For cyclic stress levels below the CLRL, the equilibrium pore water pressure at peak cyclic stress increases linearly with cyclic stress amplitude (equilibrium lines).
5. Both the CLRL and the slope of the equilibrium lines depend primarily on the clay plasticity index.
6. Strain development with number of cycles appears to be directly related to the change in principal effective stress ratio.

2.3 Fast undrained cyclic loading

A large amount of research has been carried out on the response of clays to fast undrained cyclic loading as indicated on table 2.2. The label "fast cyclic loading" refers to stress controlled undrained triaxial tests where the measurement of pore water pressure is considered unreliable. This category includes stress controlled undrained cyclic loading tests on clays with periods ranging from 1 second to 30 minutes. During stress controlled cyclic loading the strain rate varies within a loading cycle. Such a variation in strain rate becomes significant when large strains are developed in a cycle. This leads to consider the clay response as unreliable.

For most clays behaviour under both one-way and two-way cyclic loading modes has been studied. For clarity the two modes of cyclic loading will be considered separately in this literature survey.

2.3.1 Fast one-way cyclic loading

Under fast one-way cyclic compression loading all normally consolidated clays reported by previous investigators show some similarity in strain response pattern with normally consolidated clays under slow one-way cyclic loading. The pattern of strain development with number of cycles depends on the cyclic stress level as shown in figure 2.6 for normally consolidated Drammen clay (4). Either mean strains increase gradually to reach a value higher than the failure strain in monotonic loading, and failure is deemed to have occurred by cyclic loading; or mean strain development tends toward a nonfailure equilibrium plateau. For cyclic

Table 2.2 - Clays Tested in Fast Undrained Cyclic Loading by Previous Investigators

Material Tested	Reference Authors	LL (%)	PL (%)	%<2μ (%)	Sample Condition	Mode of Loading	Loading Period	Number of Cycles
Happisburgh till	Takahashi, Hight & Vaughan	25	12	15	Remoulded	one-way two-way	30 min	50
Keuper Marl	Brown, Lashine, Hyde, Conn, Ward	32	18	18	Remoulded	one-way	0.1, 0.2 s	10^4
Hamilton clay	Wilson, Greenwood	34	20	8	Undisturbed	one-way	2 min	1000
Outardes river clay Sensitivity=380 Sensitivity= 35	Lee	20-23 32-36	11-15 17-19	12-24 12-24	Undisturbed	one-way two-way	1 s	300
Grande Baleine clay Sensitivity=300	Lefebvre & Leboeuf	34	22	59	Undisturbed	one-way	0.5, 2, 15 & 100 s	220
Ottawa clay Sensitivity=15 to 25	Mitchell & King	34-41	18-20		Undisturbed	one-way	10 & 20 s	500
Drammen clay	Andersen, et al.	55	28	50	Undisturbed	one-way two-way	10 & 20 s	5000
Haga clay	Lacasse	40-45	25-30	40-60	Undisturbed	one-way two-way	1 to 15 s	1000
Seattle clay	Sherif & Wu	52	26	30	Remoulded	one-way	0.5 & 1 s	7200
Georgia Kaolin	Sheu	45	25	62	Remoulded	one-way two-way	16 min	1000
N.J marine clay	Koutsoftas	66	28		Undisturbed	two-way	1 & 5 s	5000
Kaolin	Brewer	65	30	92	Remoulded	one-way	2.5, 100 s	1000
Kaolinite hydrate UF	Motherwell & Wright	82	42	100	Remoulded	one-way	10 & 20 s	500
Senri clay	Matsui, et al.	93	38	43	Remoulded	two-way	2 to 50 s	50000
S.F. Bay mud	Seed & Chan	88	43		Undisturbed	one-way two-way	1 to 20 s	1000
Tama loam	Ishihara, Yasuda	90	50	30	Undisturbed	one-way	1 s	30
Halloysite	Taylor & Bacchus	62	36		Remoulded	two-way	5 s	100
Cloverdale clay	Jitno & Vaid	52	26	49	Undisturbed	two-way	10 s	400

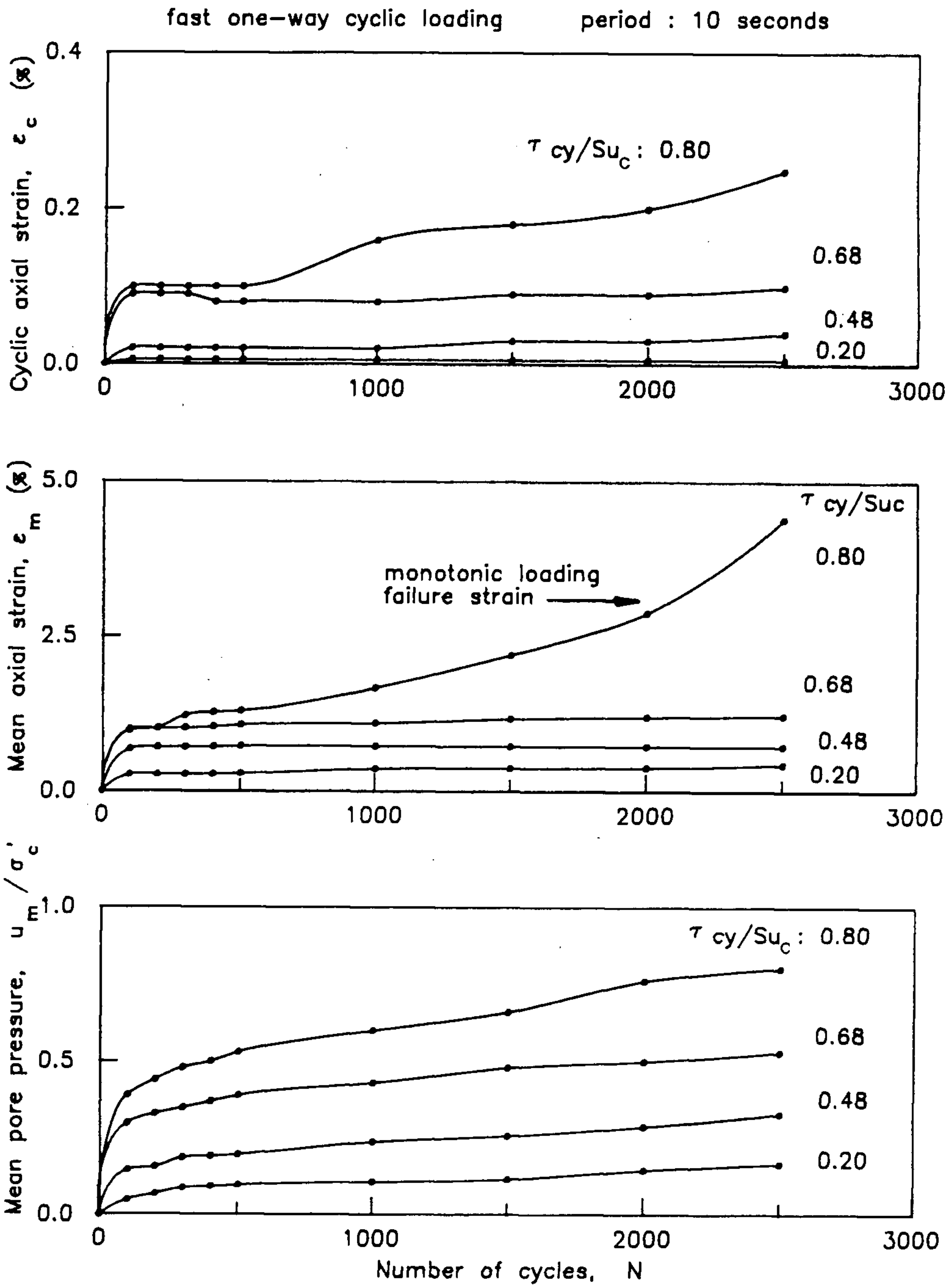


Fig 2.6 Development of axial strain and pore pressure with number of cycles during fast one-way undrained cyclic loading of normally consolidated Drammen clay (data from Andersen et al, 1980).

stress levels leading to failure, the rate of mean strain development per cycle increases gradually and the mean pore water pressure tends toward a limiting value. However, for cyclic stress levels not leading to failure the mean pore water pressure development with number of cycles does not reach a true equilibrium plateau even for a cyclic stress level as low as 0.20 . The mean pore water pressure continues to increase at a small rate per cycle. It is significant that several loading cycles are required for the mean pore water pressure to reach a constant rate of development per cycle. This is an indication that under fast cyclic loading the pore water pressure does not fully equalize in the specimen particularly in the initial loading cycles. It has been suggested that during fast cyclic loading tests to a large number of cycles the cyclic pore water pressure may not have sufficient time to equalize within the specimen but the residual pore water pressure would not suffer from such limitation because of the long test duration (3). For Drammen clay, a frequency of cyclic loading equal to 0.1 Hz has commonly been used and the total test duration is approximately 7 hours. The residual pore water pressure should be reliable for such long test duration. However, the residual pore water pressure has generally been observed to continue to increase upon arrest of fast cyclic loading on normally consolidated clays such as San Fancisco bay mud and Cloverdale clay (103, 57). Consequently, under fast cyclic loading, the concept of a critical level of repeated loading below which the amount of strain and pore water pressure developed during cyclic loading is limited is questionable because the residual pore water pressure does not reach an equilibrium plateau.

For remolded Keuper Marl, a silty clay with plasticity index equal to 14 percent (49, 50) the peak points of the effective stress path during fast one-way cyclic loading have been observed to migrate beyond the slow monotonic loading failure envelope. This behaviour may be explained by the apparent overconsolidation of the clay due to undrained cyclic loading (50). However the migration of the effective stress path beyond the monotonic loading failure envelope is in contradiction with the results of slow one-way cyclic tests (96, 127). Therefore some doubt remains on the reliablility of the effective stress state of the clay both at the residual and peak points during fast cyclic loading.

2.3.2 Fast two-way cyclic loading

Most undrained cyclic loading tests with stress reversal consisted of symmetrical loading pulses starting with the compression pulse. Symmetrical two-way cyclic compression-extension loading is known to impose a more severe loading condition on clays than one-way cyclic compression loading (71, 72, 103, 113). Figure 2.7 shows a comparison between the effect of one-way and two-way cyclic loading to a constant cyclic stress level on the strain response of normally consolidated Happisburgh till (39, 110). For comparison, one cycle of one-way cyclic compression loading is counted as half a cycle in two-way cyclic compression-extension loading. Two-way cyclic loading is characterized by larger cyclic strain amplitudes than one-way cyclic loading. Moreover, both mean and residual strain development indicate an extension of the specimen with number of cycles. While the difference between mean and residual strain values is small under one-way cyclic loading, it is considerable under two-way cyclic loading. The

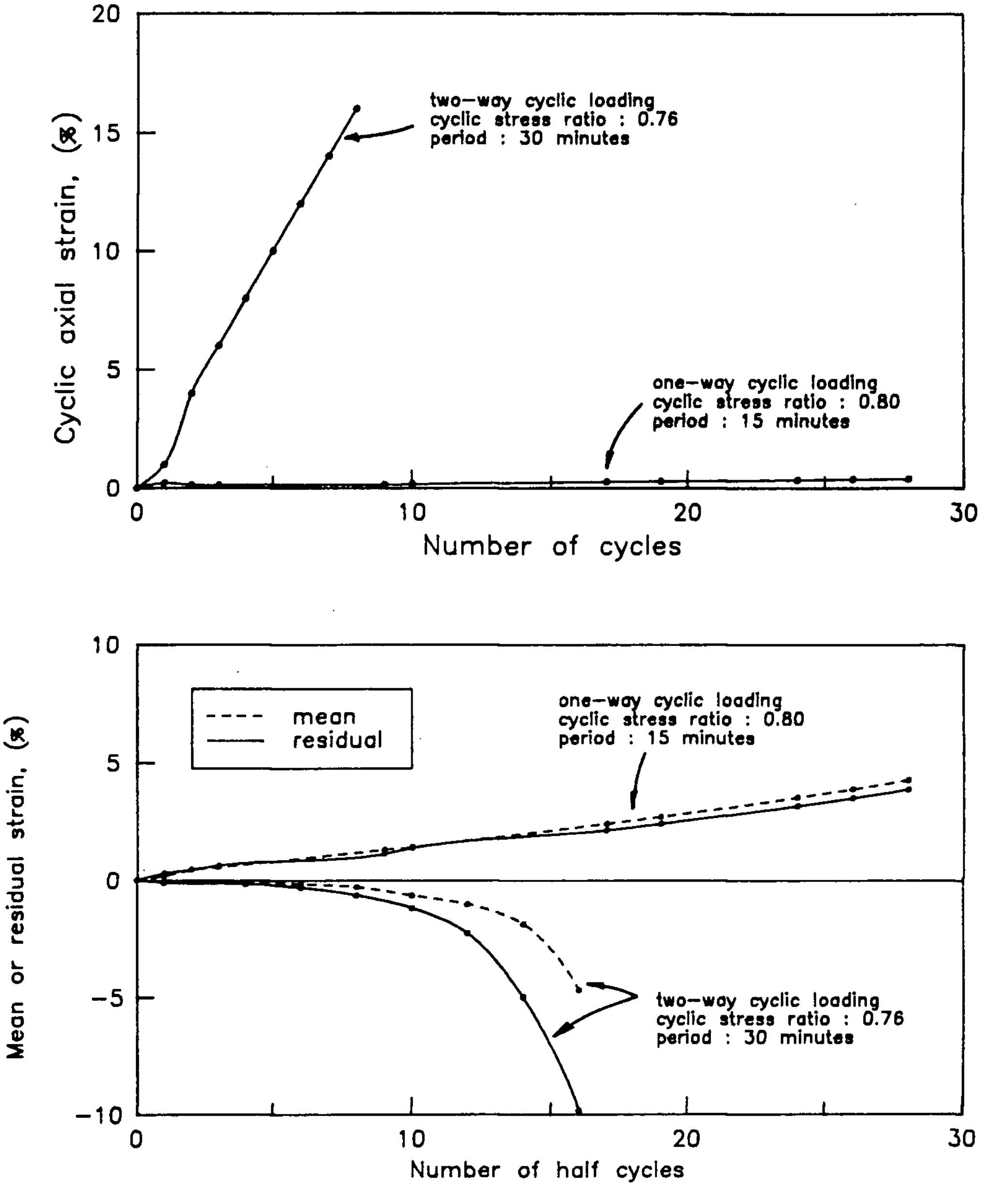


Fig 2.7 Comparison between one-way and two-way undrained cyclic loading of normally consolidated Happisburgh till (data from Takahashi, 1981).

residual strain is generally larger than the mean strain under two-way cyclic loading and the difference between the two strain values accentuates with furtherloading cycles. The larger cyclic strain amplitude in two-way cyclic loading implies larger changes in cyclic pore water pressure. Consequently, a more pronounced nonuniform pore water pressure distribution will be present within the specimen under two-way cyclic loading than under one-way cyclic loading.

The effective stress path followed by normally consolidated Happisburgh till exhibits clear signs of large pore water pressure gradients within the specimen during stress controlled cyclic loading (110, 111). Figure 2.8 shows that with faster rates of loading the migration of the effective stress path beyond the reference effective stress failure envelope becomes more pronounced particularly on the extension phase. A similar observation is shown in figure 2.9 for a reconstituted Japanese commercial clay tested under fast cyclic loading with a constant total mean normal stress (81). In fact, the effective stress path for Happisburgh till travels even beyond the 45 degree line, thereby indicating a negative effective stress condition within the specimen. It is not clear why the migration of the cyclic effective stress path beyond the monotonic loading failure envelope is more marked on the extension phase than on the compression phase. For both Happisburgh till and the Japanese commercial clay the pore water pressure was measured with a fast response miniature piezotransducer placed at midheight of the specimen. Consequently the effective stress response obtained shows a complex interaction between rate of loading, location of pore water pressure measuring device and material behaviour. Therefore, local measurement of the pore water pressure does not alleviate the difficulty of

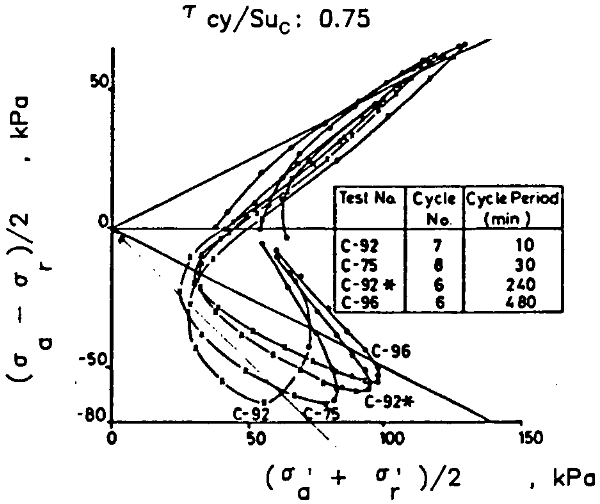


Fig 2.8 Effective stress path followed by normally consolidated Happisburgh till during two-way undrained cyclic loading at various frequencies (data from Takahashi, 1981).

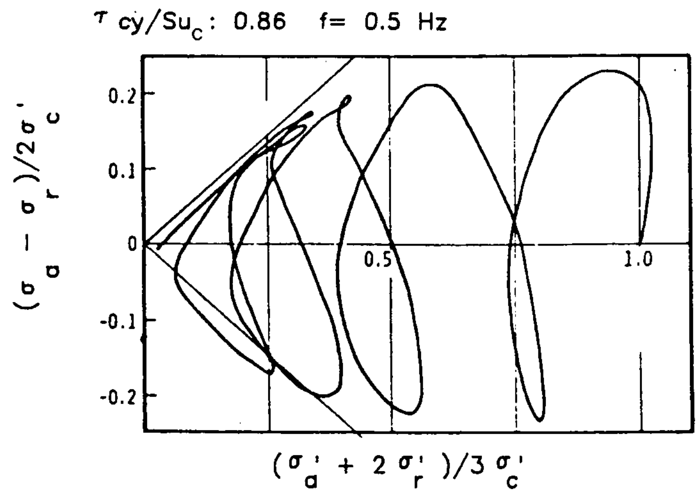


Fig 2.9 Effective stress path followed by a normally consolidated commercial clay during fast two-way undrained cyclic loading with constant total mean normal stress (data from Matsui and Abe, 1981).

interpretation caused by pore water pressure gradients within the specimen due to fast cyclic loading. These observations point to questionable effective stress interpretation of fast undrained cyclic loading tests particularly under two-way cyclic loading.

Despite the unreliable pore water pressure measured in fast undrained cyclic loading tests, a broad relationship was proposed to relate the increase in cyclic strain amplitude to the increase in principal effective stress ratio at the peak of each loading cycle for Drammen clay as shown in figure 2.10 (4, 8, 9). Although such relationship may be justified by previous findings based on slow one-way cyclic loading tests, it suffers from the enormous scatter in the data on Drammen clay mostly caused by the unreliable pore water pressure pointed out previously. In particular, it is not clear whether such a relationship is independent of cyclic stress level.

The development of cyclic strain has also been related to the damping ratio determined from the area of the stress-strain hysteresis loops followed by the clay. For normally consolidated Drammen clay it was found that the damping ratio either remained constant or decreased with increasing cyclic strain amplitudes (4). This finding is contradictory to the correlation common to various clays showing that the damping ratio generally increases with cyclic strain amplitudes (102, 109).

Hysteretic work accumulated during undrained cyclic loading has been related to residual pore water pressure by various researchers for both sand and clay soils (115, 32, 57). The proposed correlation between hysteretic work and residual pore water pressure has been suggested to be independent of cyclic

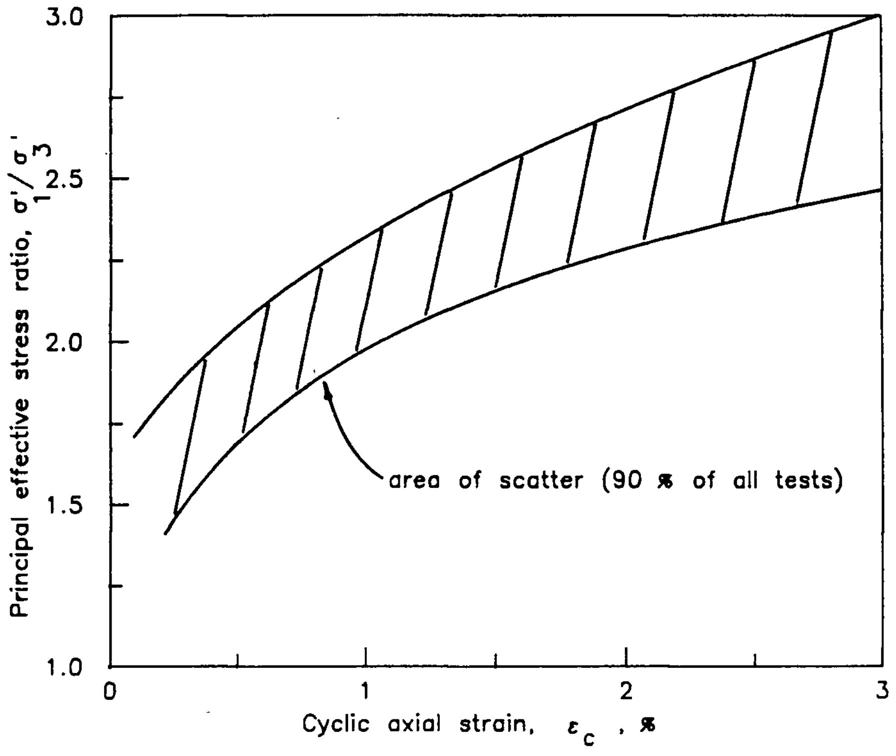


Fig 2.10 Correlation between cyclic axial strain and principal effective stress ratio. Summary of all undrained cyclic triaxial tests on Drammen clay (data from Andersen et al, 1975).

stress level. For sand (115) the observations in support of a unique relationship between hysteretic work and residual pore water pressure were based on a series of tests with a narrow range of cyclic stress levels. The effect of cyclic stress level on the correlation between hysteretic work and residual pore water pressure could not be detected. For clays (32, 57) the observations are again based on fast cyclic loading tests with unreliable pore water pressure measurements. Therefore the uniqueness of the relationship between hysteretic work and residual pore water pressure is uncertain.

With due recognition of the foregoing limitations of the large amount of data from fast cyclic loading tests, the following observations can be made :

For one-way cyclic loading:

1. The pattern of development of strain with number of cycles is similar to the pattern followed during slow one-way cyclic loading.
2. The pattern of development of pore water pressure with number of cycles is different from the pattern followed during slow one-way cyclic loading.
3. A critical level of repeated loading cannot be conclusively established because of the uncertain pore water pressure observations.

For two-way cyclic loading:

4. The cyclic strain and pore water pressure amplitudes are considerably larger than under one-way cyclic loading.
5. The relationship between cyclic strain amplitude and principal effective stress ratio requires clarification.
6. The possible effect of cyclic stress level on the correlation between hysteretic work and residual pore water pressure needs further examination.

2.4 Postcyclic loading response

The response of clays to postcyclic undrained monotonic loading is reported in terms of changes in undrained strength and stiffness with respect to clay response to monotonic compression loading before cyclic loading. All clays tested by previous investigators showed some decrease in undrained strength and a considerable degradation in deformation modulus. The decrease in undrained strength ranges from zero to 50 percent. The amount of change in undrained strength and stiffness depends on the soil type and the cyclic loading parameters (4, 39, 57, 58, 82, 97, 108, 114). The change in undrained strength and stress-strain characteristics of the clay due to cyclic loading cannot be correlated to a single measurable parameter such as cyclic strain amplitude or residual pore water pressure. Cyclic loading conditions (one-way or two-way loading), cyclic stress level, number of cycles and direction of loading would influence the postcyclic response of the clay. It is beyond the scope of this study to assess the effects of the various factors outlined. However, the role played by the change in effective stress due to cyclic loading in the response of clay to postcyclic loading will be highlighted.

In view of the above mentioned very limited amount of reliable data, this thesis will attempt to fill the gap in our knowledge of undrained clay behaviour when subjected to cyclic reversal in stress and strain. Slow cyclic loading rates will be applied to ensure a reliable pore water pressure measurement. A correct effective stress interpretation of the response of clay to undrained cyclic loading will then be possible.

EXPERIMENTATION

In this chapter, a description of the loading system and the measuring instruments used in this study is presented. The material tested is described together with its basic properties. The testing programme is then outlined followed by the test procedures. Both stress and strain controlled loading modes in the conventional triaxial apparatus are used and the conditions for the application of each loading mode are discussed.

3.1 Loading system

For cyclic loading tests, stress controlled loading is commonly used in the conventional triaxial apparatus. However, a combination loading system that enables switching from stress to strain controlled loading or vice-versa part way into the test is desirable (117). A schematic diagram of the combination hydraulic-pneumatic loading system used in this study is shown in figure 3.1.

The axial load is applied to the clay specimen by means of a rolling diaphragm (Bellofram) double acting, water saturated piston. When the piston is not transmitting any load, it is kept pressurized with a base pressure in both chambers controlled by regulators R3 and R4. Each side of the piston is connected to the hydraulic strain control as well as the pneumatic stress control.

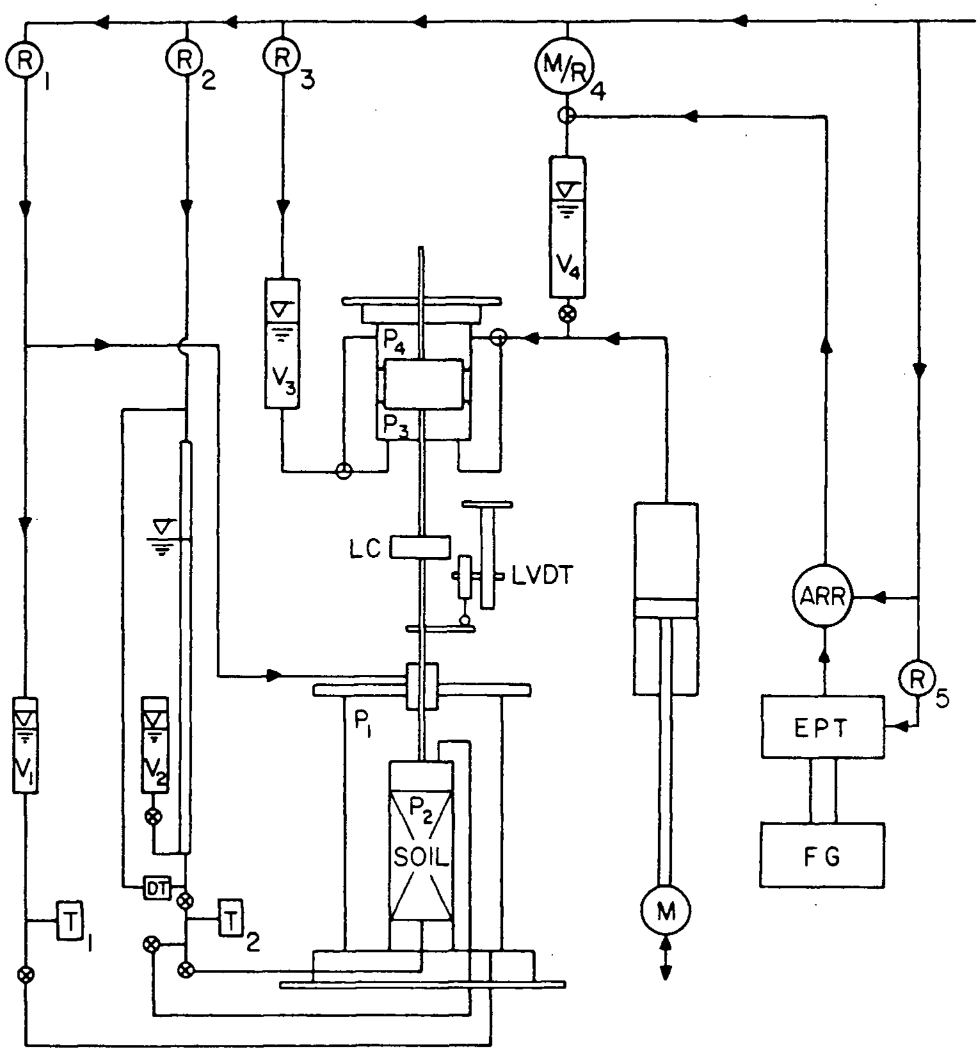


Fig 3.1 Layout of the stress and strain controlled loading system used in this study.

The strain control unit consists of a saturated displacement plunger activated by a strain drive M. The plunger feeds water at a constant rate to the loading piston resulting in a constant rate of axial strain loading. For constant strain rate axial compression loading, water is fed into the upper chamber of the loading piston while the lower chamber drains freely to a constant pressure (controlled by regulator R3) in the reservoir V3. The operations on the two chambers are reversed to apply extension loading. Axial stress control is achieved by delivering a desired air pressure to the loading piston through reservoir V4. Pressure can be admitted either to the top or bottom chambers of the piston while the other side drains freely to a constant pressure in reservoir V3. Stress controlled loading may be applied by using the motorized regulator M/R4. The direction of movement of the motorized regulator may be selected to switch from compression to extension and vice-versa during loading.

The cyclic loading subunit of the stress control consists of an electropneumatic transducer (EPT) driven by a function generator (FG). The electropneumatic transducer converts the input voltage signal into a proportional pressure output. This enables choice of cyclic loading pulse shape, amplitude and frequency by appropriate selection of electrical signal on the function generator. The adjustable ratio relay amplifies the output of the electropneumatic transducer for feeding into the loading piston. The cyclic pressure is fed into the upper chamber of the piston if the initial direction of loading is in compression. If the initial direction of loading is in extension then the cyclic pressure is fed into the lower chamber of the piston.

The cyclic loading subunit of the strain control is activated by electronic input/output modules connected to the data acquisition system. A software program is used to turn the motor drive on or off and reverse the direction of displacement at will.

For completeness, the electronic sensors used for measurement are also illustrated in figure 3.1. These include cell and pore water pressure transducers T1 and T2, axial force transducer LC, axial displacement transducer LVDT and differential pressure transducer DT for volume change measurements.

3.2. Test measurements

The measurement of the axial load during cyclic loading must be reliable. Since an external load cell is used in this study, minimizing ram friction is imperative. Ram friction was reduced to a negligible amount by the use of a continuously air leaking seal (34, 57, 128). A schematic drawing of the frictionless seal is shown on figure 3.2. The loading ram is guided by two precision stainless steel bushings located at both ends of the seal casing. A fixed stainless steel ring that has no contact with the loading ram is located at midheight in the internal wall of the seal unit. The air pressure applied in the seal casing is supplied by the same regulator that controls the triaxial cell water pressure. This ensures the seal for the confinement chamber and provides a continuous air leak upwards around the loading ram with a negligible friction from the bushings.

The measurement of axial deformation during undrained cyclic loading must also be reliable. Hence, the measurement technique must be simple and

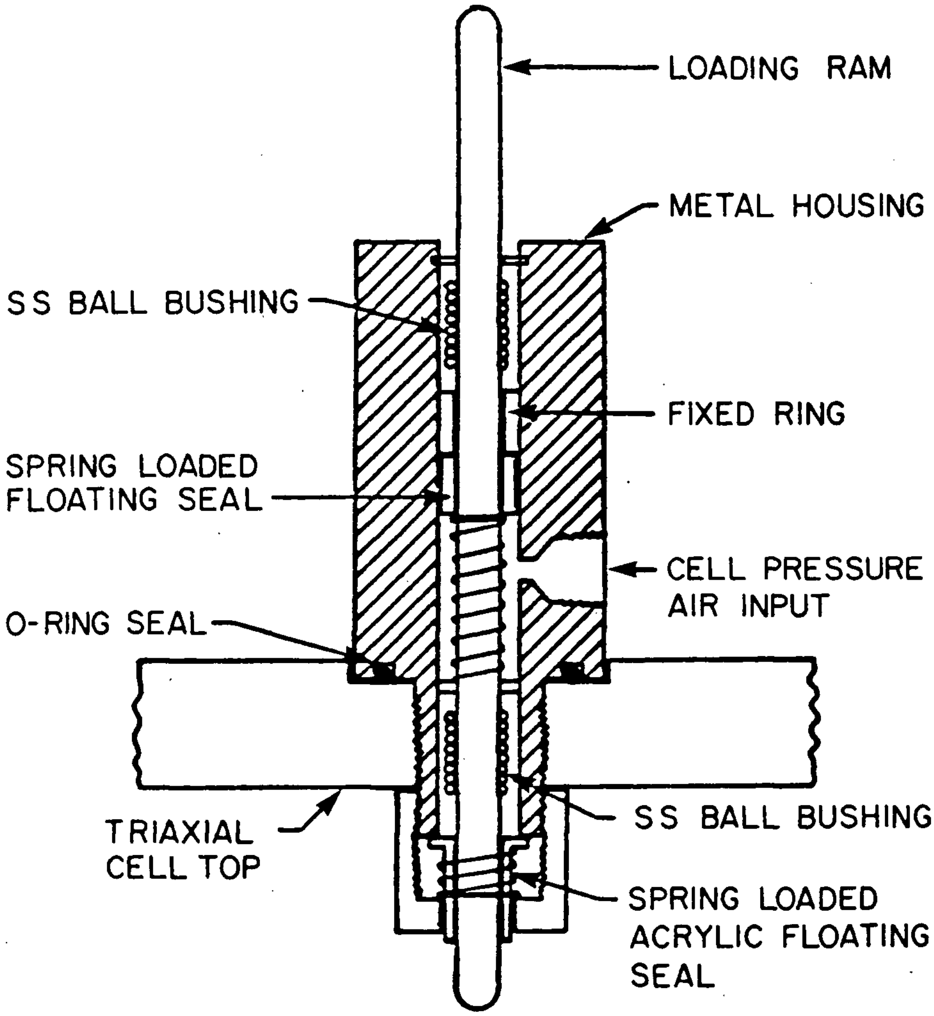


Fig 3.2 Hydrostatic seal system for the low friction triaxial cell used in this study.

repeatable. In this study, the axial strain was determined based on the overall vertical deformation of the specimen measured at the boundary.

For simplicity, the pore water pressure was also measured at the end of the specimen. Hence the use of a slow rate of loading is imperative to achieve confidence in the measured pore water pressure. All tests were performed on clay in fully saturated conditions and the length of specimen drainage lines was minimized to reduce the time lag in the pore water pressure measurement. Diffusion loops (3 millimetre outside diameter, 1 meter long thick wall nylon tubing) separated the pressure transducers from air-water interfaces to maintain pore water pressure measuring system and cell water free from any air diffusion. A careful selection of a pore pressure sensor with minimal compliance was made. The pressure sensors used in this study required a very small volume change to be activated. A full scale pressure of 700 kPa produces a volume change at the diaphragm less than 0.0033 cubic millimetres.

All tests were performed in a controlled temperature environment with maximum fluctuations of less than 0.5 degree celsius. Therefore, all test measurements were essentially independent of temperature effects.

Automatic data logging was carried out using a Hewlett Packard 3497A data acquisition system controlled by an IBM personal computer. In addition to digital recording, a linear analog chart recorder was placed in parallel to follow the test progress chronologically.

Because of the long duration of slow cyclic tests on clays the stability of the electronic transducers must be assessed. Figure 3.3 shows the fluctuations and drift of the force, pressure and displacement electronic measuring instruments

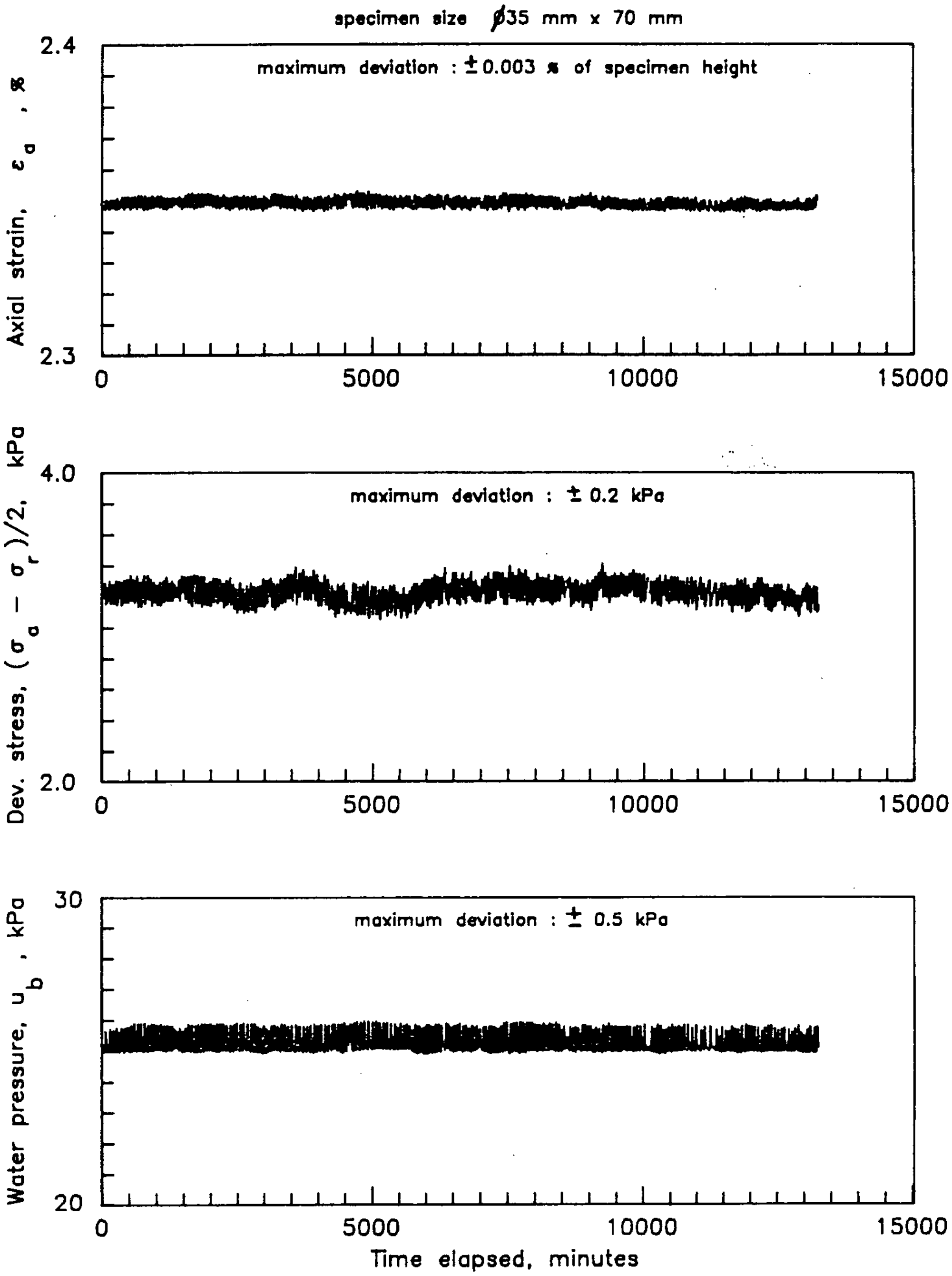


Fig 3.3 Long term stability of test measurements under a constant load on triaxial aluminum specimen.

assembled to sense an aluminum specimen under typical test conditions. For a test duration of approximately 10 to 15 days, both the fluctuations and the drift in the electronic sensors may be seen to be negligible for the size of specimen used and the level of accuracy required.

3.3 Material tested

The material tested is a soft, grey, undisturbed clay called Cloverdale clay. Homogenuous block samples of the clay were obtained from a depth of 2.0 to 2.6 meters below ground level along highway one, within the district of Cloverdale, 30 km east of Vancouver, British Columbia. The block samples were wrapped with a thick coat of wax and stored in a controlled humidity room until needed for testing. The geological history and deposition process of Cloverdale clay are related to the withdrawal of the Vashon ice from the Fraser Lowland in British Columbia between 13000 and 11000 years ago (14). Cloverdale clay appears to have been deposited in a marine environment following the ice retreat.

The physical properties of Cloverdale clay are outlined on table 3.1. The similarity in physical properties between Cloverdale clay and Drammen clay (4, 27) will make direct comparisons between the behaviour of the two clays very convenient. The mineralogical composition of Cloverdale clay was determined by qualitative X-ray diffraction. Kaolinite and montmorillonite are the clay minerals present. Quartz and feldspar are present as relict minerals. The relative quantity of each mineral constituent was not determined accurately.

The undrained strength of Cloverdale clay in its natural state was measured by pocket torvane and laboratory vane shear apparatus. The sensitivity

Table 3.1

Physical properties of Cloverdale clay

Natural water content	51 % ± 3 %
Liquid limit	51 % ± 3 %
Plastic limit	24 % ± 3 %
Plasticity Index	27 % ± 3 %
Liquidity Index	1.0
Degree of saturation	100 %
Specific gravity at 20° C	2.79
Clay fraction (d < 0.002 mm)	49 %
Silt fraction (0.002 mm < d < 0.06 mm)	45 %
Activity	0.55
Sensitivity (Lab. vane)	16
Past maximum consolidation pressure	95 kPa
Undrained strength (Lab. vane)	15 kPa
Salt content of pore fluid	5 g/l

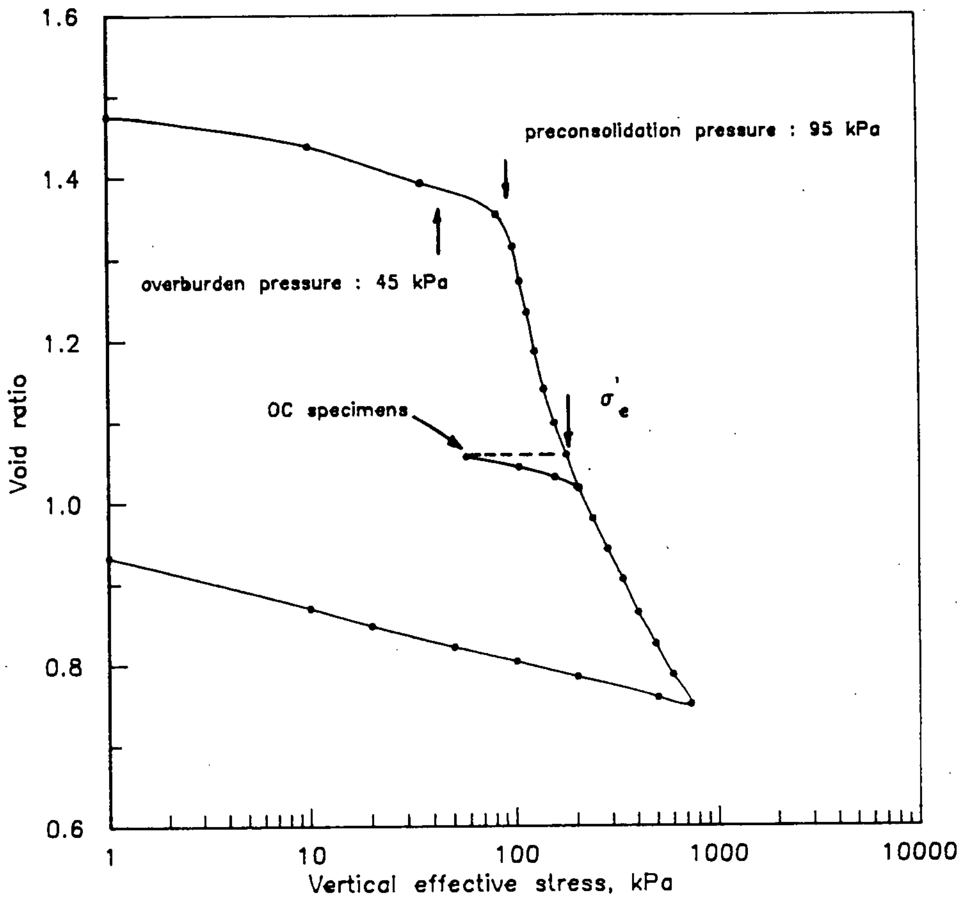


Fig. 3.4 Relationship between void ratio and vertical effective stress during strain controlled one-dimensional consolidation of Cloverdale clay.

of the clay was also determined by the laboratory vane shear test on the natural clay previously remolded by several gyrations of the vane blades. Cloverdale clay is of very soft consistency and of medium sensitivity.

The consolidation characteristics of undisturbed Cloverdale clay were determined by a strain controlled oedometer test using a constant strain rate equal to 1.7 percent per hour. The test results in figure 3.4 show that the block samples were obtained from a horizon of lightly overconsolidated clay (OCR = 2). A marked compressibility will be expected for consolidation stresses larger than the past maximum pressure estimated at 95 kPa.

3.4 Testing programme

Test series I

A series of monotonic loading tests were perfomed on normally consolidated and overconsolidated specimens of Cloverdale clay to establish a reference base for the clay response to undrained cyclic loading. Both compression and extension loading modes were considered. Extension loading was used to obtain information on the effect of direction of loading on stress-strain response. For comparison, overconsolidation ratios ranging from 1.3 to 4.0 were selected to cover the range of overconsolidation ratios expected to result from undrained cyclic loading of normally consolidated clay.

Test series II

This series of tests consisted of slow two-way cyclic loading under constant cyclic stress amplitude on normally consolidated clay. These tests included symmetrical cyclic compression-extension and cyclic extension-compression loading.

The purpose of this test series was to study:

. the effect of a systematic variation in the cyclic stress amplitude on stress -strain response in terms of effective stresses; and,

. the effect of a change in the initial direction of loading on stress-strain response.

Test series III

This series of tests consisted of slow two-way cyclic loading under a constant principal effective stress ratio amplitude on normally consolidated clay. The purpose of this test series was to study:

. the effect of a systematic variation in principal effective stress ratio amplitude on the clay response; and,

. the relationship between principal effective stress ratio and cyclic strains.

Some tests in series II and III included a step increase in deviatoric stress amplitude or effective stress ratio amplitude to determine the clay response to a controlled change in cyclic stress level.

After termination of cyclic loading most specimens were sheared under slow undrained strain controlled monotonic loading for assessment of stress-strain and strength response.

3.5 Test procedures

3.5.1 Specimen preparation

Cylindrical triaxial specimens with a nominal cross-sectional area of 10 cm^2 and a height to diameter ratio approximately equal to 2 were used. These dimensions were selected to minimize end restraint effects, time required for consolidation and pore water pressure nonequalization during undrained shear. For simplicity, side filter drains were not used.

Because of the soft consistency of Cloverdale clay the following specimen set up technique was used (see figure 3.5).

The specimen was temporarily seated between dry end caps and the inner latex membrane (thickness 0.20 mm) was installed on the specimen using a membrane stretcher. After releasing the membrane around the specimen, gentle finger strokes were applied to completely chase out the air trapped between the membrane and the specimen. The membrane ends were then rolled back on a single ply around the specimen and the temporary end caps gently removed. The specimen was weighed and measured, then transferred onto the triaxial cell pedestal with saturated porous stones in position. After positioning the top cap

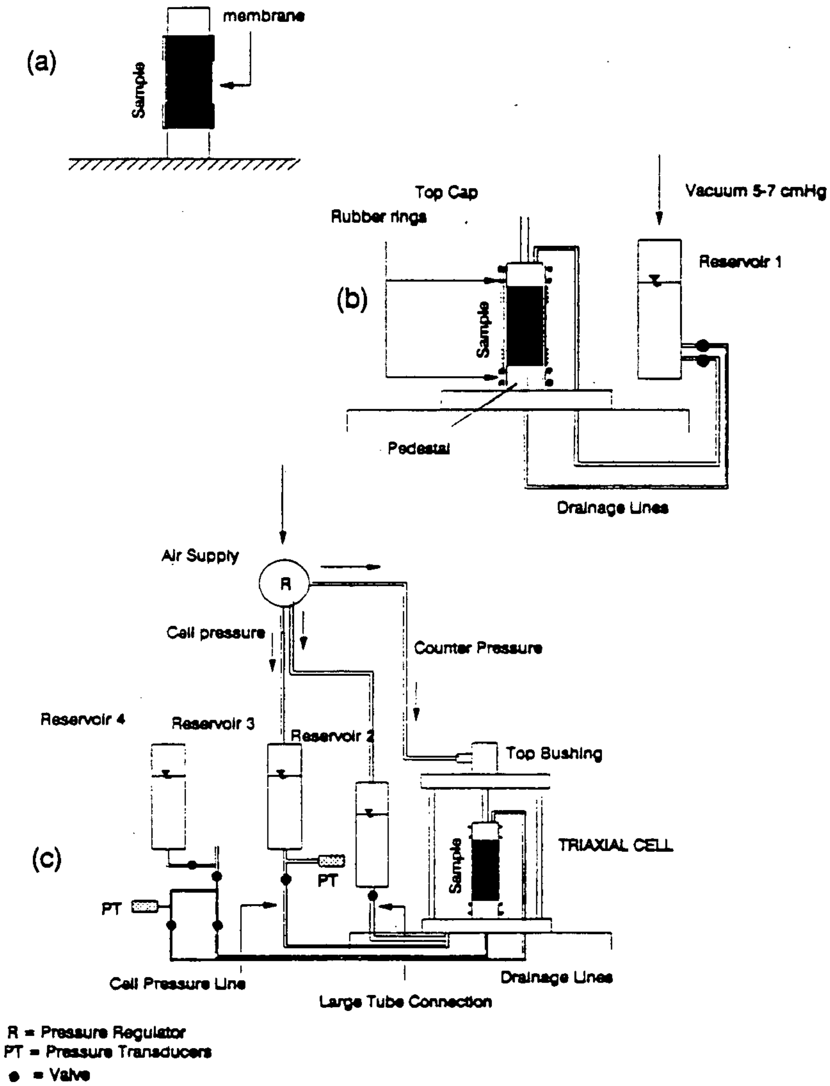


Fig 3.5 Steps in the preparation of clay specimens for triaxial testing.

the membrane was rolled around the base platen and top cap and sealed by rubber o-rings. A small vacuum of approximately 10 kPa was applied to both ends of the specimen for about 30 seconds to remove any excess water. The drainage lines were then closed to maintain the small pore water tension generated in the specimen. A film of high vacuum grease was then applied to cover completely the membrane enclosing the specimen. An outer latex membrane (thickness 0.0045 mm), previously sealed around the base platen with a rubber o-ring below the inner membrane, was then rolled up around the specimen and independently sealed against the top cap with a rubber o-ring above the inner membrane.

The specimen was left sitting undrained overnight under a hydrostatic cell pressure of about 80 kPa. The following day, the degree of saturation of the specimen was verified. The hydrostatic cell pressure was raised by increments of 50 kPa and the pore water pressure response was measured at both top and bottom ends of the specimen. All specimens tested had a final B value larger than 0.98 indicating full saturation.

3.5.2 Consolidation phase

Because of the rigid connection between the loading ram and the specimen top cap, a force equal to the cell pressure multiplied by the area of the loading ram was applied to ensure a hydrostatic loading of the specimen. In all tests the compensating force was applied through the double-acting loading piston after correcting for the weight of the top cap and the electronic sensors. When the desired cell pressure was attained, the specimen was consolidated in one stress increment for 48 hours under double drainage conditions against a back pressure equal to 100 kPa.

For overconsolidated clay, the back pressure was increased following the completion of normal consolidation. The specimen was then left to swell to the desired lower effective stress in one increment for 24 hours.

Upon completion of consolidation, the specimen was left for an undrained rest period. Figure 3.6 shows the pore water pressure developed with time due to the arrest of secondary consolidation for normally consolidated Cloverdale clay following 48 hours of consolidation. The tendency for the secondary pore water pressure to reach a plateau with time was the confirmation that the clay specimen was positively sealed.

The development of any secondary pore water pressure after the undrained rest period of 24 hours was used to correct the measurement of pore water pressure during slow cyclic loading tests (100). The correction consisted in subtracting the secondary pore water pressure value from the measured pore water pressure at corresponding elapsed times.

The correction to the pore water pressure was based on the assumption that the development of secondary pore water pressure was not affected by the shear loading. It is possible that the decrease in average effective stress during shear loading of normally consolidated clay may result in a lower secondary pore water pressure component. In any case, for the longest test duration considered (10 000 minutes), the pore water pressure correction was less than 5 percent of the effective consolidation stress.

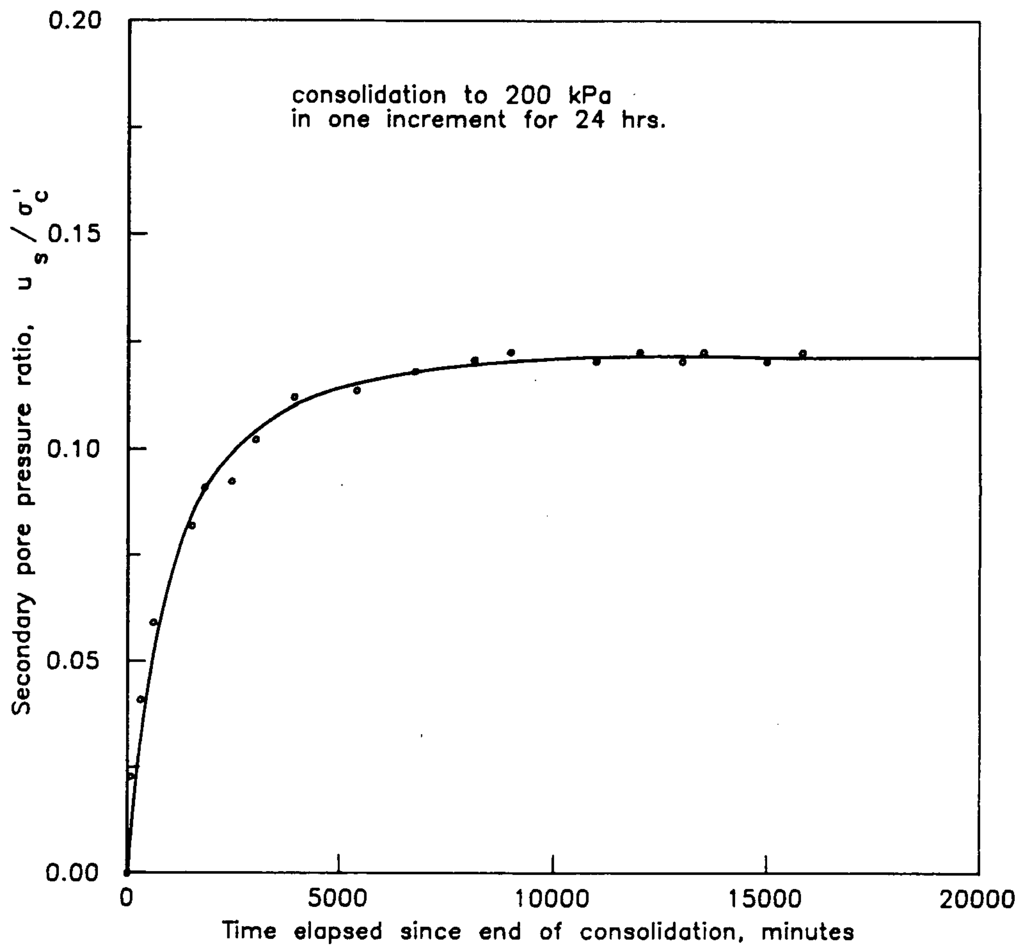


Fig 3.6 Development of pore pressure due to the arrest of secondary consolidation of Cloverdale clay.

For overconsolidated clay specimens, the undrained rest period was not allowed and shear loading commenced immediately after completion of the rebound period.

3.5.3 Shear phase

The appropriate rate of shear loading was selected by observing the stress-strain response of identical clay specimens to successively slower compression loading rates. Figure 3.7 shows that for normally consolidated Cloverdale clay, reduction of the axial strain rate below a value of 0.4 percent per hour did not have a significant effect on response to undrained triaxial compression loading. Therefore, this strain rate was considered sufficiently slow to minimize the pore water pressure gradient along the specimen for the given consolidation history. The same constant strain rate was used for overconsolidated clay although a faster loading rate would have been acceptable. For stress controlled loading, a loading rate of about 60 kPa per hour was found sufficiently slow to ensure pore water pressure equalization based on the direct observation of the clay response to various loading rates.

In slow cyclic tests, both strain and stress controlled loading modes were used. For cyclic stress levels higher than 0.7, strain controlled loading was preferred because stress controlled loading was accompanied by creep deformations. Figure 3.8 shows the occurence of creep deformation particularly upon unloading under a slow constant rate of stress loading of about 25 kPa per hour. For cyclic stress levels less than 0.5, creep deformation were minimal and a constant rate of stress cyclic loading was used instead of strain controlled

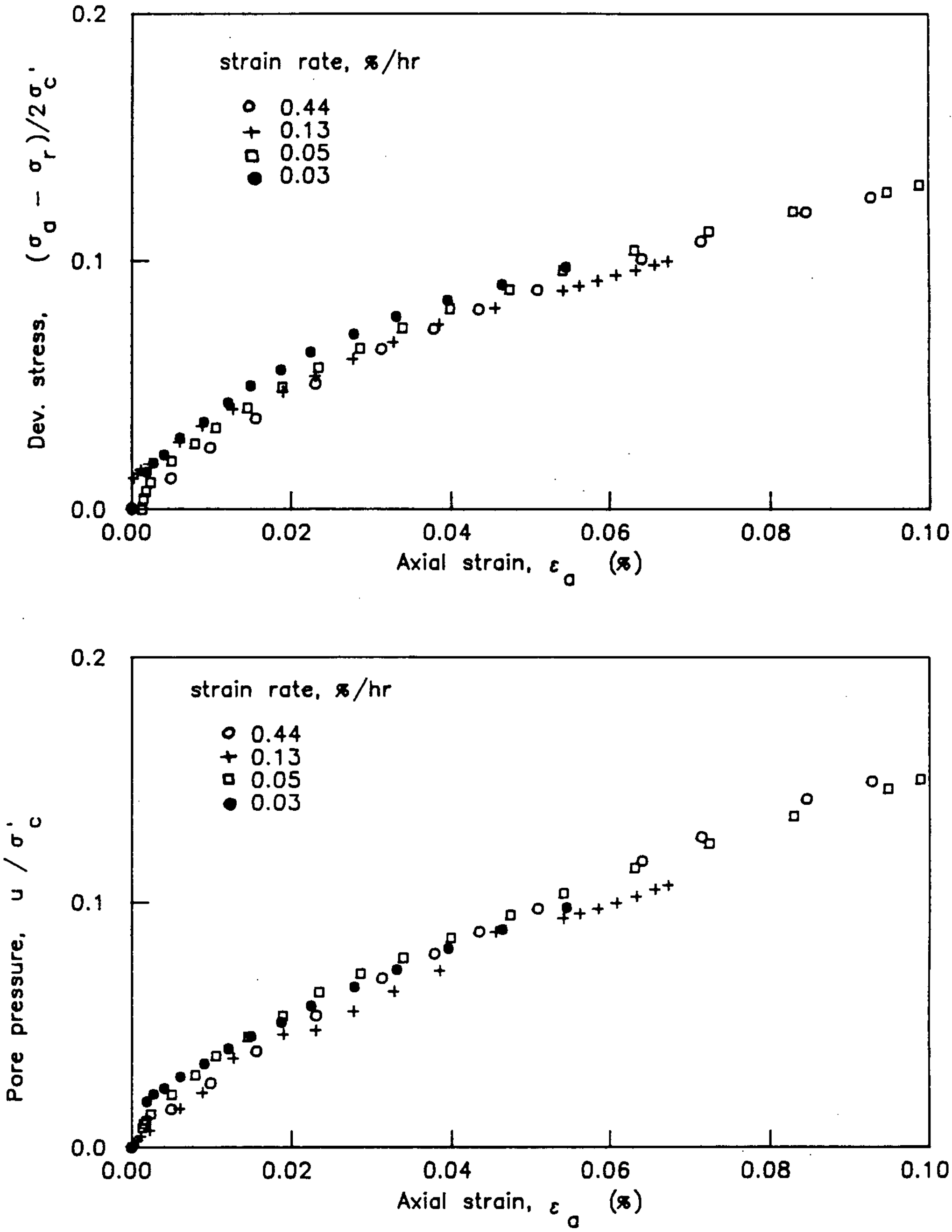


Fig 3.7 Effect of rate of strain on response of Cloverdale clay to undrained compression loading.

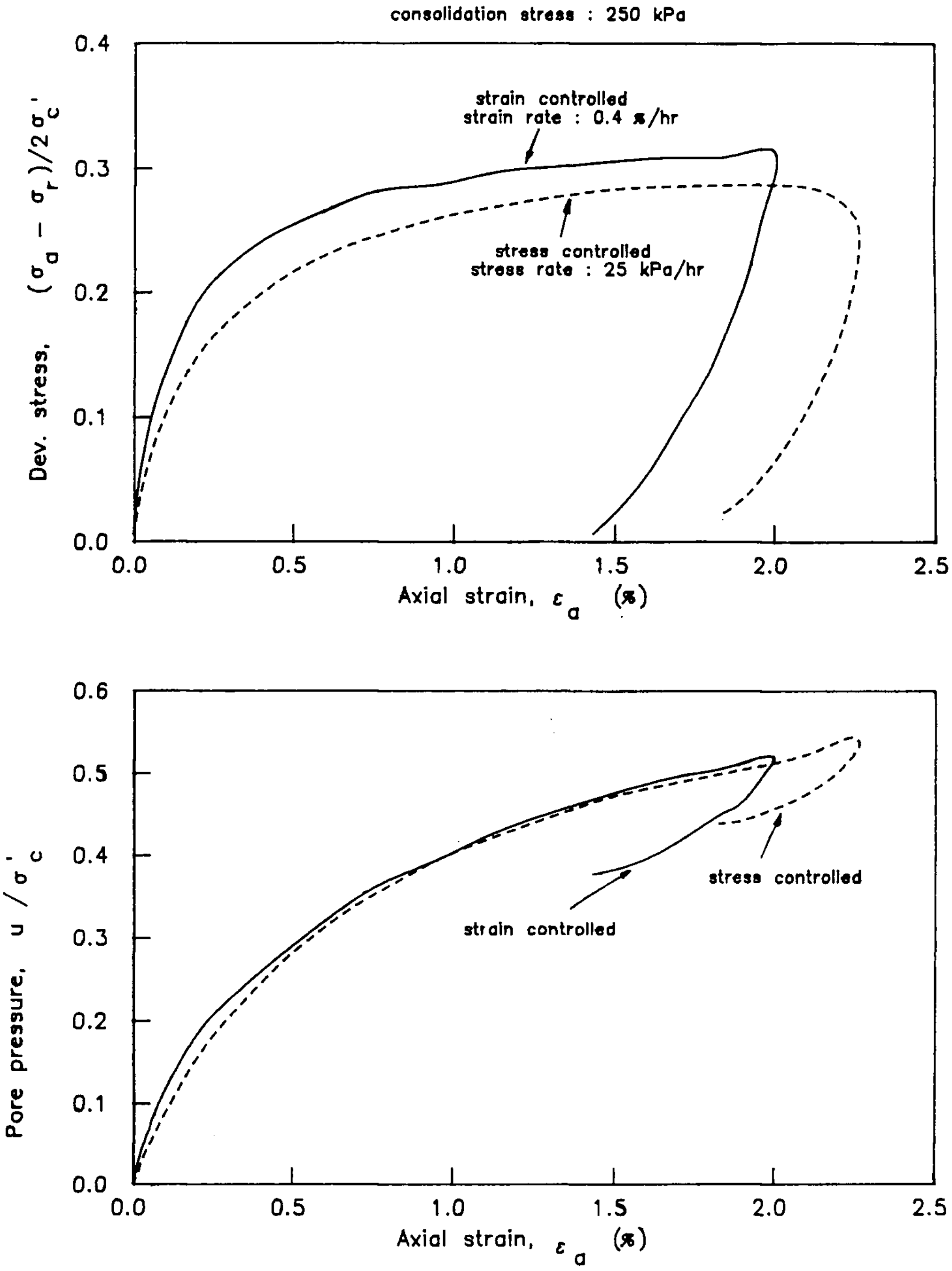


Fig 3.8 Effect of loading mode on the response of Cloverdale clay to slow undrained compression loading.

loading. In some tests to intermediate cyclic stress levels (between 0.5 and 0.7), loading was initiated under stress controlled conditions and subsequently switched to constant strain rate loading to control the development of increasingly larger axial strain amplitudes with further cycles.

All monotonic loading tests (before and after cyclic loading) were performed under strain controlled loading using a strain rate equal to 0.4 percent per hour.

3.5.4 Repeatability of test results

Several tests were reproduced under identical conditions (consolidation history, mode of loading and cyclic stress level) to assess the degree of repeatability of the experimental observations. Figure 3.9 shows the degree of repeatability of the stress-strain response to slow undrained monotonic loading for two specimens from different block samples. Figure 3.10 shows the strain and pore water pressure development during slow cyclic compression-extension loading to a constant cyclic stress level for two different specimens. These typical duplicate tests confirm that in this study the repeatability of the measurements is good.

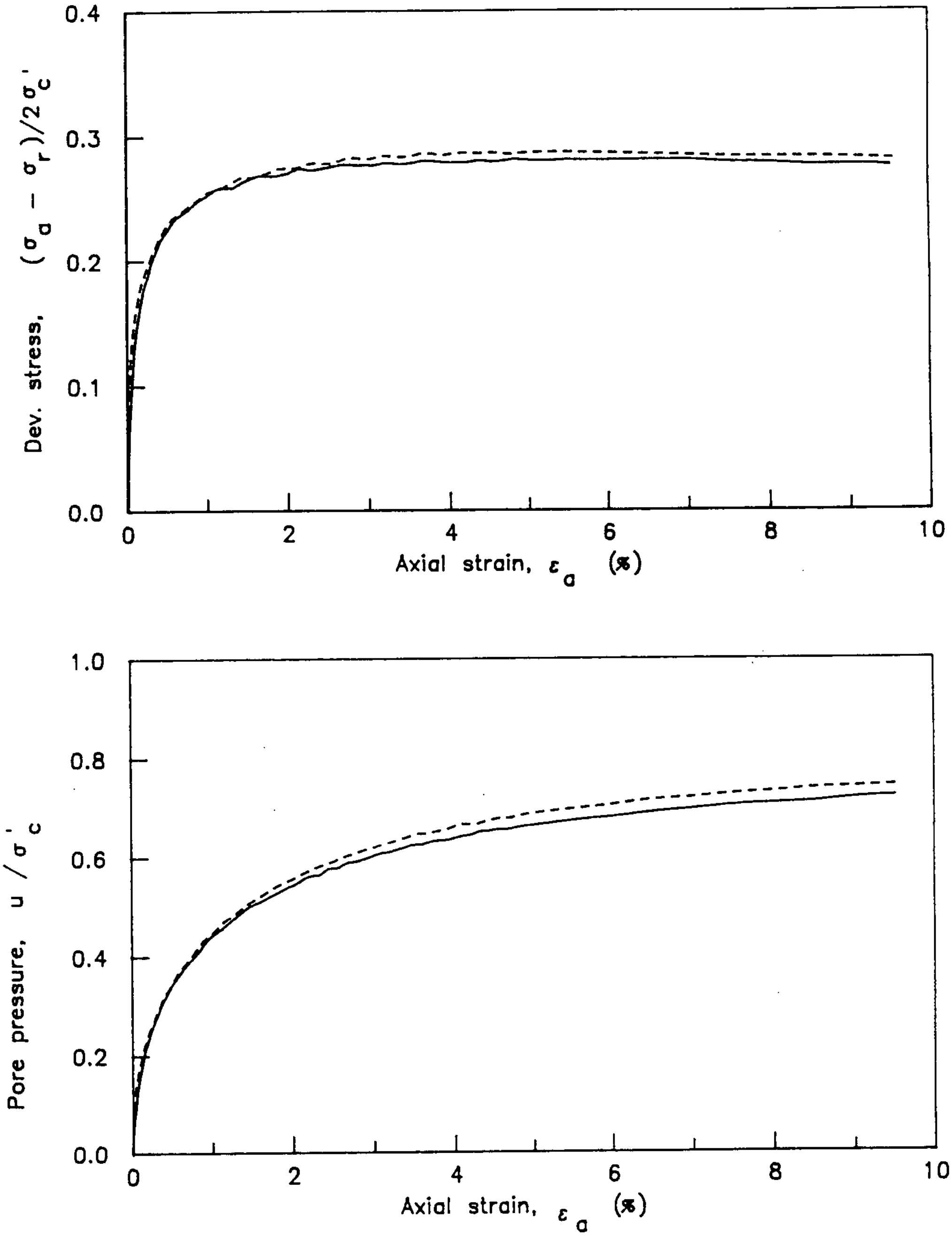


Fig 3.9 Repeatability of Cloverdale clay response to undrained monotonic compression loading.

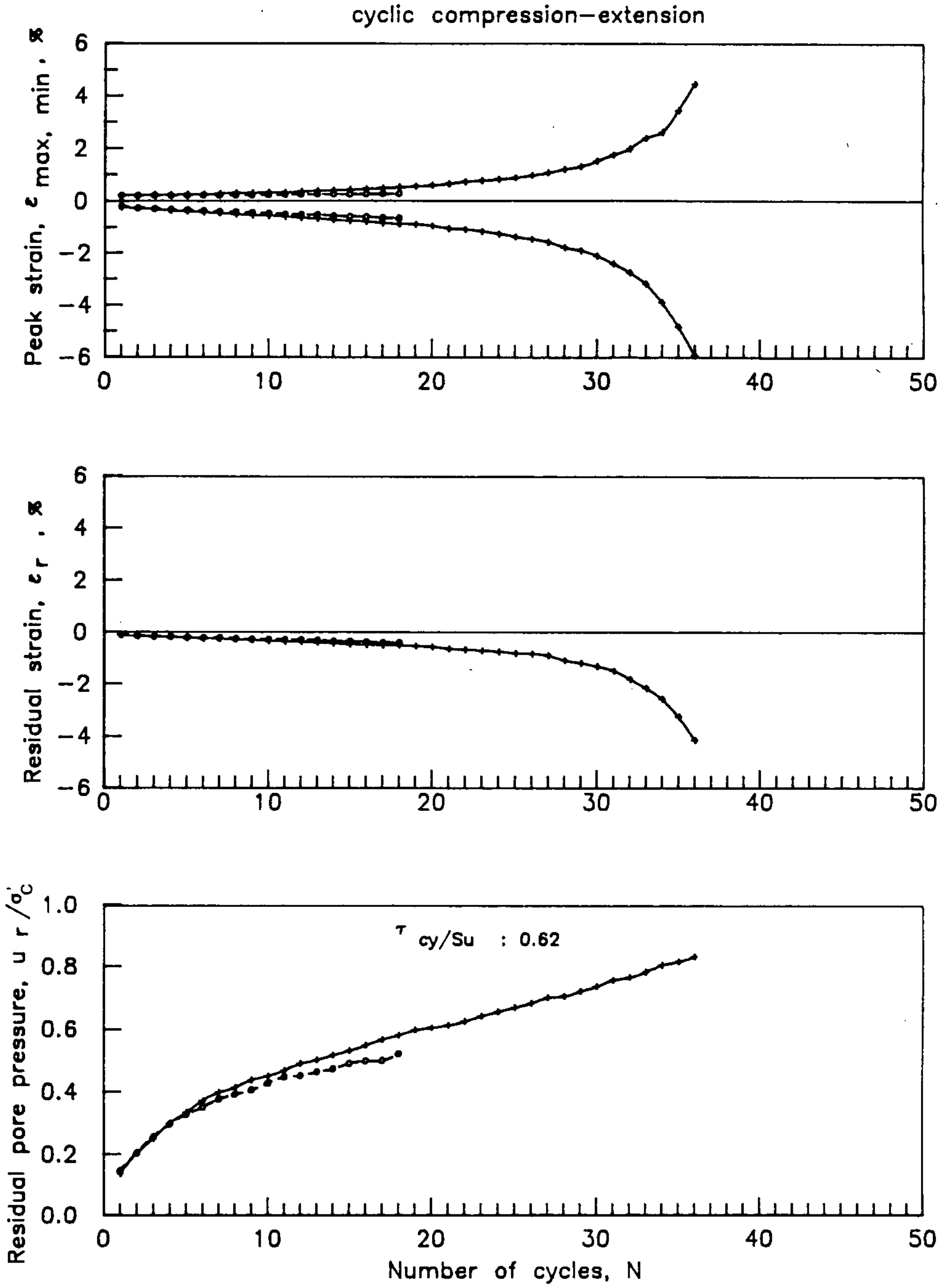


Fig 3.10 Repeatability of response of Cloverdale clay to slow two–way undrained cyclic loading to a constant cyclic stress level.

TEST RESULTS AND DISCUSSION

In this chapter the stress-strain response of isotropically consolidated Cloverdale clay to undrained monotonic and cyclic loading is described. In monotonic loading both normally consolidated and lightly overconsolidated states are considered. In cyclic loading the response of normally consolidated clay is examined under two loading modes:

- constant deviatoric stress amplitude; and,
- constant principal effective stress ratio amplitude.

The effects of a change in initial direction of cyclic loading and a step increase in cyclic stress level on the clay response are considered. The clay behaviour in postcyclic undrained monotonic loading is also described.

Like other normally consolidated clays, Cloverdale clay follows a normalized behaviour in undrained monotonic loading for consolidation stresses ranging from 200 to 400 kPa (57). All test results are therefore expressed in nondimensional form. For normally consolidated clay, stresses are normalized by the consolidation stress. For overconsolidated clay, stresses are normalized by the equivalent consolidation stress σ'_e (see figure 3.4). The equivalent consolidation stress is defined as the stress on the normal consolidation line corresponding to the same void ratio as the overconsolidated clay specimen (124, 125).

4.1 Response to undrained monotonic loading

In this section the response of Cloverdale clay to undrained monotonic loading is described. The effect of stress overconsolidation on the clay response is determined using overconsolidation ratios (OCR) ranging from 1 to 4. Overconsolidation is achieved by stress rebound from a maximum consolidation stress equal to 200 kPa. Both compression and extension loading modes are considered. The purpose of these tests is:

- to characterize the stress-strain response of Cloverdale clay to monotonic undrained loading;
- to allow comparisons between the response of Cloverdale clay and other extensively studied soft clays; and,
- to establish a reference benchmark for the interpretation of cyclic loading tests.

Figure 4.1 shows the stress-strain response of Cloverdale clay to slow (axial strain rate equal to 0.4 percent per hour) undrained monotonic loading with overconsolidation ratios ranging from 1 to 4. For normally consolidated clay, a normalized undrained strength in compression equal to 0.28 is mobilized at an axial strain equal to 4 percent. This reference undrained strength is used to determine the cyclic stress level τ_{cy}/Su_c defined earlier. Figure 4.1 also shows that overconsolidation causes a reduction in clay stiffness. This effect is more apparent in extension loading than in compression and is due to the progressively smaller effective confining stress with increasing OCR.

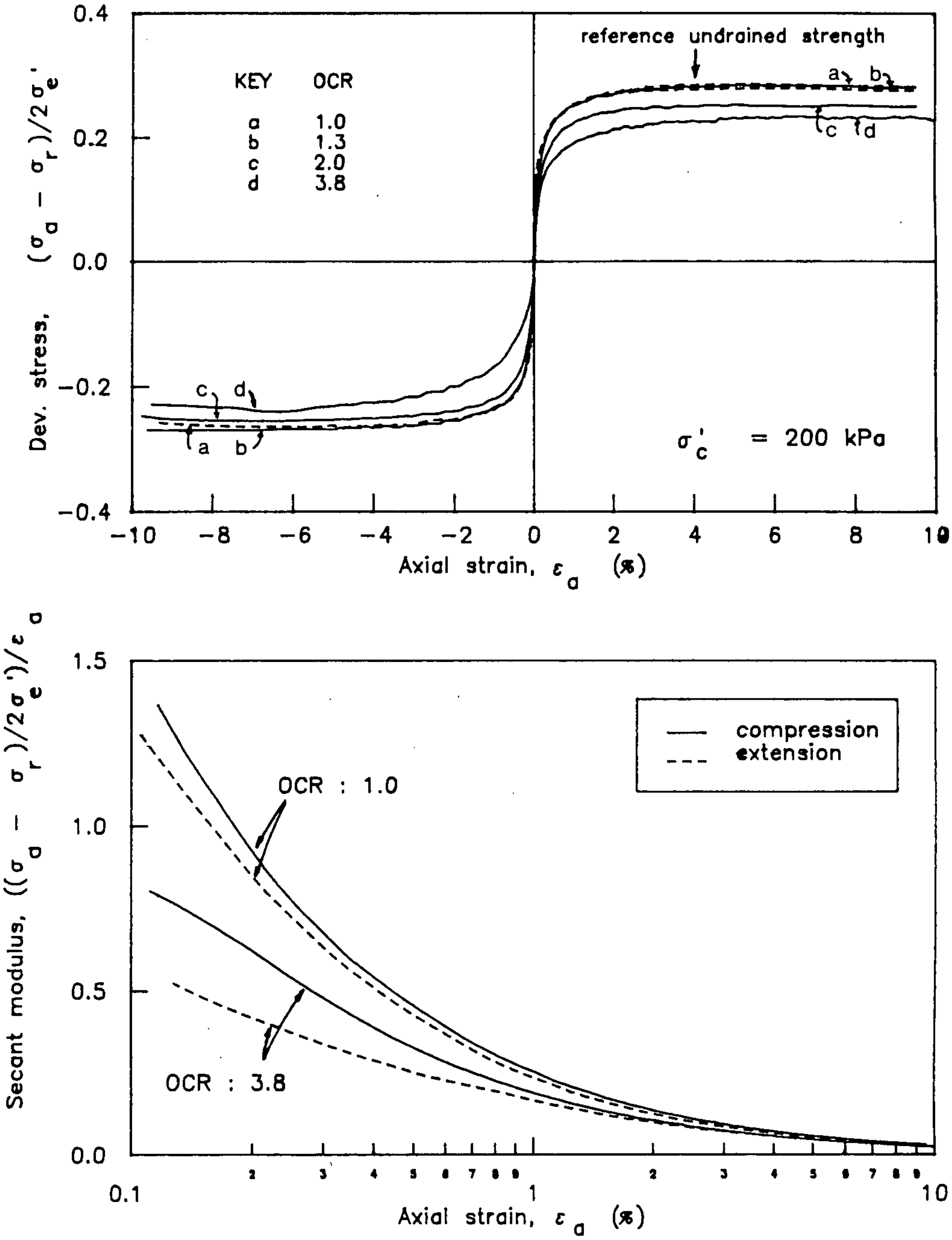


Fig 4.1 Effect of loading direction and overconsolidation ratio on response of Cloverdale clay to undrained monotonic loading.

TEST RESULTS AND DISCUSSION

Under compression loading the specimens deformed by uniform barrelling and a sliding plane was not apparent even at 25 percent axial strain when the testwas terminated. Under extension loading the specimens started showing signs of necking at about 7 percent axial strain and deformed nonuniformly from then on.

For overconsolidated clay the actual consolidation stress may also be used as a normalizing parameter. Then the normalized undrained strength increases with increasing OCR as shown in figure 4.2. However, both compression and extension loading mobilize about the same undrained strength. Figure 4.2 also shows the effect of overconsolidation on the ratio of stiffness over undrained strength. The ratio of secant modulus at a stress level equal to half the peak deviatoric stress over the undrained strength decreases with increasing OCR. The ratio of secant modulus over undrained strength for Cloverdale clay is similar to the values reported in the literature for other soft clays (125).

Most clays exhibit a softer stress-strain response in extension than in compression and the undrained strength in extension may be as much as 20 percent lower than in compression (8, 27, 39, 67, 85). This anisotropic clay response to undrained monotonic loading may be related to among other factors the role of the intermediate principal stress in the conventional triaxial test. In compression the intermediate principal stress is a minor principal stress but in extension loading the intermediate principal stress is a major principal stress. Cloverdale clay exhibits a relatively small degree of anisotropy in its stress-strain response to undrained monotonic loading.

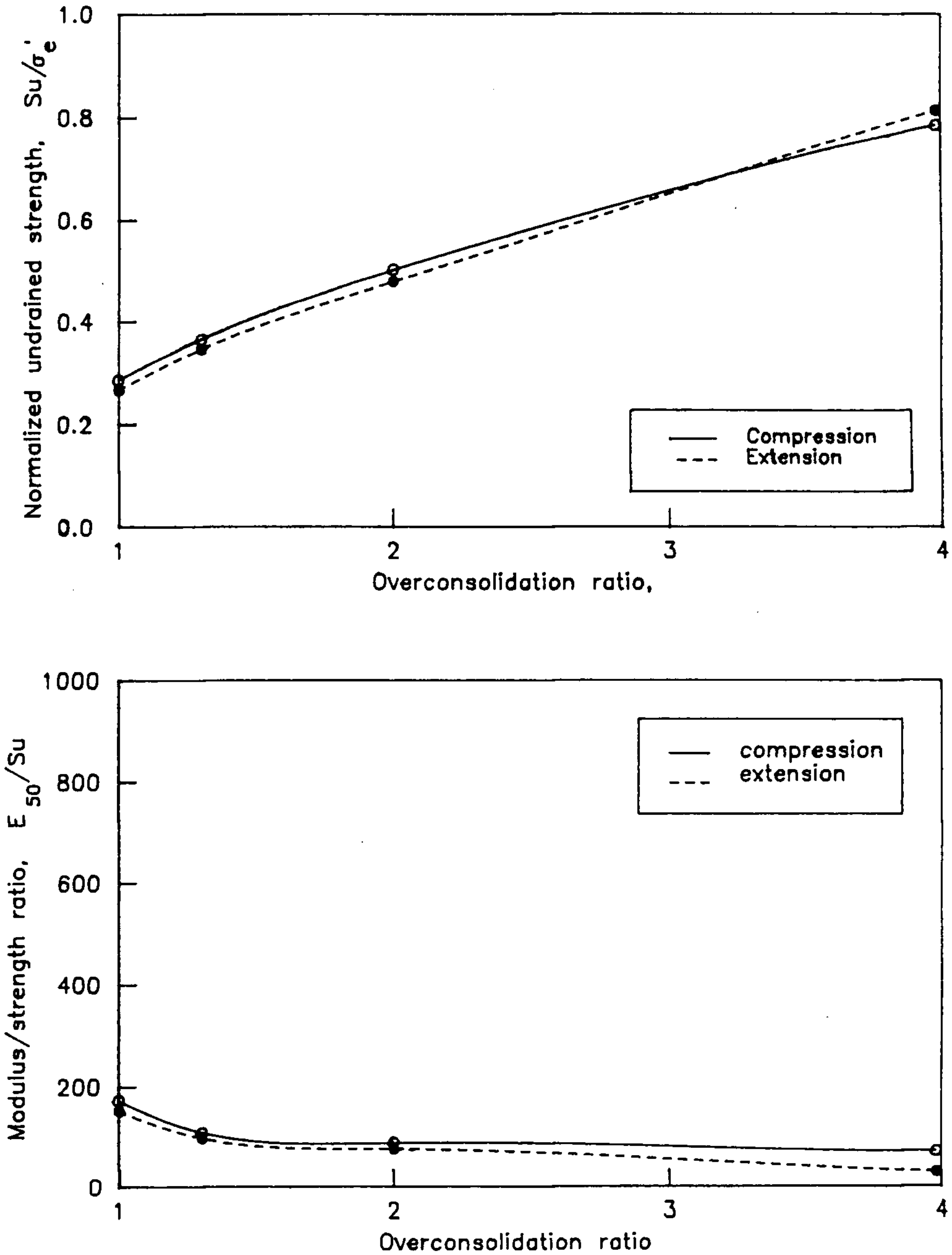


Fig 4.2 Effect of overconsolidation ratio on clay strength and deformation modulus in undrained monotonic loading.

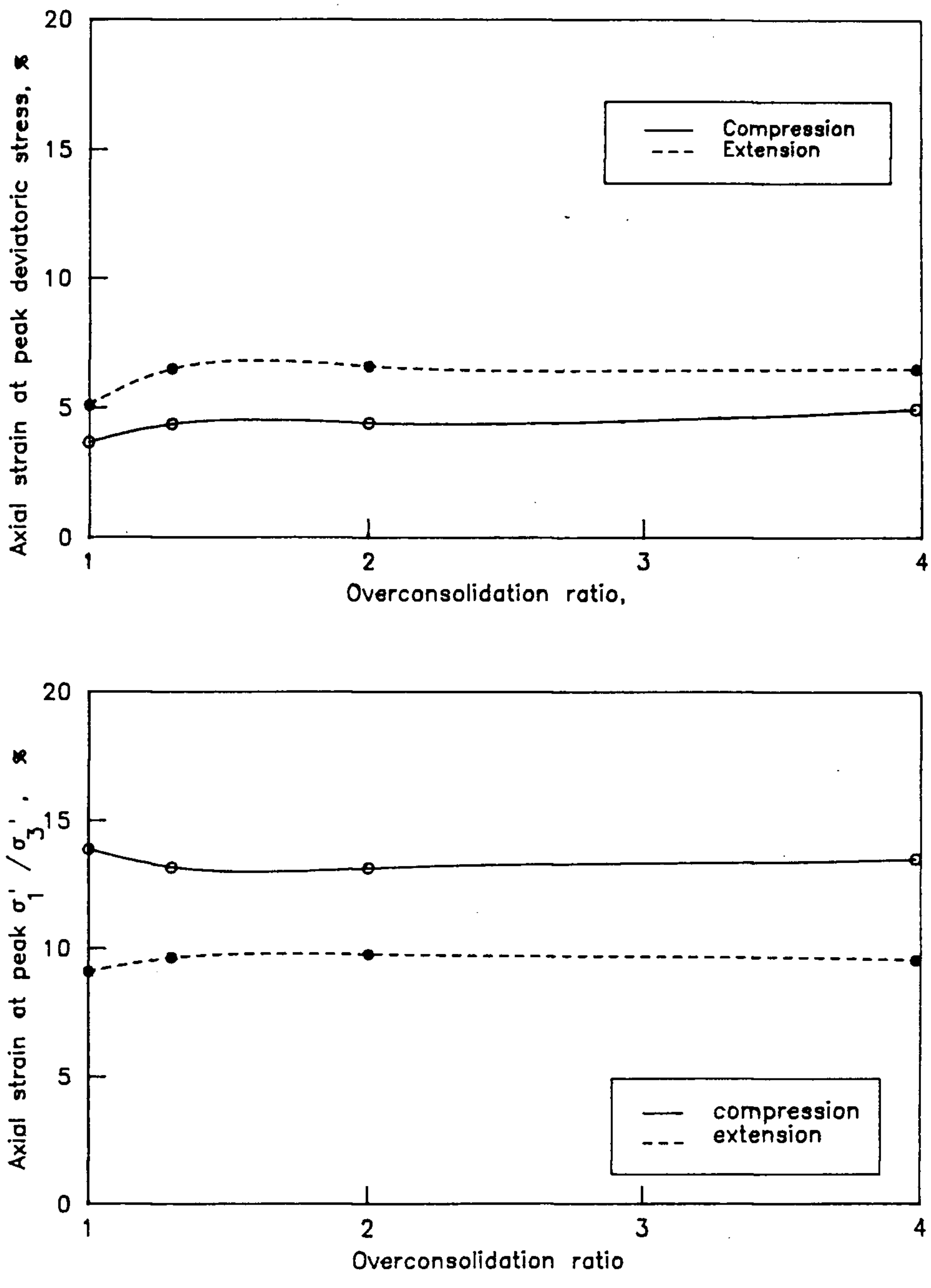


Fig 4.3 Effect of overconsolidation ratio on axial strain at failure of Cloverdale clay in undrained monotonic loading.

Figure 4.3 shows that the strain at peak deviatoric stress increases slightly with increasing OCR. Undrained strength is mobilized at a larger strain in extension loading than in compression. These observations are consistent with the small degree of anisotropy of Cloverdale clay. Figure 4.3 also indicates that peak principal effective stress ratio is reached at a considerably larger strain than peak deviatoric stress. This observation is typical of sensitive clays where pore water pressure continues to increase with strain past the peak deviatoric stress.

Figure 4.4 shows the effective stress paths followed by Cloverdale clay during undrained monotonic loading. For normally consolidated specimens the effective stress paths follow elliptic shapes typical of soft clays. For overconsolidated specimens the effective stress paths reflect the development of lower pore water pressure during shear loading with increasing overconsolidation ratio. All effective stress paths tend to converge toward a narrow region in the stress plane. A single ultimate stress point is not quite reached contrary to the concepts of critical state (93, 94).

The failure envelope is defined on the effective stress path plane at maximum principal effective stress ratio with a cohesion intercept equal to zero. A unique failure line with a Coulomb friction angle equal to 32 degrees represents the effective stress strength of Cloverdale clay in undrained monotonic compression and extension loading for OCR ranging from 1 to 4.

The contours of equal axial strains during undrained monotonic loading of Cloverdale clay are also shown in dashed lines in figure 4.4. The location of the strain contours in the effective stress path plane is consistent with the high stiffness of the clay upon initial loading. The strain contours are also consistent

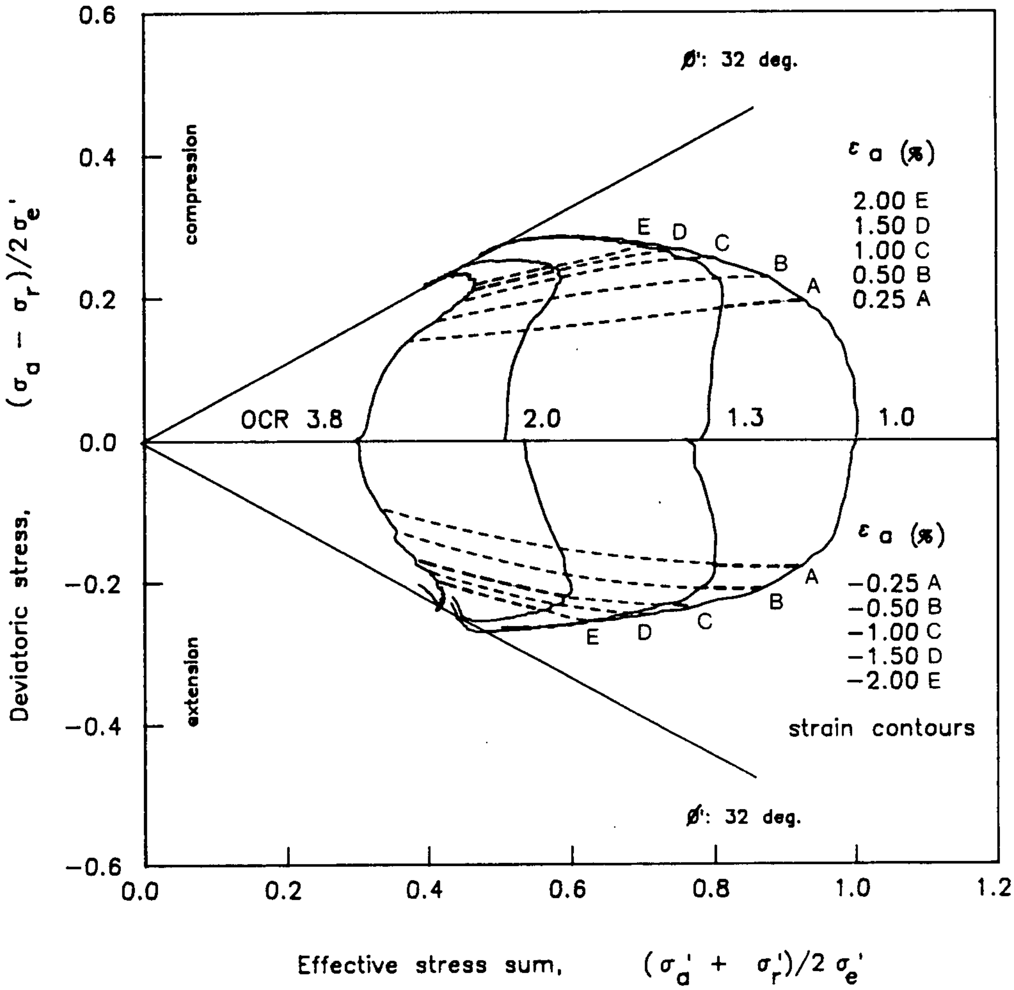


Fig 4.4 Effective stress paths and contours of equal strains of Cloverdale clay in undrained monotonic loading.

with the decrease of stiffness with increasing OCR. This pattern of strain contours will be used in the interpretation of the response of Cloverdale clay to undrained cyclic loading. The effective stress paths and strain contours of Cloverdale clay under compression and extension loading are essentially symmetric with respect to the hydrostatic stress axis. This feature is consistent with the low degree of anisotropy of the stress-strain response of isotropically consolidated Cloverdale clay to undrained monotonic loading. A comparable pattern of strain contours was reported for Drammen clay (19) and for Kaolin clay (124) in undrained monotonic loading.

The effect of rate of loading on the undrained strength and stress-strain response of soft clays to undrained monotonic loading is well documented (24, 38, 41, 65, 76, 116, 128). Generally, a lower undrained strength and a softer stress-strain relationship are obtained by decreasing the strain rate. For most clays, a decrease in undrained strength of about 8 to 10 percent is measured for a ten fold decrease in strain rate. The strain rate effect on the response of Cloverdale clay would be similar to the rate effects reported for Haney clay because of the comparable origin and properties of the two clays (116, 128).

With the exception of a low degree of anisotropy, the behaviour of Cloverdale clay under undrained monotonic loading is very similar to that of other extensively studied soft clays reported in the literature (8, 19, 27, 44, 45, 67, 78, 85, 86, 93, 116). The response of this clay to undrained monotonic loading for OCR ranging from 1 to 4 is characterized by the following points:

1. A strain hardening stress-strain relationship is followed before reaching a plateau at a given axial strain.
2. When the equivalent consolidation stress is used as normalizing parameter, the normalized undrained strength decreases with increasing OCR. The axial strain at peak deviatoric stress plateau increases slightly with OCR.
3. The stiffness and normalized undrained strength are sligthly lower in extension than in compression. The degree of anisotropic stress-strain response is small in comparison with other soft clays but it increases with increasing OCR.
4. The effective stress path followed is typical of soft clays and changes with increasing OCR to reflect the lower pore water pressure development with strain during shear loading.
5. A unique effective stress failure envelope is defined at peak principal effective stress ratio with a mobilized friction angle equal to 32 degrees and no cohesion intercept for OCR between 1 and 4.

4.2 Response to fast undrained cyclic loading

The response of Cloverdale clay to fast undrained cyclic loading was reported by Jitno (57). Stress controlled symmetrical sine pulses were applied with a frequency of 0.1 Hz to simulate conditions relevant to both seismic and wave loadings. In this study a direct comparison with the response of the same clay to similar cyclic loading conditions but at a slower loading rate is made. The influence of a nonreliable pore water pressure measurement in fast cyclic loading on the interpretation of the test results is pointed out.

4.2.1 Cyclic loading response

The dashed lines in figure 4.5 show the development of strain and pore water pressure with number of cycles during fast cyclic compression-extension loading of Cloverdale clay to various cyclic stress levels. The response is similar to Drammen clay under comparable loading conditions (4, 8, 9). The behaviour of Drammen clay is considered typical of various North Sea clay foundations for offshore platforms. The initial investigation program on the behaviour of Drammen clay in relation to offshore development included the performance of slow cyclic tests to understand the clay response to undrained cyclic loading (2, 4). Unfortunately, these slow cyclic tests were never carried out. Hence, the interpretation of the cyclic loading behaviour of Drammen clay in terms of effective stresses was limited. The effective stress response of Drammen clay to undrained cyclic loading should be similar to that of Cloverdale clay because of the similarity in their origin, their physical properties as well as their behaviour in undrained monotonic loading.

The full lines in figure 4.5 show the response of Cloverdale clay to identical cyclic stress levels and loading sequence used in fast cyclic tests, but under a slow constant rate of strain. Although the general pattern of strain and pore water pressure development with number of cycles is similar between fast and slow cyclic tests, the levels of strain and pore water pressure generated during slow cyclic loading are different. Under the similar cyclic stress level the number of

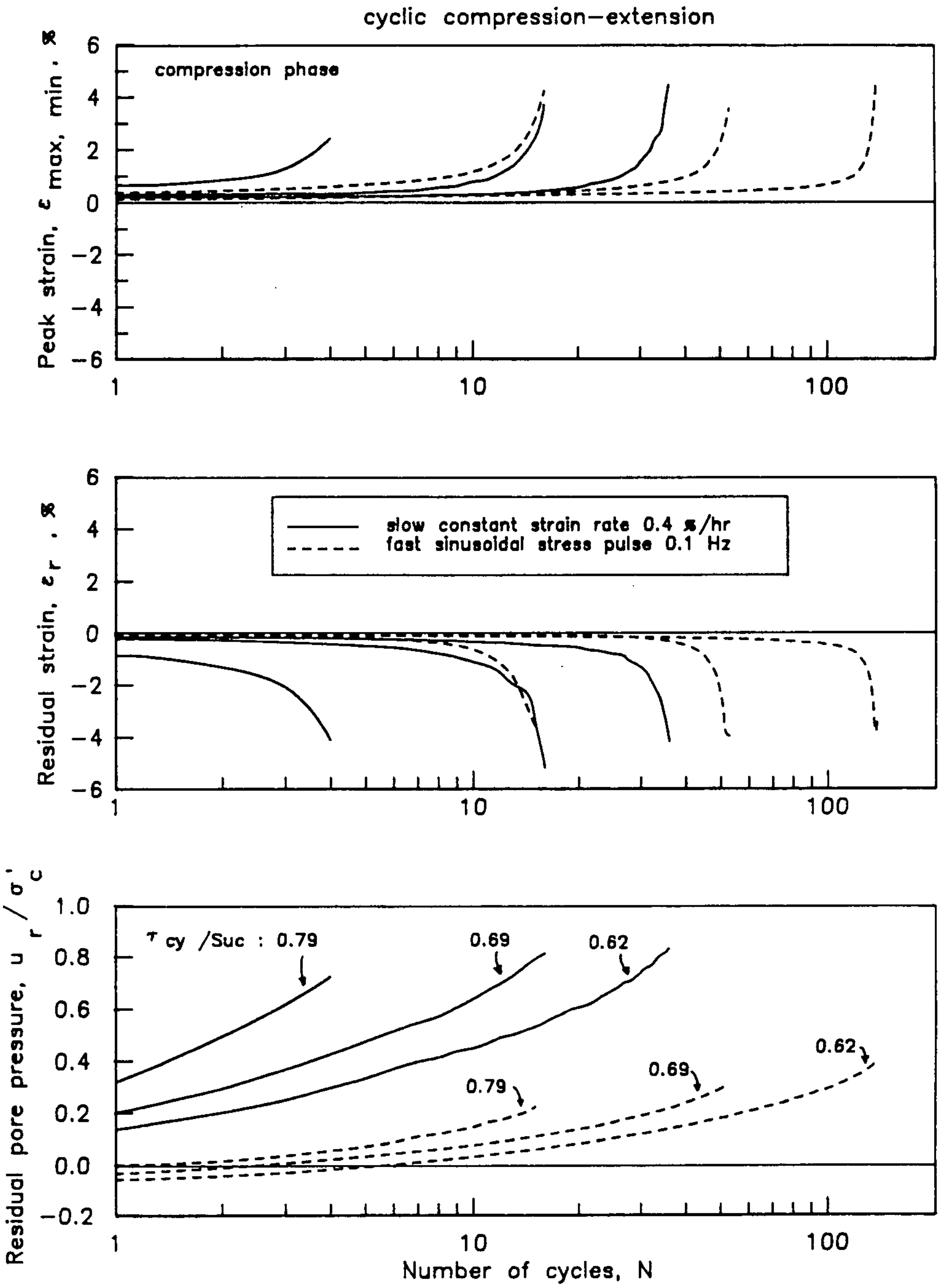


Fig 4.5 Comparison between slow and fast cyclic loading response of Cloverdale clay to two-way undrained cyclic loading to various cyclic stress levels.

cycles required to develop a given strain is considerably smaller under slow cyclic loading than under fast cyclic loading. Correspondingly, for a given number of cycles the residual pore water pressure recorded under slow cyclic loading is significantly larger than under fast cyclic loading. The low residual pore water pressure measured during fast cyclic loading cannot be explained by the time-dependent nature of the clay response. The method of pore water pressure measurement is the primary cause of the different pore water pressure response to fast and slow undrained cyclic loading. The pore water pressure was measured at the base of triaxial specimens restrained by frictional ends. As a consequence, little equalization occurred in fast tests compared to those in slow tests.

In undrained cyclic loading, the factors controlling the degree of pore water pressure equalization within triaxial clay specimens with end restraint are :

. Rate of loading;

. Specimen size;

. Cyclic stress level; and,

. Strain developed during cyclic loading.

For Drammen clay the difficulty of pore water pressure measurement during fast undrained cyclic loading was addressed by measuring the pore water pressure along the side of the specimen as well as at the ends (3). A simple test was used to verify the reliability of the pore water pressure measurement. It consisted in determining a "dynamic" Skempton B parameter by applying a cyclic change in the hydrostatic cell pressure and measuring the corresponding pore water pressure response. Incremental pore water pressure to cell pressure ratios up to 0.7 were obtained for a loading frequency of 0.1 Hz. However, this method does not guarantee that the pore water pressure response under cyclic shear stresses would be as fast because both cyclic stress level and strain developed during cyclic loading are ignored.

An alternate method of assessing the reliability of the pore water pressure response of triaxial clay specimens in fast undrained cyclic loading was applied to San Francisco bay mud (103). It consisted in measuring the pore water pressure change at the base of the specimen during an undrained rest period under zero shear stress immediately following cyclic loading. The amount of pore water pressure change and the time required for the postcyclic residual pore water pressure to stabilize was an indication of the degree of pore water pressure nonequalization within the specimen during fast cyclic loading. This method was used in fast cyclic tests on Cloverdale clay.

4.2.2 Postcyclic residual pore water pressure

The equalization of pore water pressure after fast cyclic loading was investigated on Cloverdale clay by Jitno (57). Figure 4.6 shows that for specimens that ended with 4 percent residual strain in fast two-way cyclic loading, the residual pore water pressure at end of cyclic loading doubled during the equalization period. Hence the degree of pore water pressure nonequalization during fast cyclic loading of Cloverdale clay is severe. For Drammen clay the degree of pore water pressure nonequalization would be even more severe because of the longer specimens used (5). The specimens of Drammen clay subjected to cyclic loading were 50 to 75 mm in diameter and 100 to 150 mm in

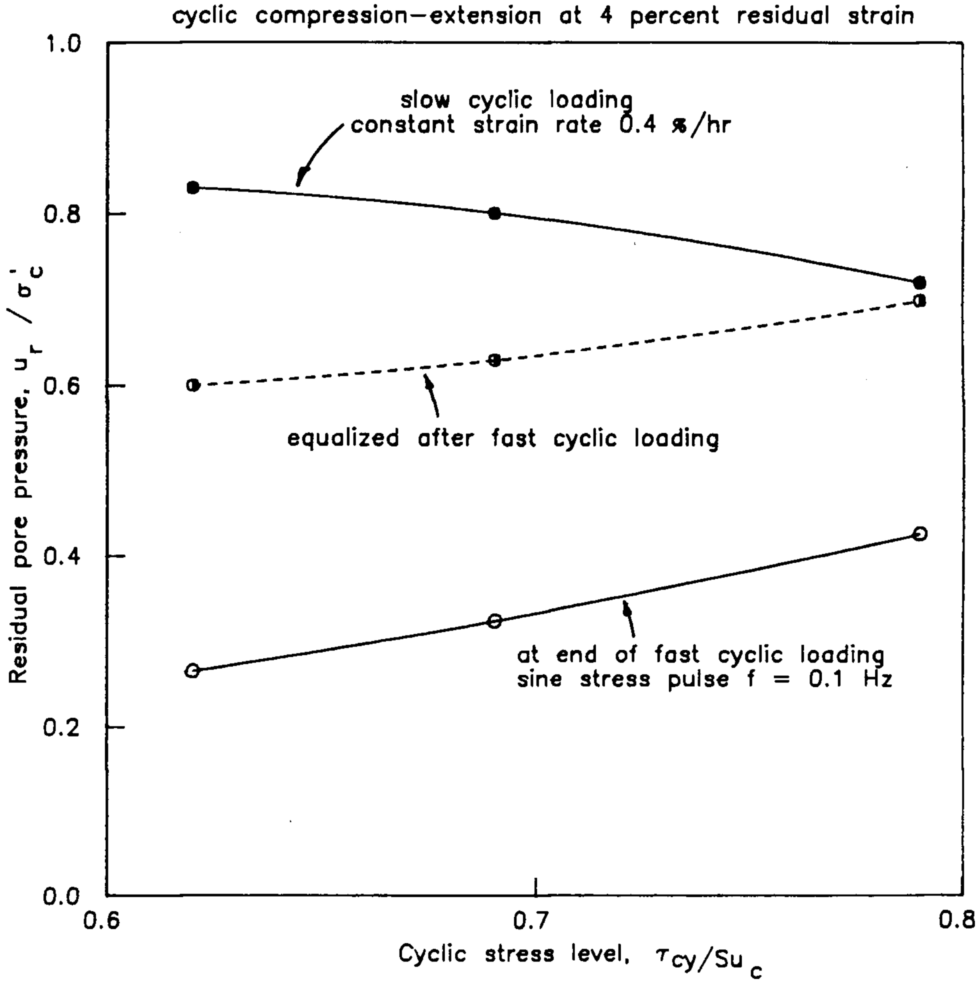


Fig 4.6 Degree of pore pressure equalization in slow and fast two–way undrained cyclic loading of Cloverdale to various cyclic stress levels.

height, whereas Cloverdale clay specimens were 35 mm in diameter and 70 mm in height.

Figure 4.6 also shows that the difference between equalized residual pore water pressure after fast cyclic loading and residual pore water pressure in slow cyclic tests tends to decrease with increasing cyclic stress level. Since for a given strain development (residual or peak) the duration of cyclic loading increases with decreasing cyclic stress levels it follows that the degree of pore water pressure nonequalization is not minimized with longer test durations. This conclusion is contrary to the common assumption that for low cyclic stress levels and longer cyclic loading durations the residual pore water pressure tends to become more uniform within the specimen.

The observation of pore water pressure equalization on Cloverdale clay after fast cyclic loading to various strain levels under a given cyclic stress amplitude showed that the larger the strain the more severe the pore water pressure nonuniformity (57).

The initial direction of cyclic loading was also found to influence the degree of pore water pressure nonequalization in fast cyclic tests. Extension-compression cyclic loading resulted in a lower degree of pore water pressure nonequalization than cyclic compression-extension (57). Figure 4.7 shows that at 4 percent residual strain, the increase in residual pore water pressure after fast cyclic extension-compression loading is smaller than after fast cyclic compression-extension. Moreover, the degree of pore water pressure nonequalization in cyclic extension-compression loading is independent of cyclic stress level. These observations will be explained later based on slow cyclic tests.

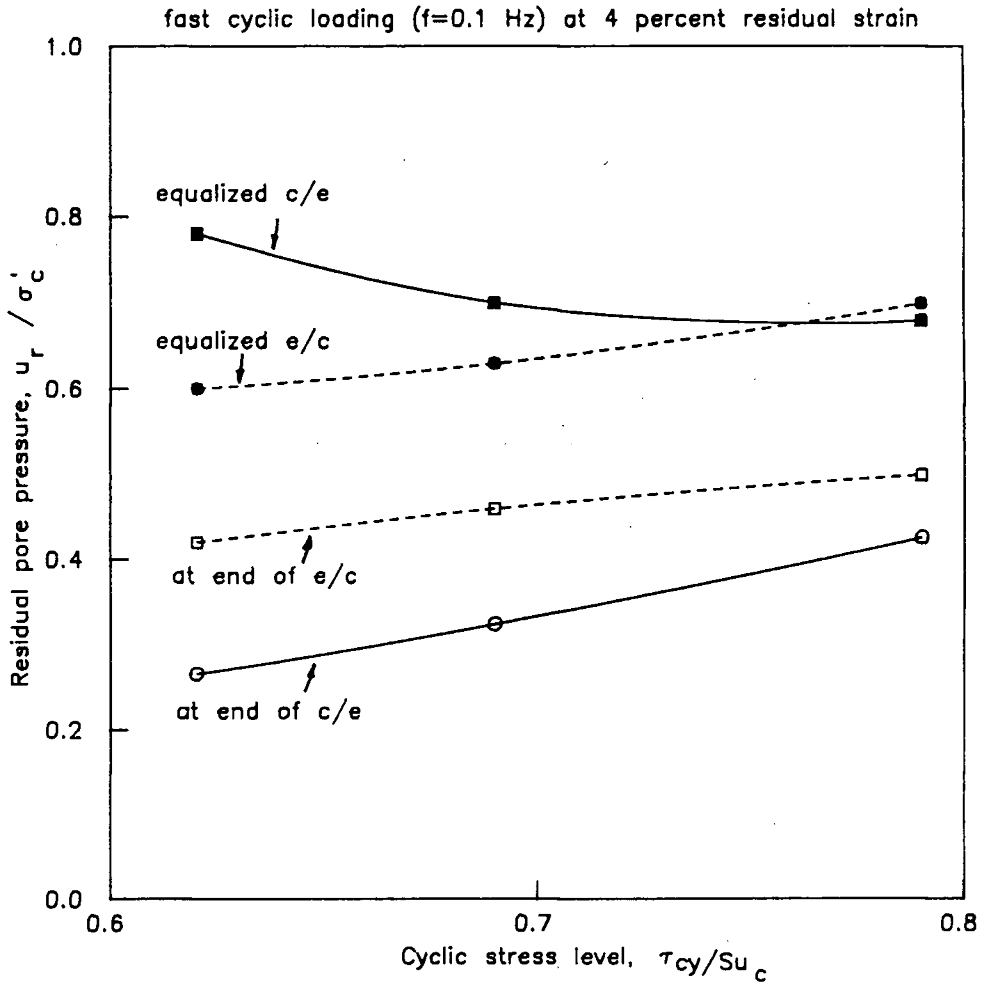


Fig 4.7 Effect of cyclic loading direction and cyclic stress amplitude on degree of pore pressure equalization at a given strain level in fast two-way undrained cyclic loading.

The direct comparison between the response of Cloverdale clay to fast and slow undrained cyclic loading clearly points out the need for reliable pore water pressure measurement when investigating clay behaviour in terms of effective stresses. Reliable pore water pressure measurements are obtained only in slow cyclic loading tests.

4.3 Response to slow undrained cyclic loading with constant stress amplitude

In this section the response of normally consolidated Cloverdale clay to slow undrained cyclic compression-extension loading under various constant deviatoric stress amplitudes is described. The range of stress amplitudes considered was sufficiently wide to determine the effect of cyclic stress level on the clay behaviour. This section deals only with cyclic loading initiated in compression. The effect of the initial direction of loading on the clay behaviour will be examined in a later section by considering data obtained by initiating cyclic loading in extension.

The stress-strain response of the clay is considered at two particular points in each loading cycle:

. at maximum cyclic stress (peak); and,

. at completion of the cycle (residual).

The stress-strain response within each loading cycle is also considered to obtain further information on its behaviour. The complete stress-strain response of the clay will allow the determination of hysteretic work and damping ratio during cyclic loading.

The response of Cloverdale clay to undrained monotonic loading is used as reference in the effective stress interpretation of response to undrained cyclic loading.

4.3.1 Peak stress-strain response

Figure 4.8 shows the development of peak strain in compression during undrained cyclic compression-extension loading at various cyclic stress levels. A logarithmic scale is used for the axial strains to show the response to the full range of cyclic stress levels. The distortion introduced by the logarithmic scale does not change the strain response patterns observed when a linear scale is used. The corresponding increase in principal effective stress ratio with number of cycles is also shown in figure 4.8. Two response patterns may be distinguished depending on the cyclic stress level.

For cyclic stress levels less than about 0.55, the development of peak strain and principal effective stress ratio tend toward equilibrium plateaus with increasing number of cycles. However a true equilibrium plateau does not appear to be reached. Strain and principal effective stress ratio at the peak points continue to increase although at decreasing rate with further cycles of loading.

For cyclic stress levels less than about 0.55, a power function can be used to describe the increase in peak strain with number of cycles as follows:

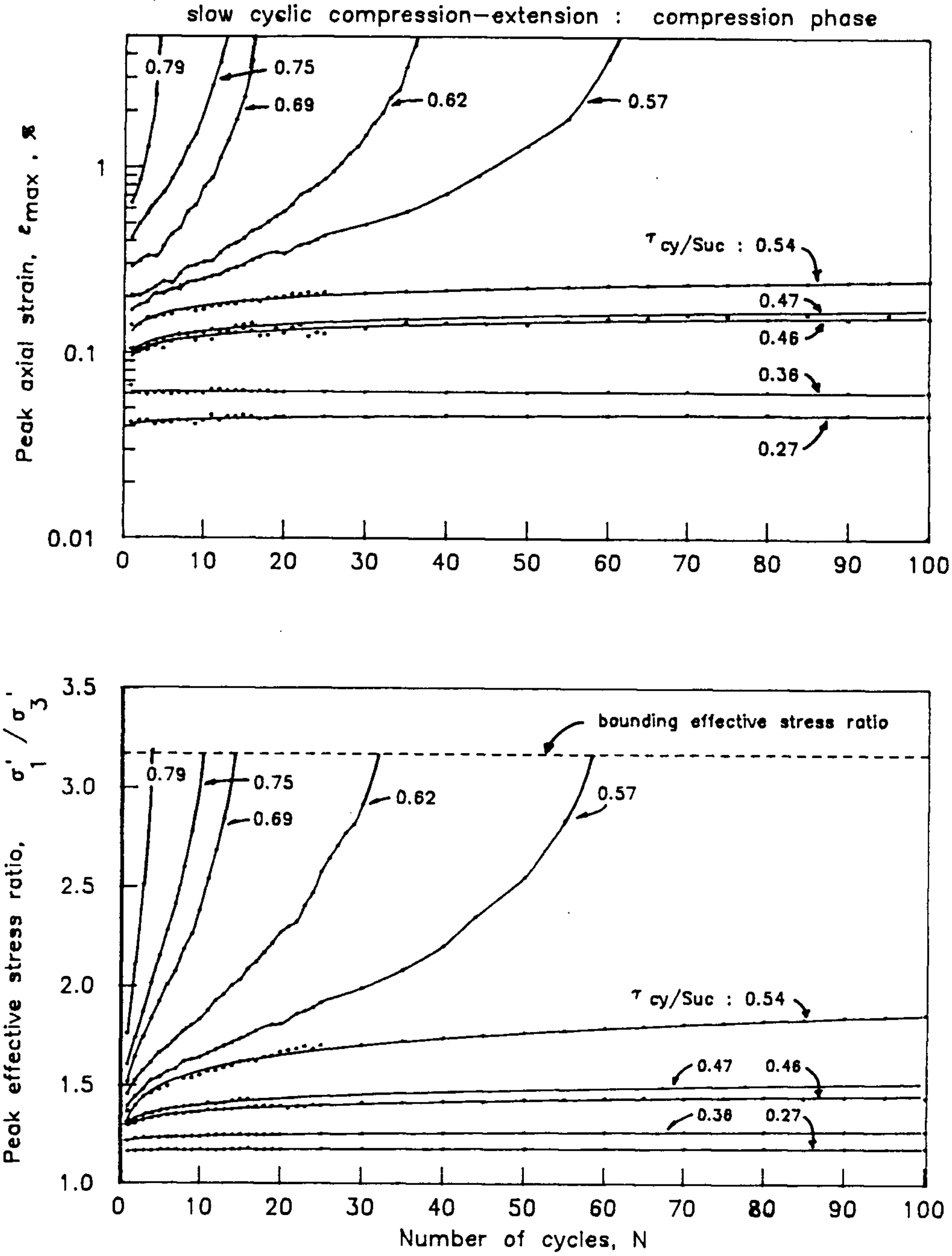


Fig 4.8 Development of peak axial strain and effective stress ratio in compression phase in slow two–way undrained cyclic loading to various cyclic stress levels.

$$\epsilon_{max} = a\,N^{b}$$

where:

ϵ_{max} = peak axial strain, %

N = number of cycles

a, b = empirical parameters depending on cyclic stress level.

A similar power function describes also the variation of peak principal effective stress ratio with number of cycles:

$$\sigma_1'/\sigma_3' = m\,N^{n}$$

where:

σ_1'/σ_3' = peak principal effective stress ratio

N = number of cycles

m, n = empirical parameters depending on cyclic stress level.

Table 4.1 lists the values of the empirical parameters applicable to the clay tested in expressing axial strain and principal effective stress ratio development at peak cyclic stress with number of cycles.

Table 4.1

Parameters for peak strain and effective stress ratio with number of cycles

Cyclic stress level	a	b	m	n	Coefficient of correlation
0.27	0.041	0.030	1.166	0.004	0.947
0.36	0.061	0.002	1.223	0.009	0.958
0.47	0.099	0.121	1.307	0.032	0.969
0.54	0.130	0.140	1.331	0.073	0.935

For cyclic stress levels higher than 0.55, the increase in peak strain per cycle accelerates after a certain number of cycles, while the effective stress ratio reaches a limiting value corresponding to the monotonic loading failure envelope defined earlier.

Similar observations were reported on Newfield clay under slow one-way cyclic loading:

. a given cyclic stress level separates the clay response into two distinct patterns; and,

. the monotonic loading failure line is the bounding limit for the principal effective stress ratio during cyclic loading.

The cyclic stress level separating the clay response in the two patterns has been used as a threshold stability criterion in one-way undrained cyclic loading by various investigators (70, 75, 77, 96, 98, 127). The response of Cloverdale clay to two-way undrained cyclic loading brings about two considerations related to cyclic stress level:

a) Below the threshold cyclic stress level, residual strain and residual pore water pressure are still increasing with cyclic loading although at a decreasing rate. A true equilibrium plateau is not reached. Hence, failure cannot be ruled out if the number of cycles becomes large.

b) Above the threshold cyclic stress level, strain starts to develop at an accelerating rate per cycle after a given number of cycles. A criterion that would signal the onset of accelerated strain development does not appear to exist.

A threshold stability criterion that would use effective stresses and thus encompass the clay response to the full range of cyclic stress levels regardless of the number of cycles applied would be desirable. The variation in the rate of strain development per cycle is now considered in search for an effective stress threshold stability criterion.

Figure 4.9 shows increase in strain per cycle with number of cycles for a cyclic stress level higher than 0.55.

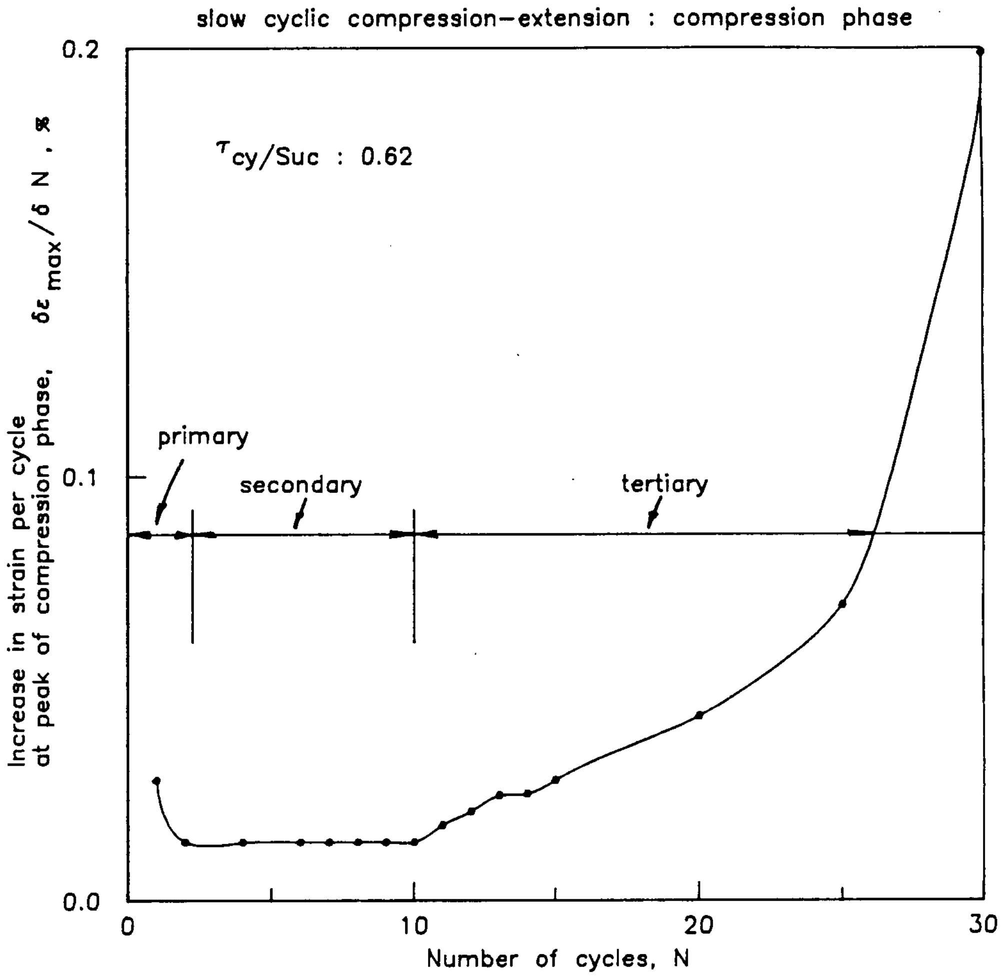


Fig 4.9 Stages of axial strain development in slow two–way undrained cyclic loading of Cloverdale clay to a constant cyclic stress level higher than 0.55.

Three stages may be distinguished:

. a primary stage characterized by development of strain at a decreasing rate per cycle. This stage is limited to few initial cycles;

. a secondary stage characterized by development of strain at an essentially constant rate per cycle. The duration of this stage increases with decreasing cyclic stress level; and,

. a tertiary stage characterized by the development of strain at an increasing rate per cycle.

The duration of the secondary stage increases with decreasing cyclic stress level as shown in figure 4.10 for cyclic stress levels higher than 0.55. For cyclic stress levels less than 0.55 the clay remains indefinitely in the secondary stage.

The rate of peak strain increase per cycle may be related to the increase in principal effective stress ratio during cyclic loading as shown in figure 4.10. An interesting observation emerges then: the onset of the tertiary stage of cyclic loading response may be seen to occur at a unique peak effective stress ratio for all cyclic stress levels higher than 0.55.

In the compression phase the threshold principal effective stress ratio signalling the onset of accelerated strain increase per cycle is about 1.9. A similar behaviour may be noted in figure 4.11 for the extension phase. In the extension phase the threshold principal effective stress ratio is about 2.0. The envelope formed by the threshold peak effective stress ratio on the effective stress path plane may thus be proposed as an effective stress stability criterion against large strain development during undrained cyclic loading.

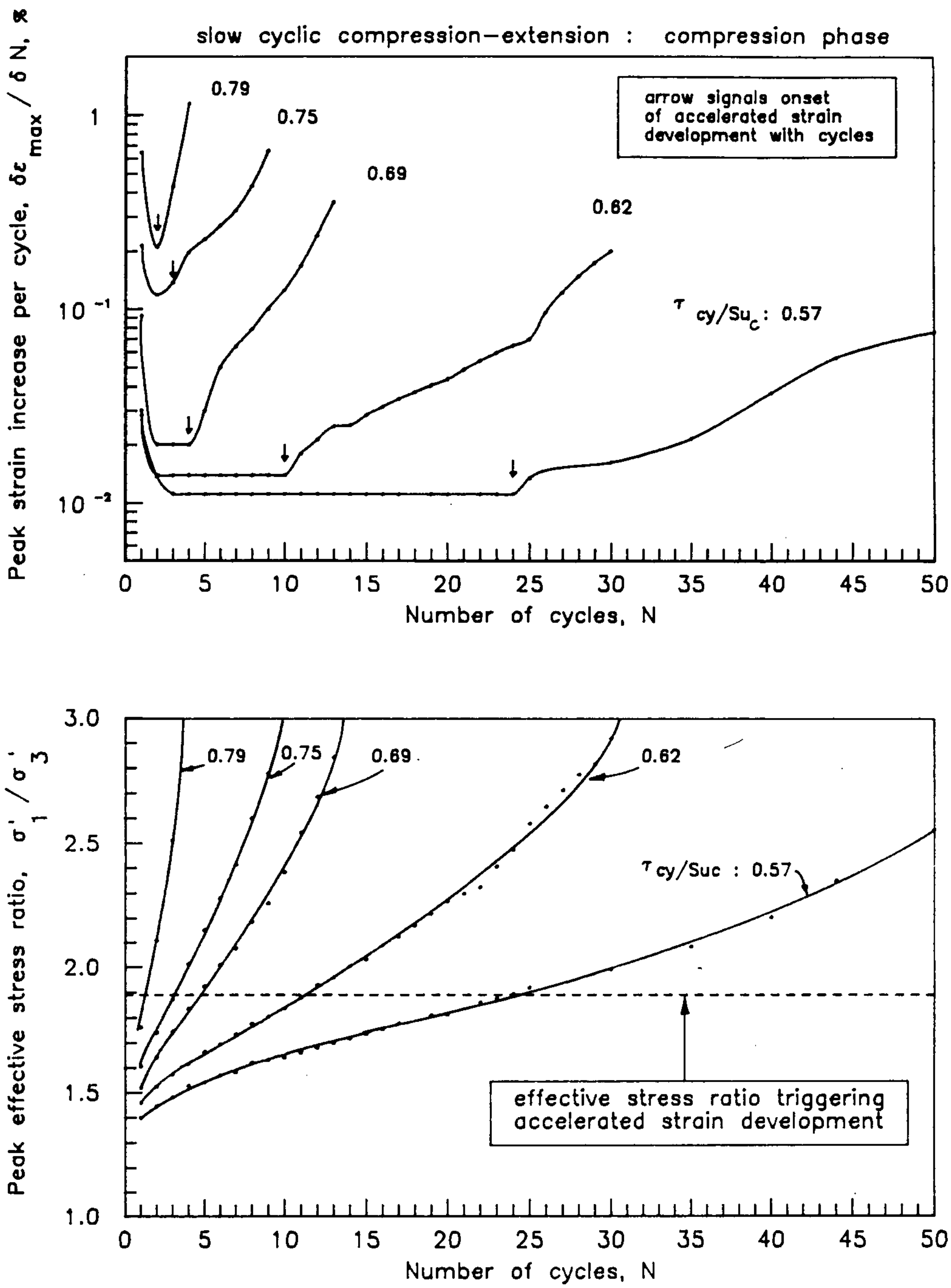
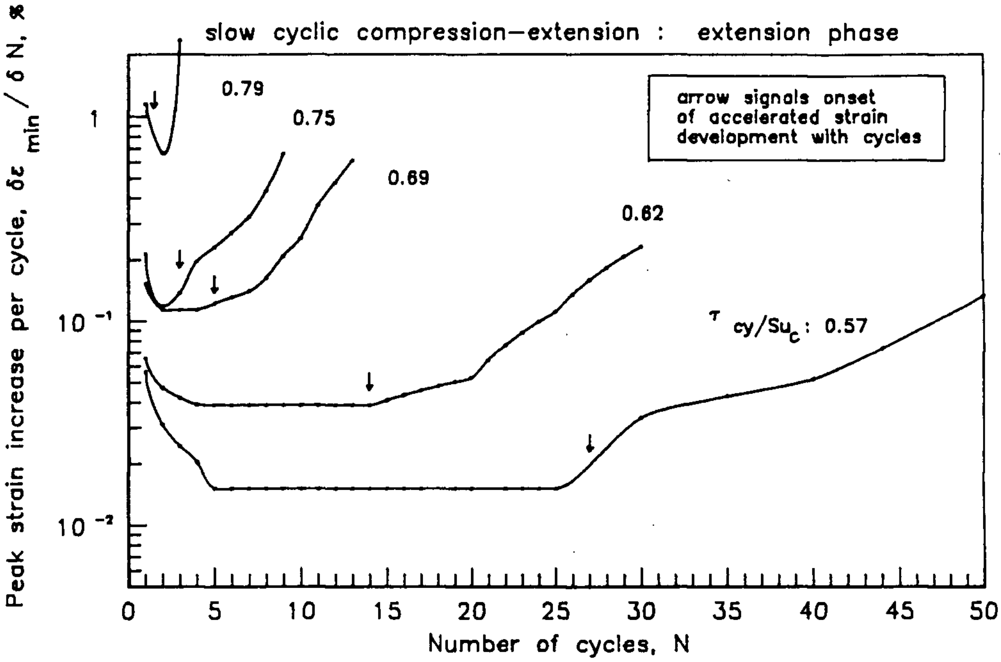


Fig 4.10 Variation of strain increase per cycle at peak of compression phase and location of threshold effective stress ratio triggering accelerated strain increase per cycle in slow two–way undrained cyclic loading.



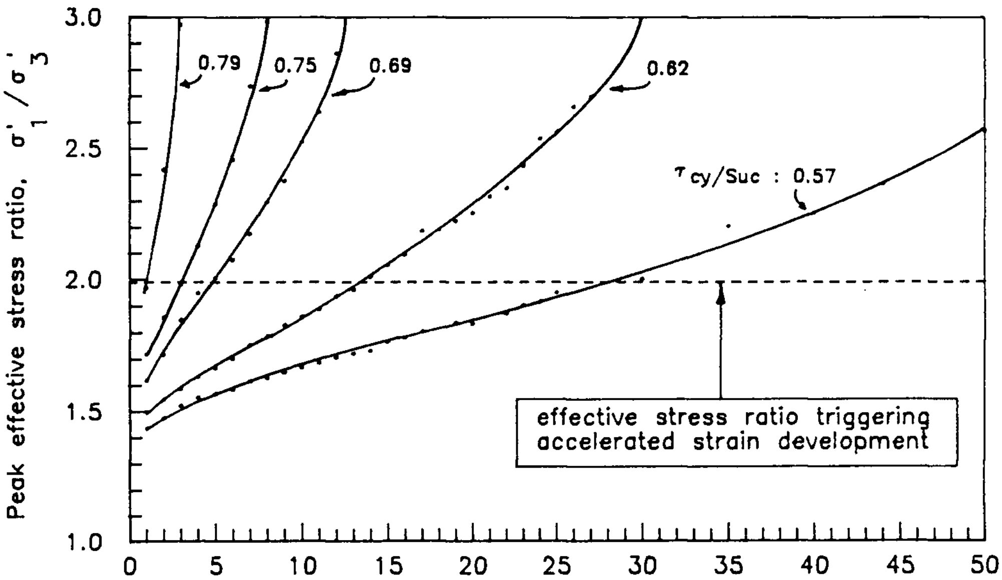


Fig 4.11 Variation of strain increase per cycle at peak of extension phase and location of threshold effective stress ratio triggering accelerated strain increase per cycle in slow two-way undrained cyclic loading.

Figure 4.12 shows the number of cycles required to reach the threshold principal effective stress ratio triggering accelerated strain increase per cycle for cyclic stress levels ranging from 0.55 to 0.8. This plot allows the extrapolation of the test results to other cyclic stress levels within the range considered. For cyclic stress levels below 0.55 the power function defined previously may be used to estimate the number of cycles required to reach the threshold principal effective stress ratio signalling instability. The number of cycles required to reach failure is also shown in figure 4.12 for cyclic stress levels ranging from 0.55 to 0.8. The region between the two curves represents the zone of instability where large strains leading to failure will develop with further cyclic loading.

Figure 4.13 shows the contours of equal axial strains at peak cyclic stress on the effective stress path plane. The stable region is defined below the threshold principal effective stress ratio where the peak strains are less than 0.3 percent. The unstable region lies between the threshold principal effective stress ratio and failure lines where the peak axial strains are larger than 0.3 percent. Under all cyclic stress levels, the clay may reach the unstable region if the number of cycles is sufficiently large to develop a principal effective stress ratios higher than the threshold value. However, for cyclic stress levels less than 0.55, the clay tested would remain in the stable region if the number of cycles is less than 100.

The contours of equal peak axial strains during two-way undrained cyclic loading are different from the essentially linear strain contours during undrained monotonic loading (see figure 4.4). Thus, there is no direct correspondence between the strains developed during two-way undrained cyclic loading and the strains due to undrained monotonic loading. Furthermore, the strain contours of

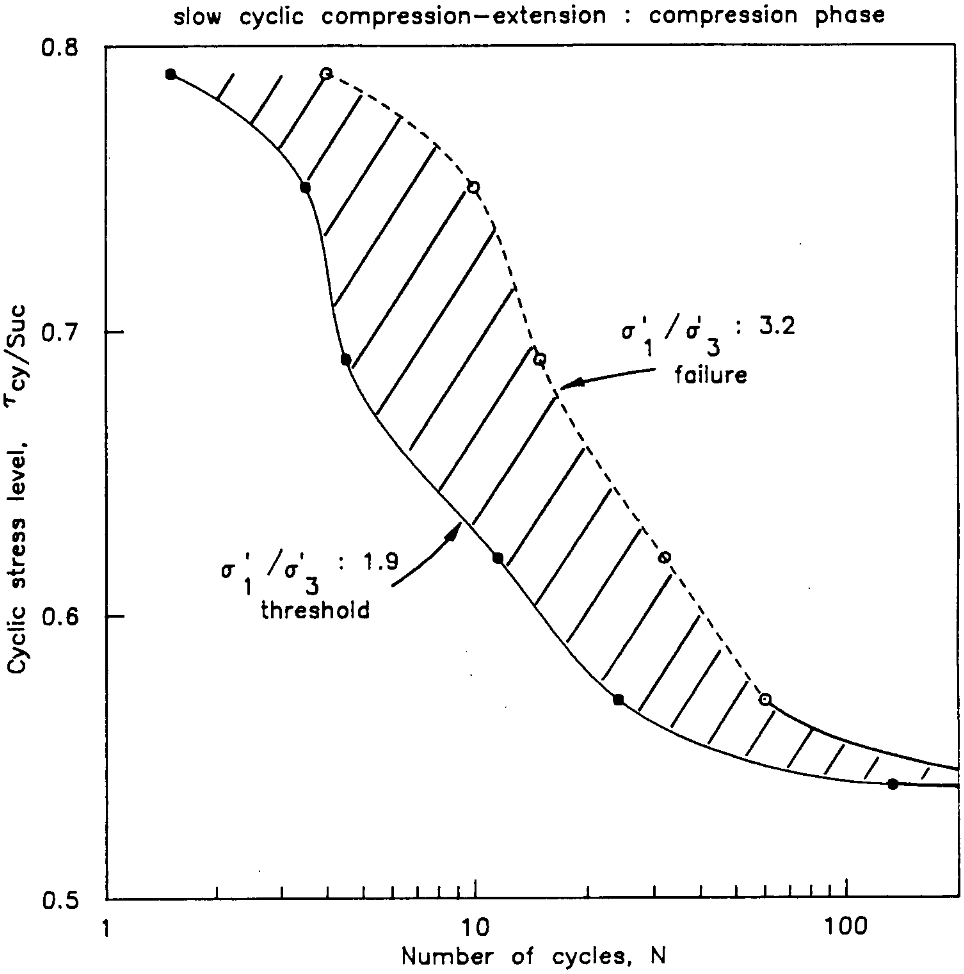


Fig 4.12 Number of cycles to reach the threshold principal effective stress ratio triggerring accelerated strain increase per cycle in slow two-way undrained cyclic loading.

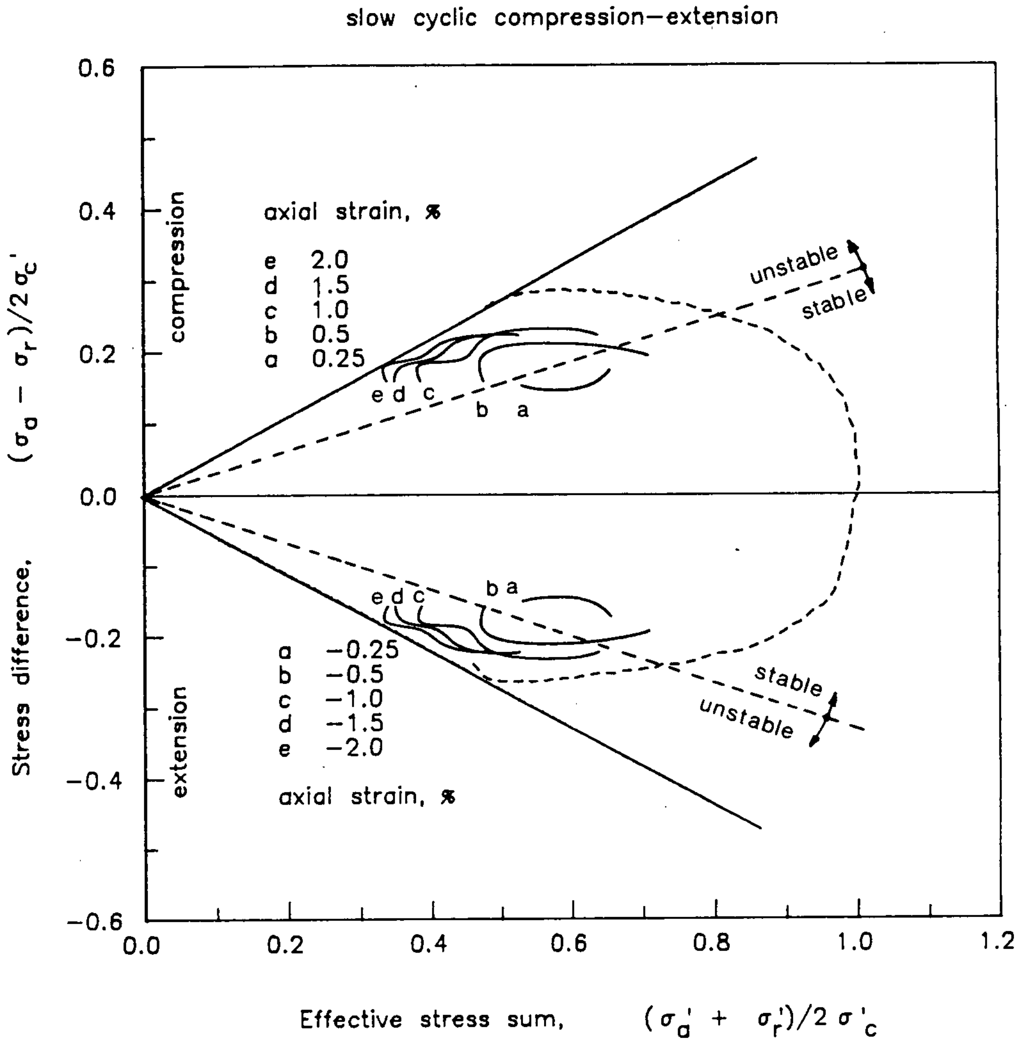


Fig 4.13 Contours of equal axial strains at peak of cyclic stress in slow two–way undrained cyclic loading to various cyclic stress levels.

Cloverdale clay under cyclic loading are also different from the linear strain contours observed on Newfield clay under cyclic loading (96). This difference is due to the absence of strain reversal in one-way cyclic loading of Newfield clay.

Figure 4.14 may be used to estimate the peak axial strain and the principal effective stress ratio developed under a given number of cycles for cyclic stress levels ranging from 0.55 to 0.8. For cyclic stress levels less than 0.55 the empirical power function relating the peak axial strain or the peak principal effective stress ratio to the number of cycles may be used. The peak axial strain and peak principal effective stress ratio developed under a given cyclic stress ratio may also be estimated from the contours of equal number of cycles shown in figure 4.15. For clarity, the contours of equal number of cycles are limited to 20 cycles and cyclic stress levels ranging from 0.55 to 0.8.

The contours of equal number of cycles are plotted on the effective stress path plane in figure 4.16. An interesting observation emerges then: For a given number of cycles at various cyclic stress levels, the effective stress state of the clay lies on a unique curve comparable to the stable state boundary surface in monotonic loading (93, 94).

The stable state boundary surface corresponds to the effective stress path followed during undrained monotonic loading shown in curved dashed lines. Hence, each contour of equal number of cycles on the effective stress path plane represents the gradual collapse of the stable state boundary surface during undrained cyclic loading. In the collapsed stable state boundary surface the symmetry between compression and extension phase around the hydrostatic stress axis is maintained. The concept of a collapsing stable state boundary

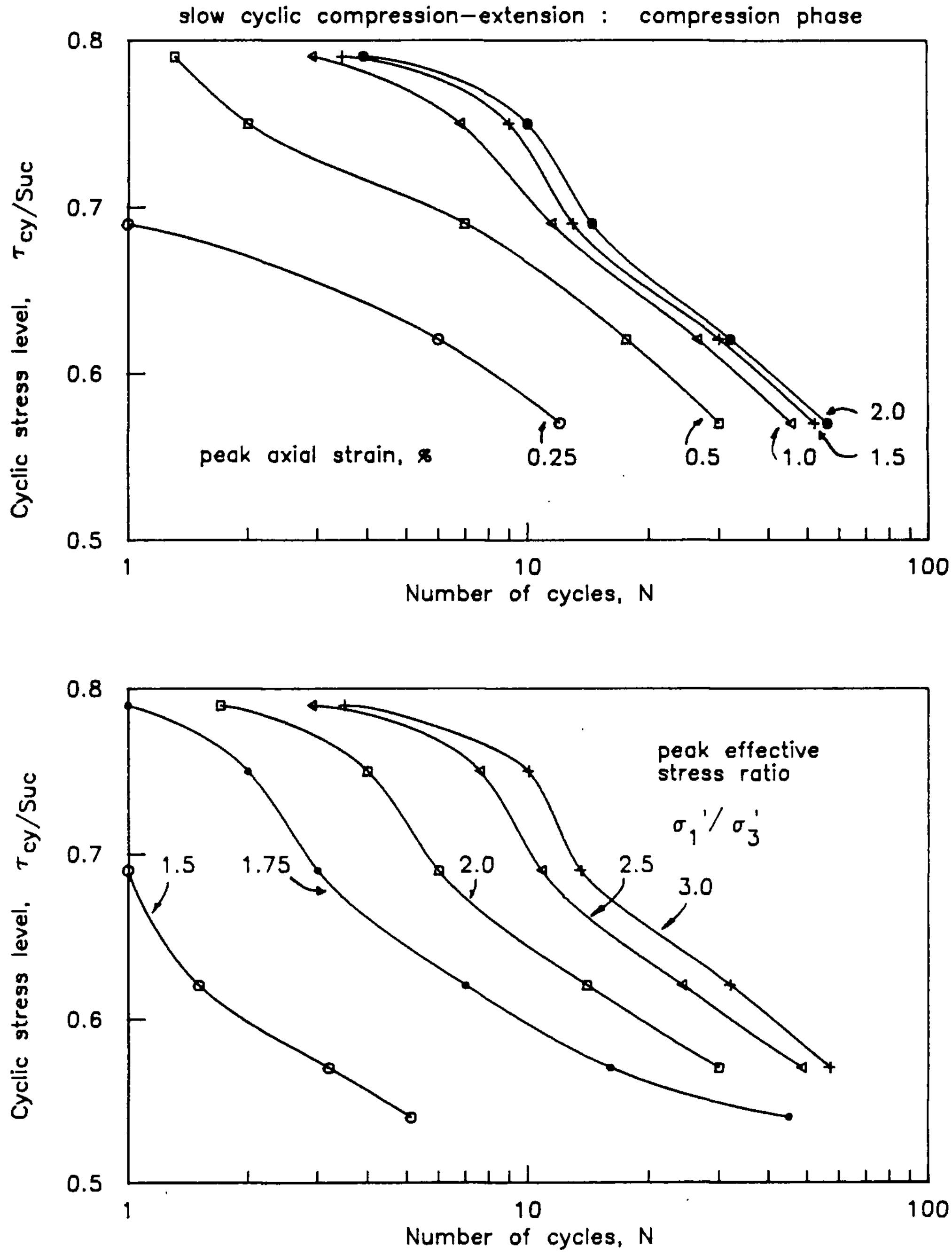


Fig 4.14 Contours of equal peak axial strains and equal peak effective stress ratios in slow two-way undrained cyclic loading to various cyclic stress levels. Compression phase.

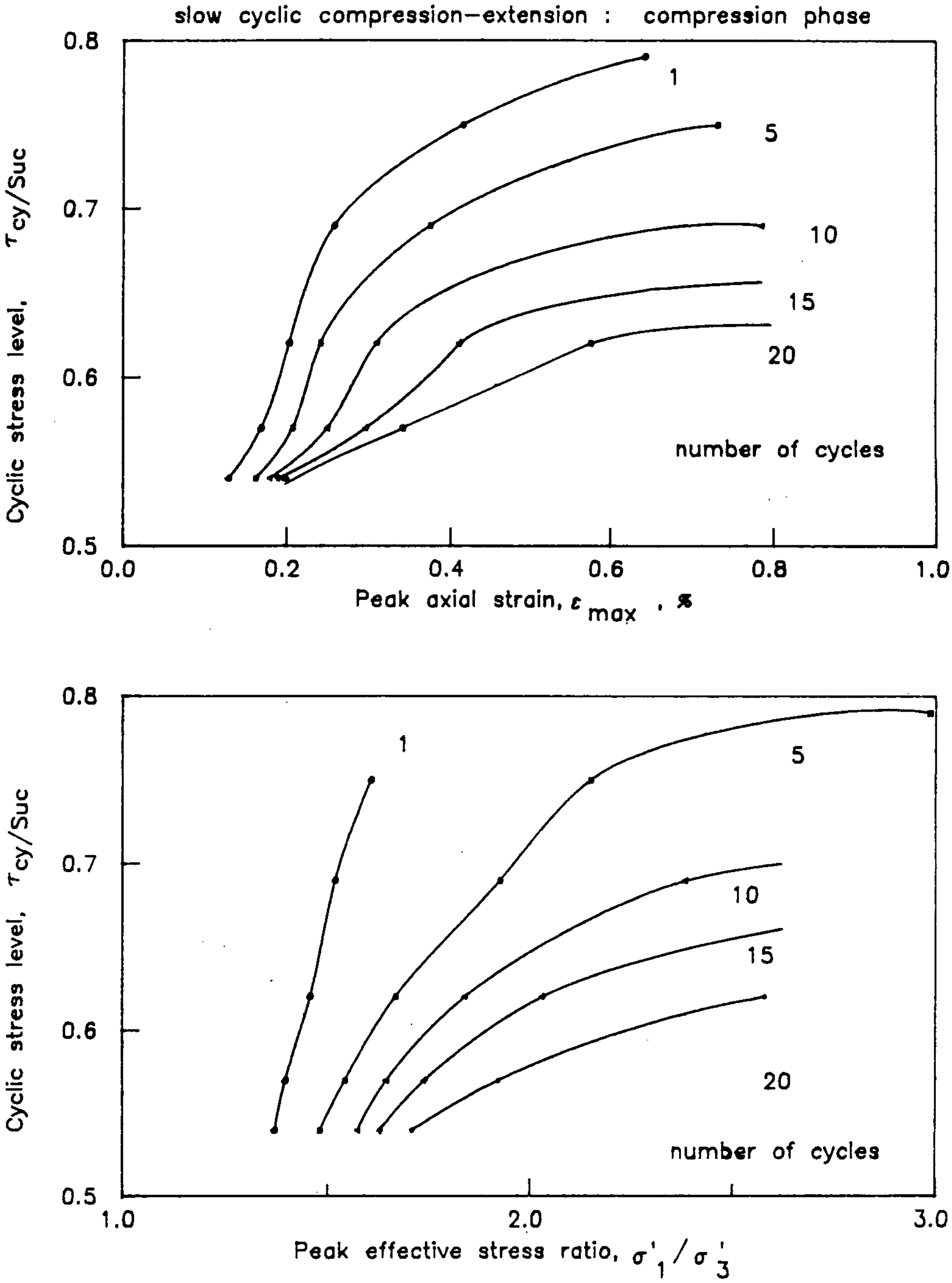


Fig 4.15 Contours of equal number of cycles to predict axial strains and principal effective stress ratios at peak of compression phase for various cyclic stress levels.

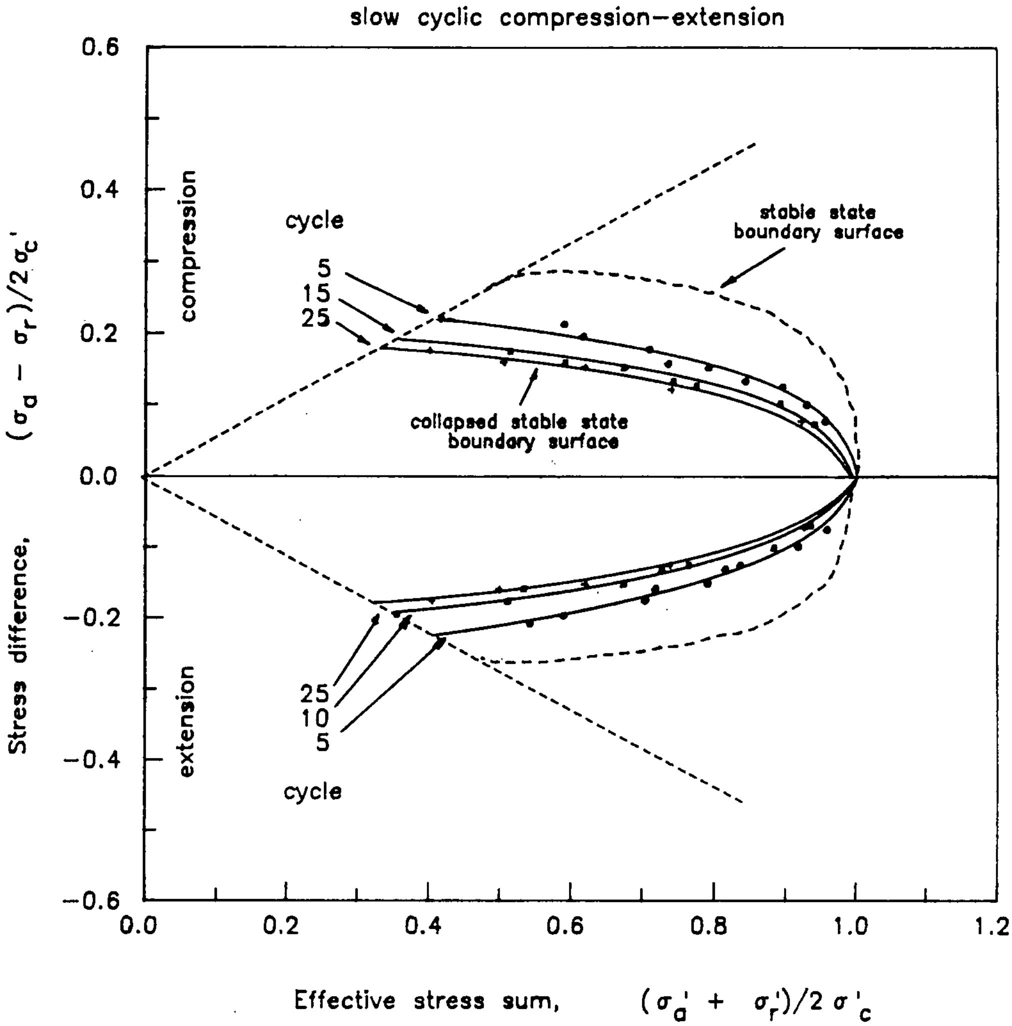


Fig 4.16 Contours of equal number of cycles at peak of cyclic stress on the effective stress path plane in slow two–way undrained cyclic loading.

surface may be useful for the analytical modelling of clay response to undrained cyclic loading.

In analytical modelling of undrained behaviour, the principal effective stress ratio plays an important role in the prediction of strains (93, 120). It is then desirable to relate the development of strains at the peaks of cyclic stress to the corresponding principal effective stress ratio in each phase. Figure 4.17 shows the effect of cyclic stress level on the relationship between peak axial strain and principal effective stress ratio during two-way cyclic loading. The clay response during undrained monotonic loading is shown in dashed lines for reference. The relationship between principal effective stress ratio and peak axial strain depends both on the cyclic stress level and the phase considered. With increasing cyclic stress level, a larger peak strain is developed upon initial loading in compression and this shift is maintained with further loading cycles. The principal effective stress ratio versus strain relationship in the extension phase is softer than in the compression phase. Hence, a given peak principal effective stress ratio corresponds to larger axial strains in extension than in compression. Therefore, when the relationship between principal effective stress ratio and peak strain is used for analytical modelling of clay behaviour, a distinction should be made between the two loading phases in a cycle.

The distinction between each loading phase may be circumvented by considering the loss in clay stiffness during undrained two-way cyclic loading based on peak-to-peak secant modulus. Figure 4.18 shows that the relationship between secant modulus and peak-to-peak axial strain forms a narrow band for the full range of cyclic stress levels considered. The lower limit of the band

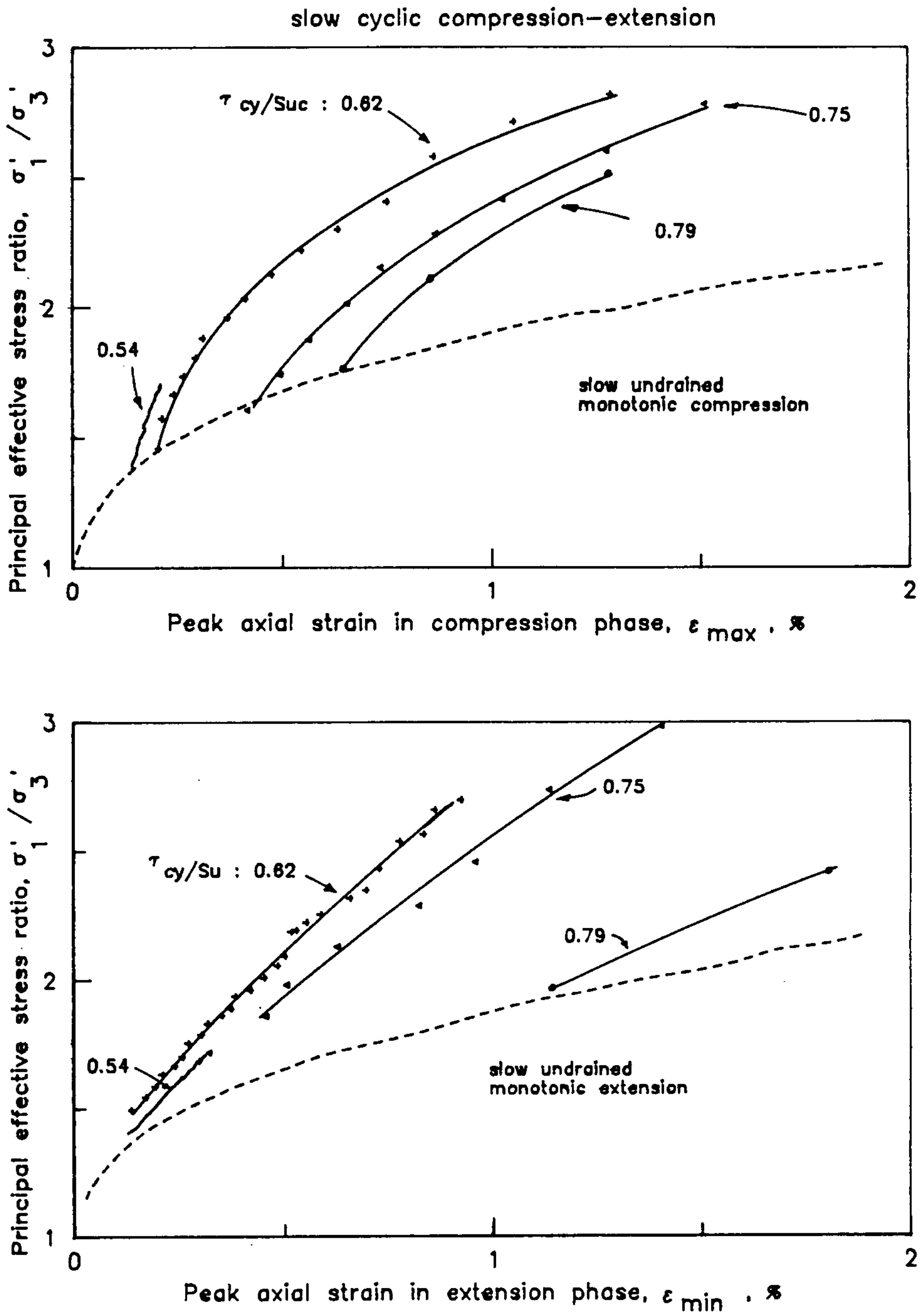


Fig 4.17 Effect of cyclic stress level and loading phase on the relationship between axial strain and principal effective stress ratio at peak of cyclic stress in slow two-way undrained cyclic loading.

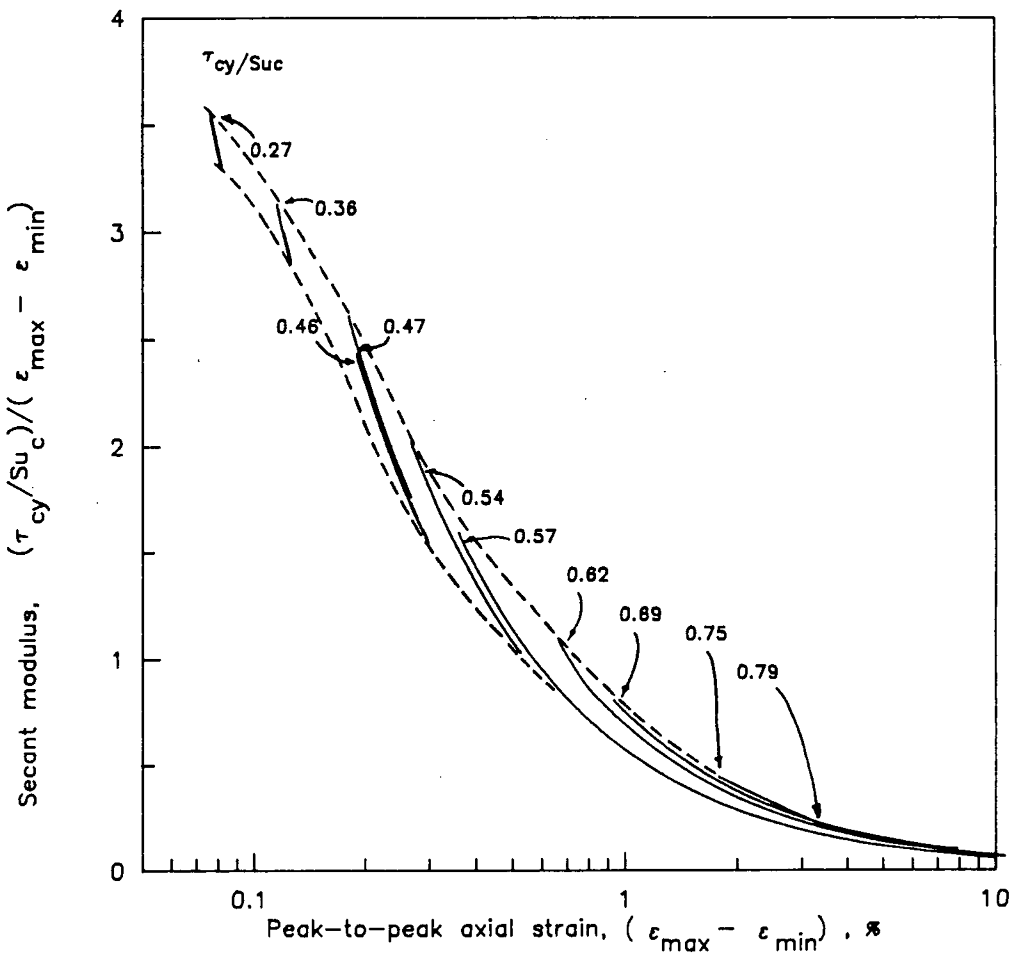


Fig 4.18 Relationship between secant modulus and peak-to-peak axial strain during slow two-way undrained cyclic loading to various cyclic stress levels.

constitutes a relationship comparable to the attenuation curve determined from constant strain amplitude cyclic loading and resonant column tests and may be used in a similar way (51, 52, 102).

4.3.2 Residual stress-strain response

The determination of residual strain and pore water pressure developed during undrained cyclic loading is useful in assessing the effect of cyclic events on clay foundations. The insitu measurement of residual strain and pore water pressure could be used to verify the prediction of foundation performance under cyclic loads. The residual stress-strain conditions could also be used to assess clay strength and stiffness available in postcyclic loading. Clay foundations could then be designed to maintain residual stress-strain conditions within tolerable limits.

Figure 4.19 shows the development of residual strain and residual pore water pressure with cyclic loading under various cyclic stress levels. For all cyclic stress levels, the residual strains are on the extension side and the residual pore water pressure is positive. Similarly to the peak stress-strain response with number of cycles, two response patterns may be distinguished depending on the cyclic stress level.

For cyclic stress levels less than about 0.55 the development of residual strain and pore water pressure with number of cycles tend toward equilibrium plateaus. However true equilibrium is not reached and the residual strain and pore water pressure continue to increase although at a decreasing rate with further cycles of loading.

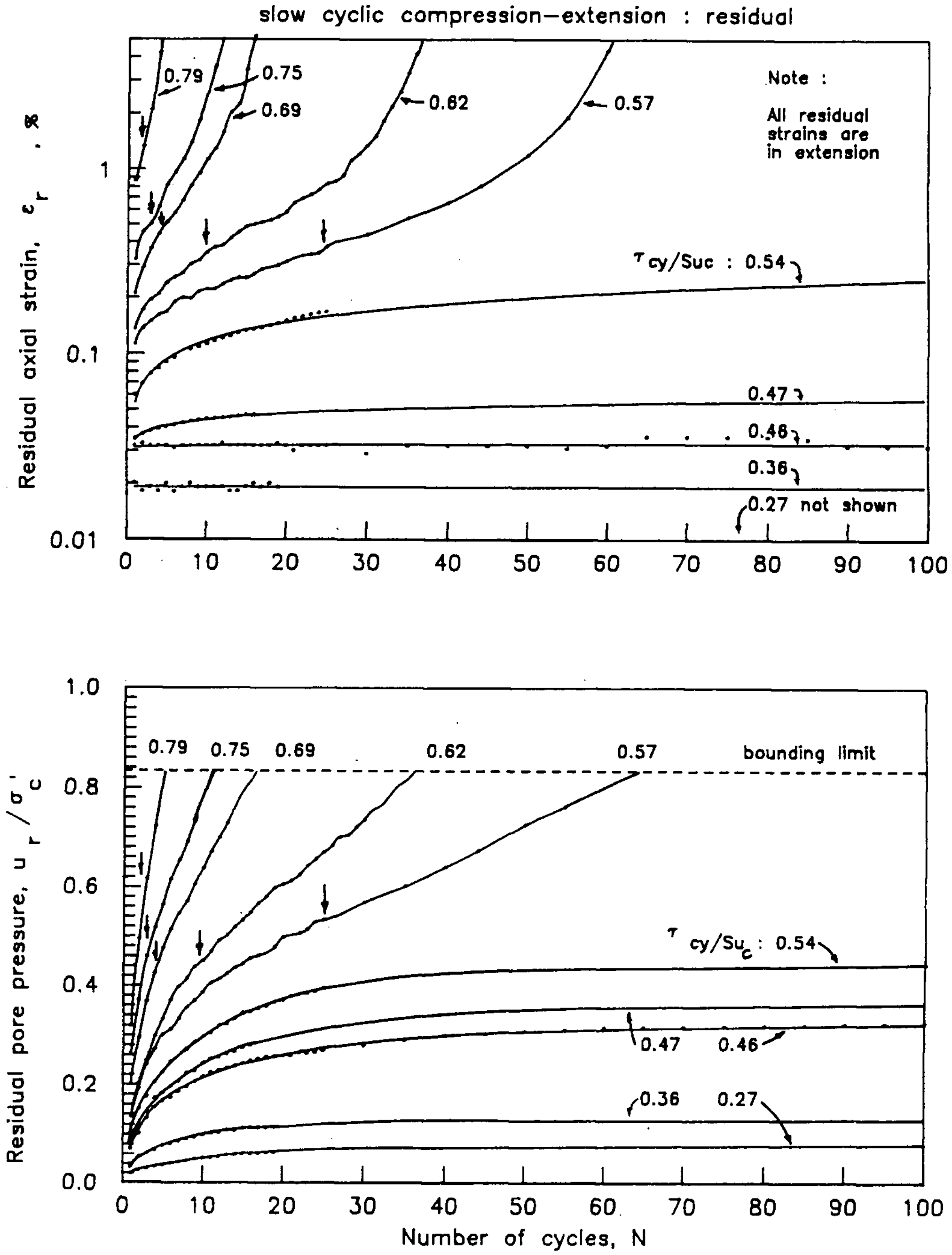


Fig 4.19 Development of residual axial strain and residual pore pressure in slow two–way undrained cyclic loading to various cyclic stress levels.

For cyclic stress levels less than 0.55 the maximum residual pore water pressure developed remains less than 50 percent of the consolidation stress.

A power function also decribes well the development of residual strains with number of cycles as follows:

$$\epsilon_r = a' N^{b'}$$

where:

ϵ_r = residual axial strain, %

N = number of cycles

a', b' = empirical parameters depending on cyclic stress level.

A similar power function describes the development of residual pore water pressure with number of cycles for cyclic stress level less than 0.55:

$$u_r / \sigma_c' = m' N^{n'}$$

where:

u_r / σ_c' = normalized residual pore pressure

N = number of cycles

m', n' = empirical parameters depending on cyclic stress level.

Table 4.2 lists the values of the empirical parameters for the clay tested in expressing residual axial strain and pore water pressure development with number of cycles.

Table 4.2

Parameters for residual strain and pore pressure with number of cycles

Cyclic stress level	a'	b'	m'	n'	Coefficient of correlation
0.27	0.009	0.046	0.019	0.283	0.954
0.36	0.019	0.002	0.039	0.261	0.936
0.47	0.034	0.110	0.086	0.311	0.967
0.54	0.054	0.333	0.111	0.299	0.934

For cyclic stress levels higher than 0.55, the residual strain starts to accelerate after a given number of cycles while the residual pore water pressure tends to increase linearly with number of cycles before reaching a limit equal to about 80 percent of the consolidation stress. The straight arrows in figure 4.19 indicate the points where the threshold principal effective stress ratio triggering accelerated strain increase per cycle is reached. The onset of instability signalled by the threshold principal effective stress ratio also corresponds to the acceleration of residual strain increase per cycle. It further corresponds to the onset of linear increase in residual pore water pressure with number of cycles.

The contours of equal residual strains and equal residual pore pressures are shown in figure 4.20. These contours allow the extrapolation of the test results to other cyclic stress levels ranging from 0.5 to 0.8. The contours of equal residual strains during fast cyclic loading of Cloverdale clay (57) and Drammen clay (4) are different from the contours obtained in slow cyclic loading tests. The difference being more marked in the region of small number of cycles. This difference in strain contours may be due to the nonequalized pore water pressure in fast cyclic tests. The contours of equal number of cycles shown in figure 4.21 also allow an estimate of the residual strain and pore water pressure developed under a given number of cycles for cyclic stress levels ranging from 0.55 to 0.8.

The development of strains under constant cyclic stress amplitude represents a progressive degradation in clay stiffness. This change in stiffness may be directly related to the development of residual pore water pressure. Figure 4.22 shows the loss of clay stiffness with increasing residual pore water pressure under various cyclic stress levels. The peak-to-peak secant modulus decreases essentially linearly with increasing residual pore water pressure for each cyclic stress level. The slope of the linear function between secant modulus and residual pore water pressure decreases with increasing cyclic stress level. For cyclic stress levels higher than about 0.55 a marked stiffness degradation occurs when residual pore pressures exceed about 50 percent of the consolidation stress. For all cyclic stress levels, the relationship between stiffness and residual pore water

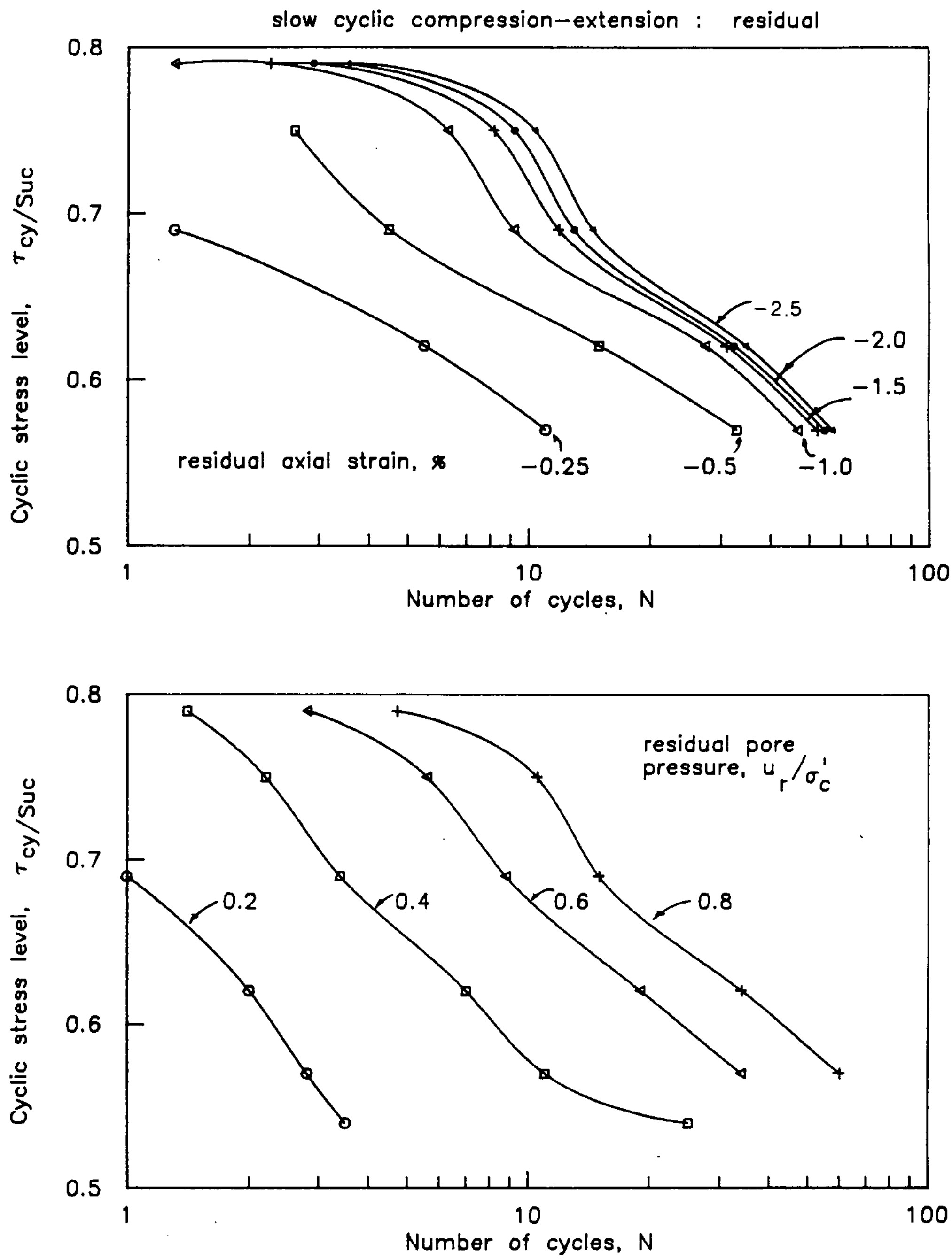
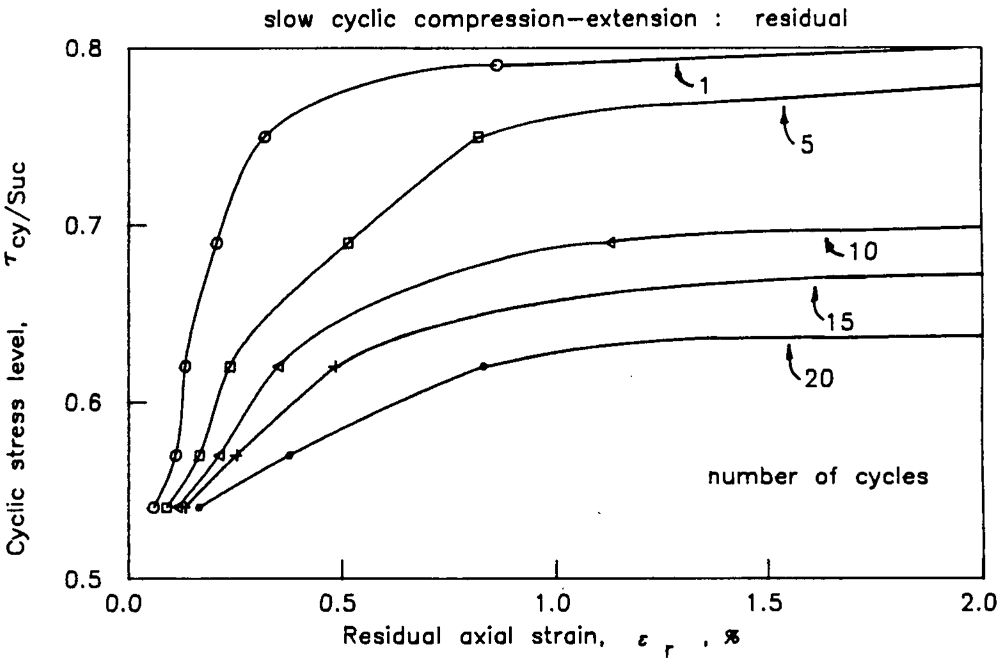


Fig 4.20 Contours of equal residual axial strains and equal residual pore pressure in slow two-way undrained cyclic loading to cyclic stress levels higher than 0.55.



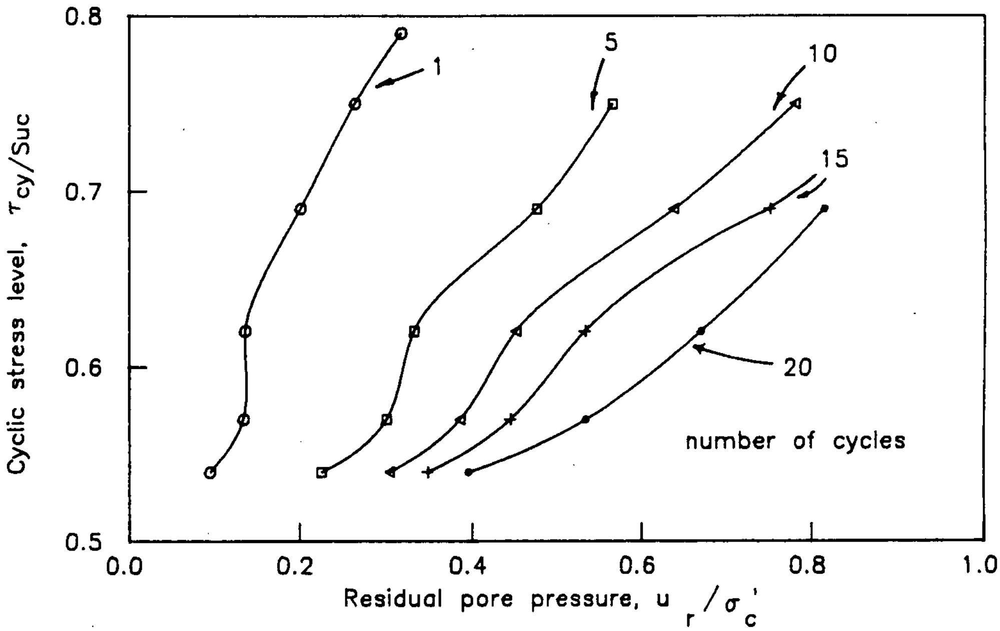


Fig 4.21 Contours of equal number of cycles to predict residual strain and residual pore pressure in slow two−way undrained cyclic loading to cyclic stress levels higher than 0.55.

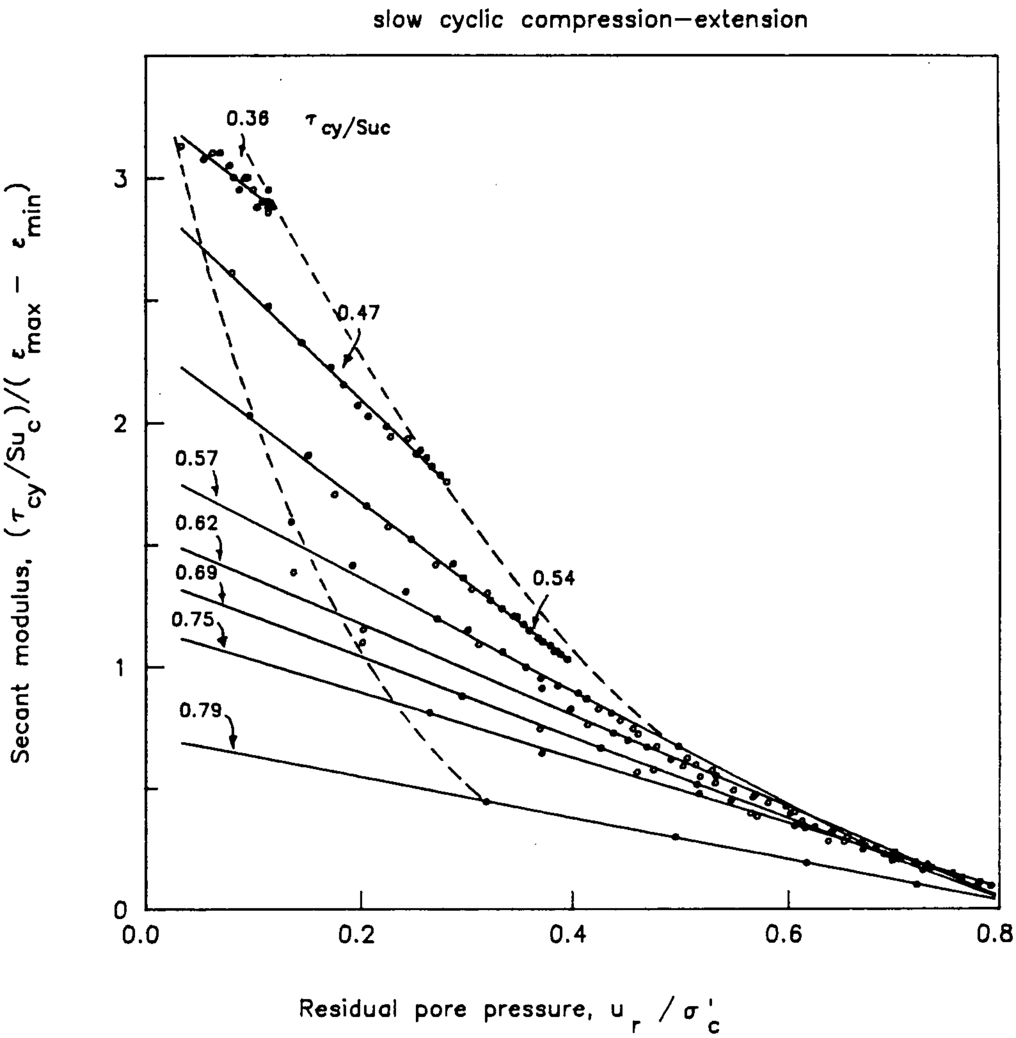


Fig 4.22 Relationship between secant modulus and residual pore pressure in slow two-way undrained cyclic loading to various cyclic stress levels.

pressure is bounded by two envelopes. These bounding envelopes delineate the range of stiffness available during cyclic loading for each cyclic stress level.

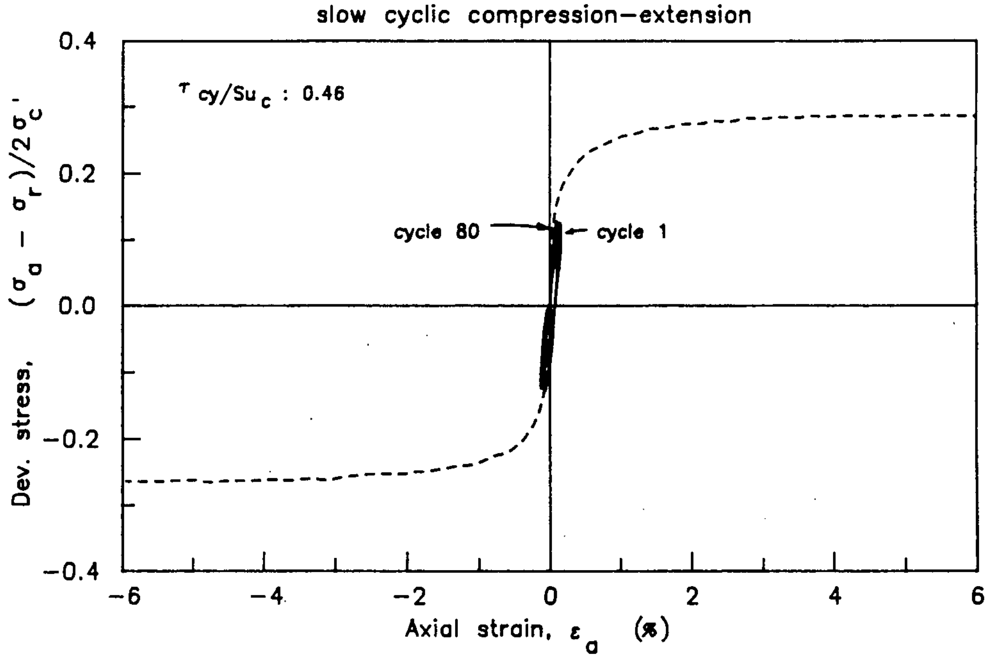
The change in stiffness with number of cycles is a discrete measure of the overall changes in clay stress-strain response within each cycle. The complete stress-strain response of the clay to cyclic loading is reflected by the work dissipated within each cycle and the associated damping developed. Both cumulative hysteretic work and damping ratio are likely to be related to residual strain and residual pore water pressure generated during undrained cyclic loading.

4.3.3 Hysteresis work and damping ratio

The determination of hysteretic work and damping ratio during cyclic loading of clay requires estimating the area of the stress-strain hysteresis loop within each cycle (102). In this study both computer calculations and planimetry were used to estimate the stress-strain loop areas. Both methods resulted in identical values of hysteretic work.

Figure 4.23 shows the typical stress-strain hysteresis loops of normally consolidated Cloverdale clay in slow two-way undrained cyclic loading at two cyclic stress levels. The response of the clay to undrained monotonic loading is also shown by dashed lines for reference.

For a cyclic stress level less than about 0.55, the stress-strain hysteresis loops maintain about the same size and show a limited migration toward extension. For a cyclic stress level higher than about 0.55, the stress-strain hysteresis loops increase in size and show an accelerated migration toward the



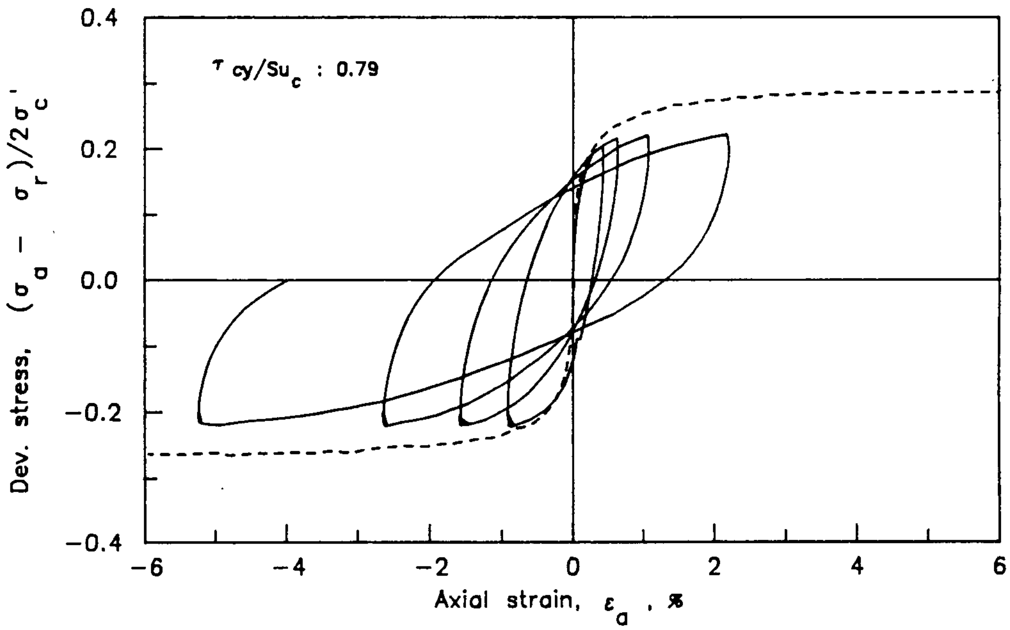
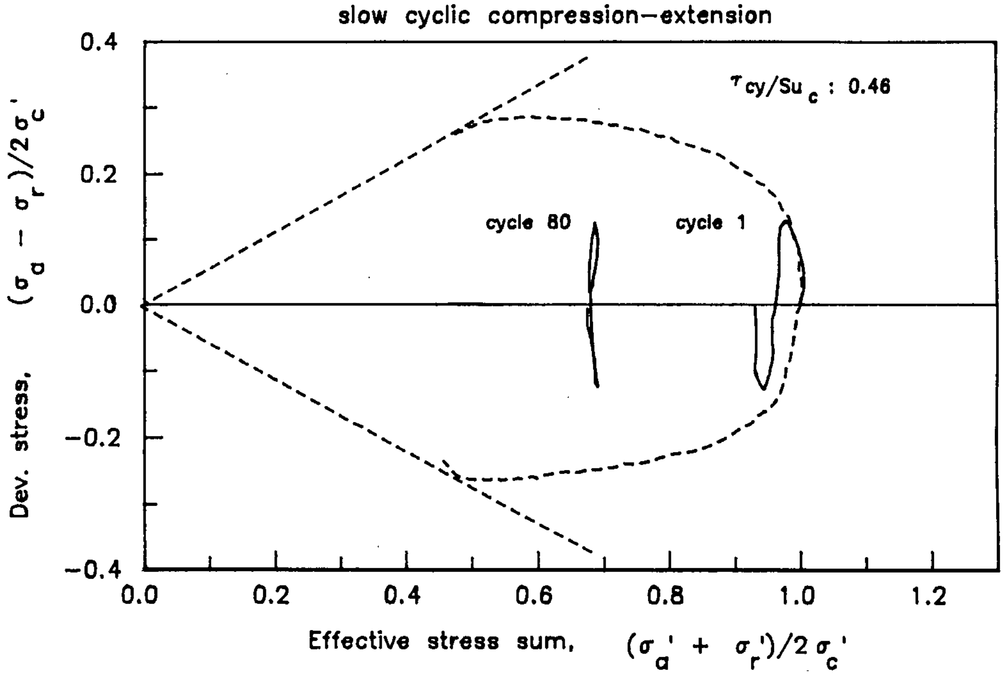


Fig 4.23 Stress–strain hysteresis loops for Cloverdale clay in slow two–way undrained cyclic loading to two constant cyclic stress levels.

extension side. The clay stiffness upon unloading from peak of cyclic stress is high and appears to be independent of strain level and loading phase. Within each cycle the stiffness decreases markedly when stress-strain straddles the zero cyclic stress axis. This behaviour could be due to the sudden principal stress rotation when the cyclic stress crosses the hydrostatic stress axis. Principal stress rotation changes the intermediate principal stress from minor to major when moving from compression to extension and from minor to major when returning into compression. It also involves changing the major principal stress direction from coincident with material deposition to perpendicular to material deposition.

Figure 4.24 shows the effective stress path followed by Cloverdale clay during two-way undrained cyclic loading to two cyclic stress levels. For a cyclic stress level less than 0.55, the migration of the effective stress path toward the origin of stress axes is limited to a maximum of about 50 percent of the consolidation stress. For a cyclic stress level higher than 0.55, the migration continues until it becomes bounded by the monotonic loading failure line. The residual effective stress is then limited to a maximum of about 20 percent of the consolidation stress. The stress-strain response of Cloverdale clay to two-way undrained cyclic is complex: it is both cyclic stress level and cycle number dependent. There is no reason, a priori, to believe that the correlation between cumulative hysteretic work and residual pore water pressure may be independent of cyclic stress level.

Figure 4.25 shows the relationship between cumulative hysteretic work, residual strain and residual pore water pressure for Cloverdale clay. For cyclic stress levels less than about 0.55, cumulative hysteretic work continues to



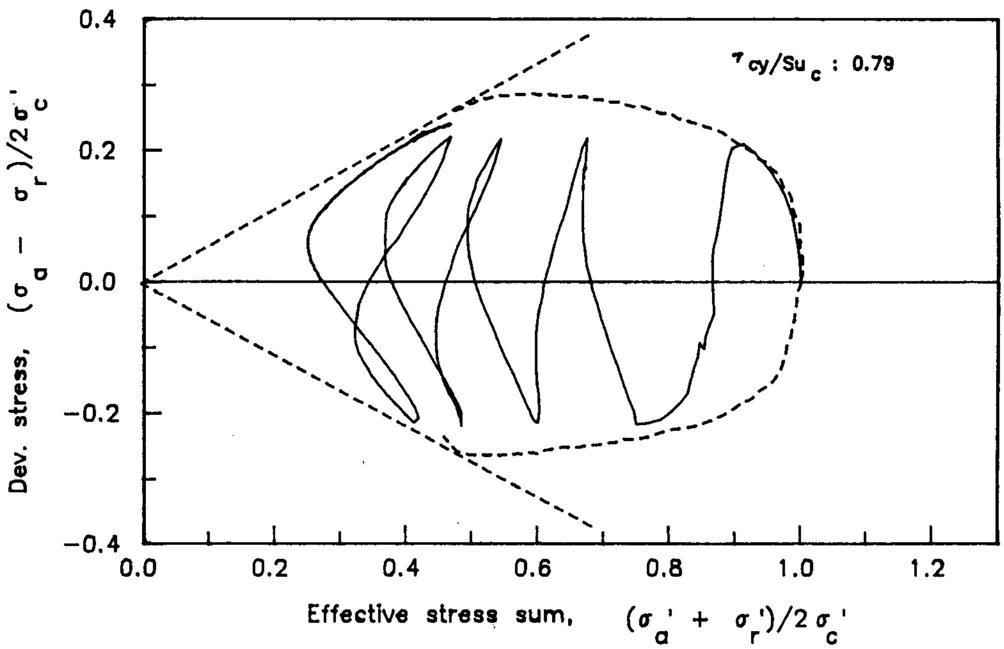


Fig 4.24 Effective stress path for Cloverdale in slow two—way undrained cyclic loading to two constant cyclic stress levels.

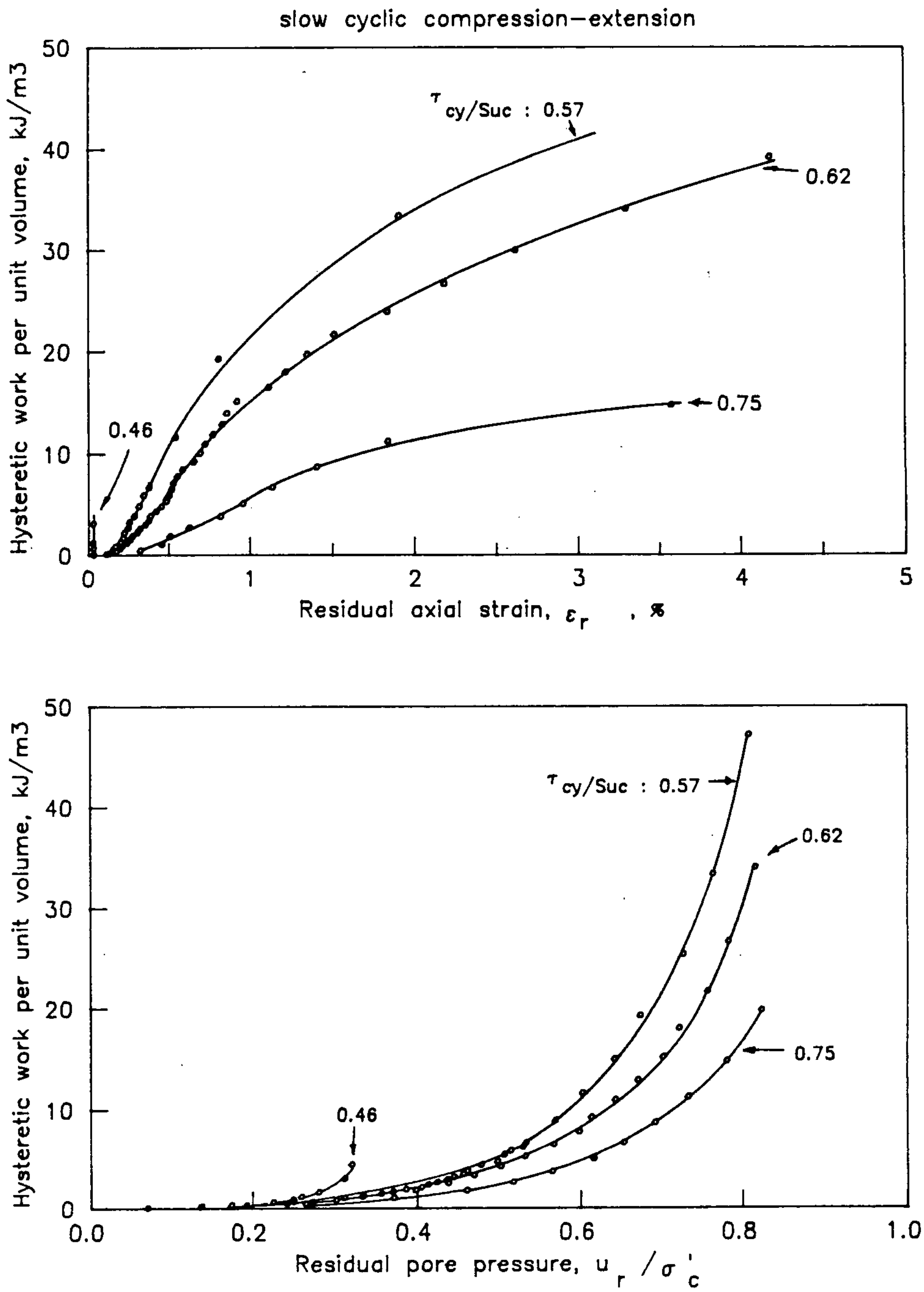


Fig 4.25 Relationship between hysteretic work, residual axial strain and residual pore pressure during slow two—way undrained cyclic loading to various cyclic stress levels.

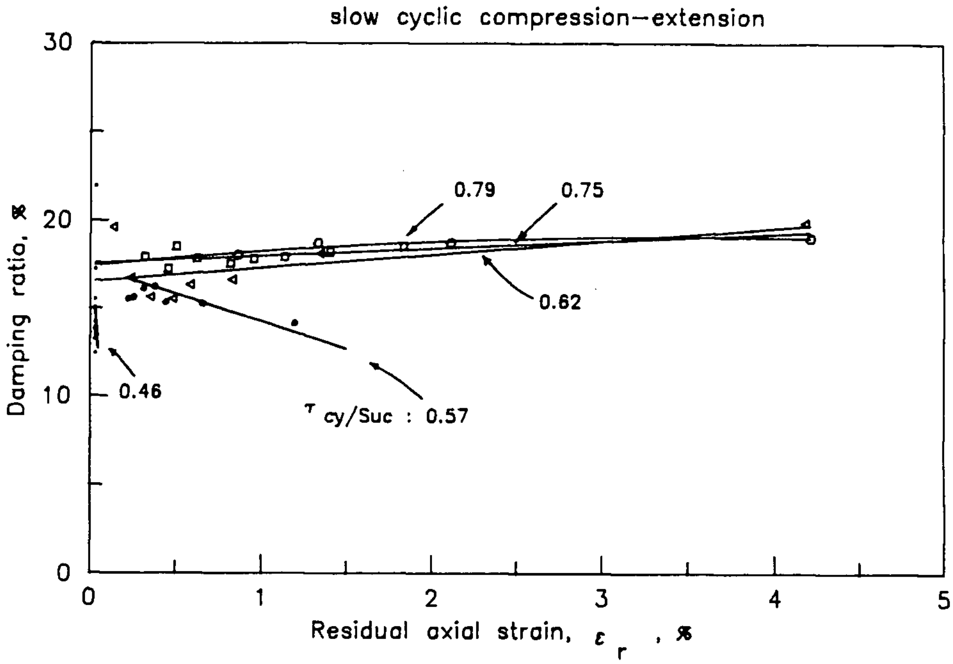
increase with further loading cycles despite the apparent equilibrium plateau reached by residual strain and pore water pressure. For cyclic stress levels higher than 0.55, the cumulative hysteretic work until a given value of residual strain or residual pore water pressure decreases with increasing cyclic stress level. These observations are contrary to previous findings from fast cyclic tests on clay promoting a unique relationship between cumulative hysteretic work and residual pore water pressure (32, 57). The unreliable pore water pressure measurement during fast cyclic loading would clearly be the cause of the discrepancy between the results of slow and fast tests.

Cumulative hysteretic work is a lumped function that includes effects of the following parameters:

. cyclic stress level;
. cumulative strain level; and,
. number of cycles.

Cumulative hysteretic work may be considered as a measure of cumulative damage caused by cyclic loading. Likewise cumulative residual pore water pressure may be considered as a measure of cumulative damage during undrained cyclic loading. Both definitions of cumulative damage are fatigue parameters that depend on the cyclic stress level. The response of Cloverdale clay shows that the dependence of the fatigue parameters on cyclic stress level is maintained when the two parameters are related.

Figure 4.26 shows the relationship between damping ratio, residual strain and residual pore water pressure. It may be seen that damping ratio is essentially



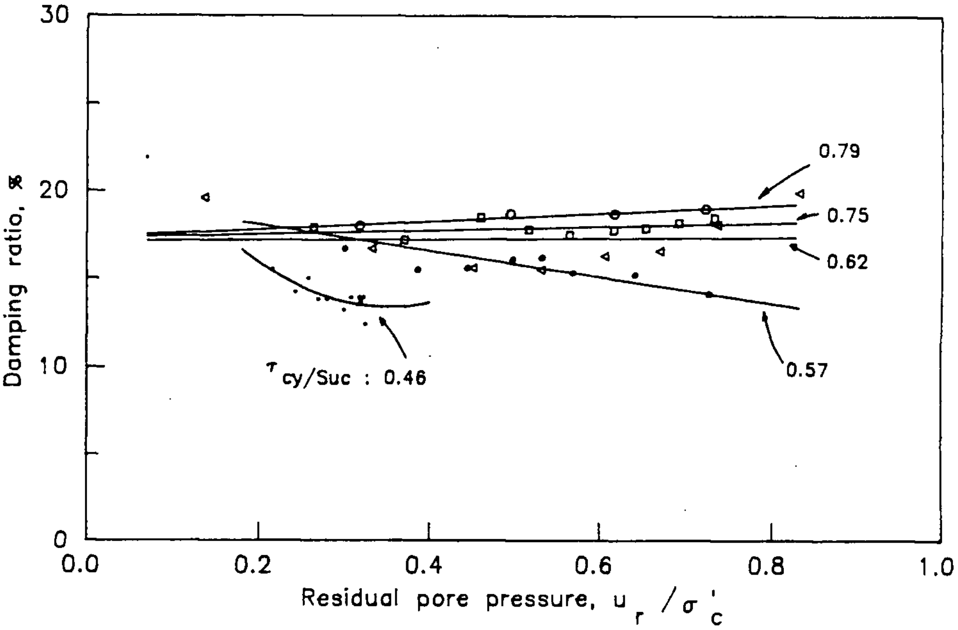


Fig 4.26 Relationship between damping ratio, residual axial strain and and residual pore pressure during slow two–way undrained cyclic loading to various cyclic stress levels.

independent of cyclic stress level. A similar observation was reported for Drammen clay under two-way cyclic loading. This behaviour may be related to the open and nonsymmetric hysteresis stress-strain loops obtained particularly large strains develop under high cyclic stress levels. Therefore, the effect of cyclic stress level must be taken into account in the effective stress analysis of hysteretic phenomena during undrained cyclic loading of clays.

Another factor that should be taken into account is the initial direction of cyclic loading with respect to the natural direction of material deposition.

4.3.4 Effect of initial direction of cyclic loading

The effect of the initial direction of loading on the response of Cloverdale clay to slow two-way undrained cyclic loading is shown in figure 4.27. Cyclic compression-extension (c/e) response is compared to cyclic extension-compression (e/c) response for a cyclic stress level approximately equal to 0.7. Cyclic e/c generates larger peak axial strains than cyclic c/e. Residual strains are about the same for the two modes of cyclic loading but develop in the direction opposite to the initial direction of loading. Cyclic e/c generates larger residual pore pressures than cyclic c/e. Therefore, residual pore water pressure would be better related to peak axial strain development than to residual strains. A similar dependence of stress-strain response on initial loading direction was reported for Cloverdale clay in fast cyclic tests (57).

Figure 4.28 shows the development of principal effective stress ratio with number of cycles at peak of cyclic stress in each phase. Cyclic e/c mobilizes increasingly larger peak effective stress ratios than cyclic c/e. This observation

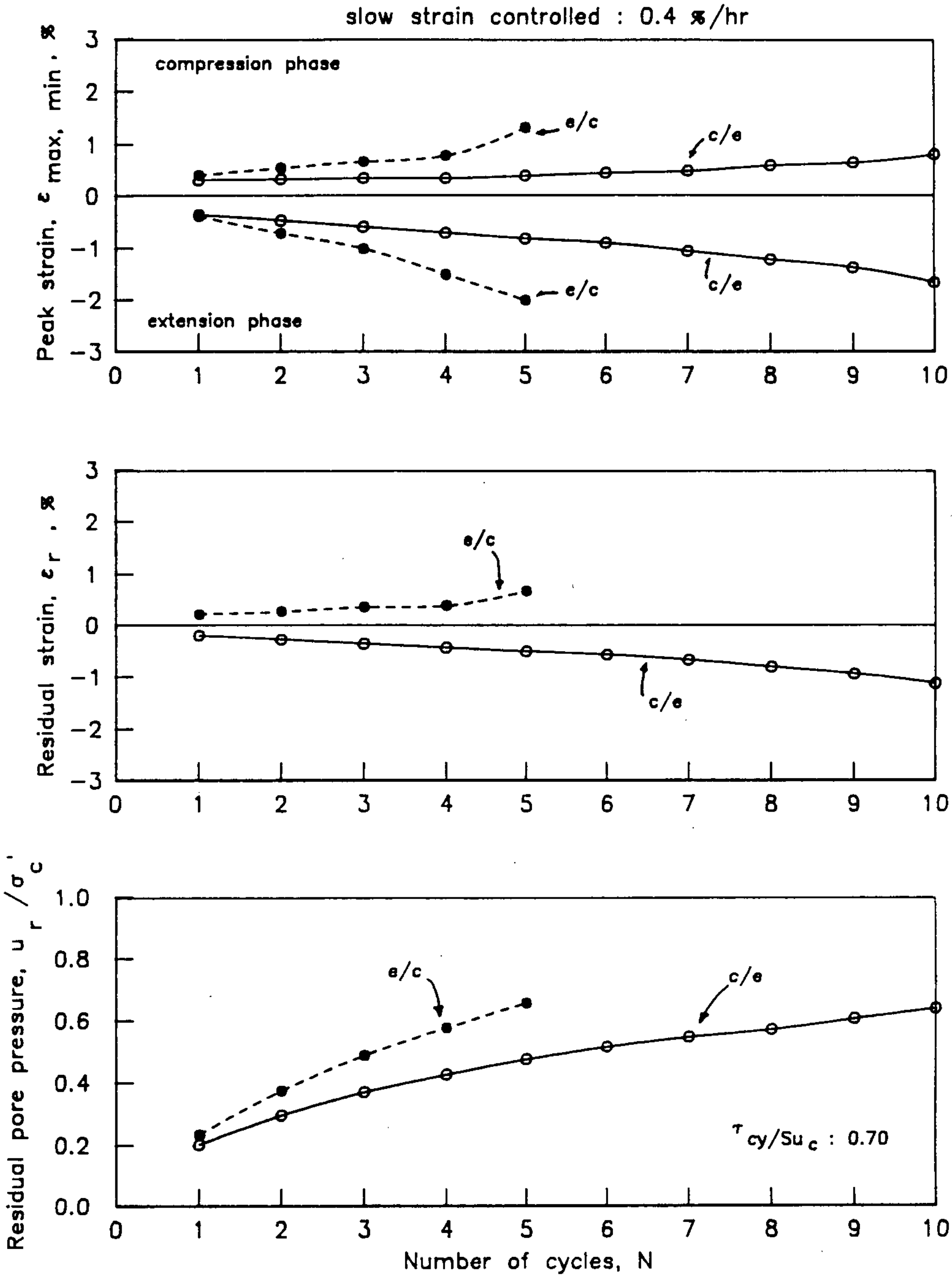


Fig 4.27 Effect of initial direction of loading on clay response to slow two-way undrained cyclic loading to a constant cyclic stress level.

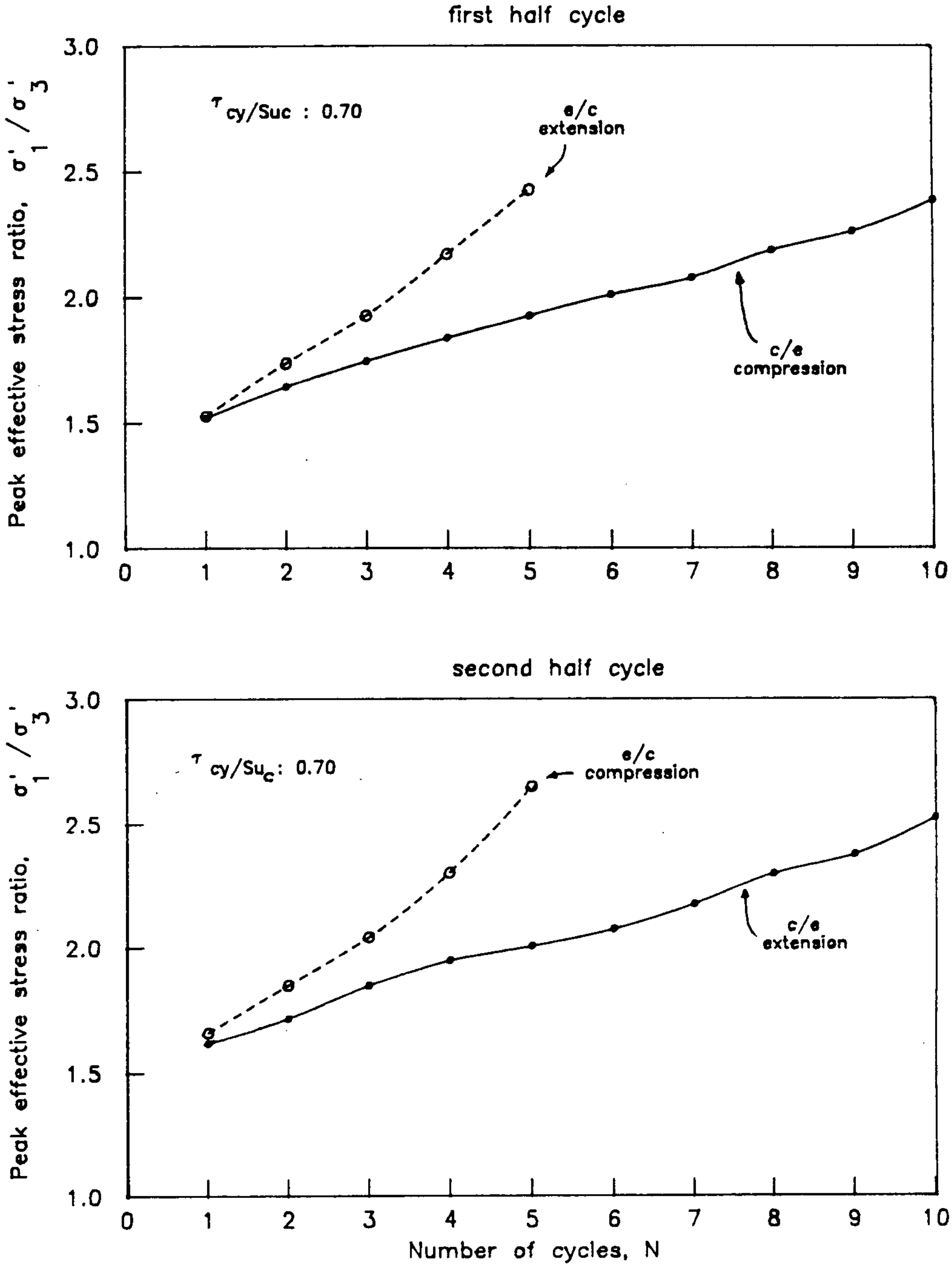


Fig 4.28 Effect of initial direction of loading on development of principal effective stress ratio at peak of cyclic stress in slow two-way undrained cyclic loading.

would be consistent with larger peak strains developed by cyclic extension-compression if the relationship between principal effective stress ratio and strain at peak of cyclic stress were unique. However, it was shown earlier that such relationship in the extension phase is softer than in the compression phase (see figure 4.17). Figure 4.29 shows that this trend is maintained regardless of initial loading direction. Hence, for the same effective stress ratio, peak strains are invariably larger in extension than in compression. This relationship explains that in extension-compression loading peak axial strains are larger than in compression-extension loading for the same number of cycles.

Figures 4.30 and 4.31 show the effect of initial direction of loading on the complete stress-strain response of Cloverdale clay to two-way undrained cyclic loading at the same cyclic stress level. For the same number of cycles, cyclic loading initiated in extension causes larger stiffness degradation than cyclic loading initiated in compression. Correspondingly, the effective stress path for loading initiated in extension migrates toward the stress axes origin at a faster rate than loading initiated in compression. The change in residual pore water pressure between cycles decreases as the effective stress path approaches the failure line. Consequently this would explain that cyclic extension-compression suffers less pore water pressure nonequalization than cyclic compression-extension for the same number of cycles as was indicated by postcyclic residual pore water pressure in fast tests.

These observations show that the initial direction of loading plays an important role in the stress-strain response of clay to two-way undrained cyclic

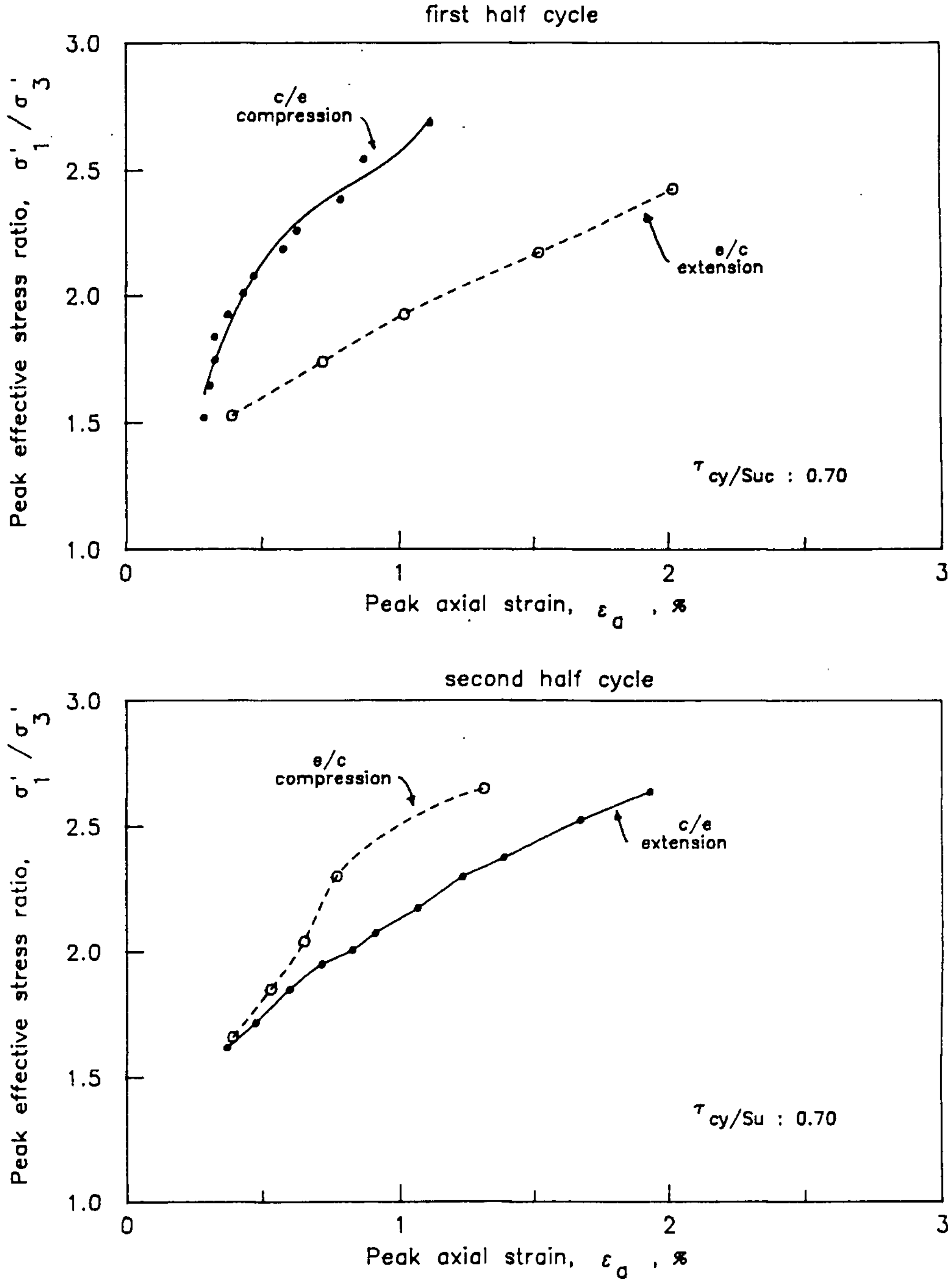
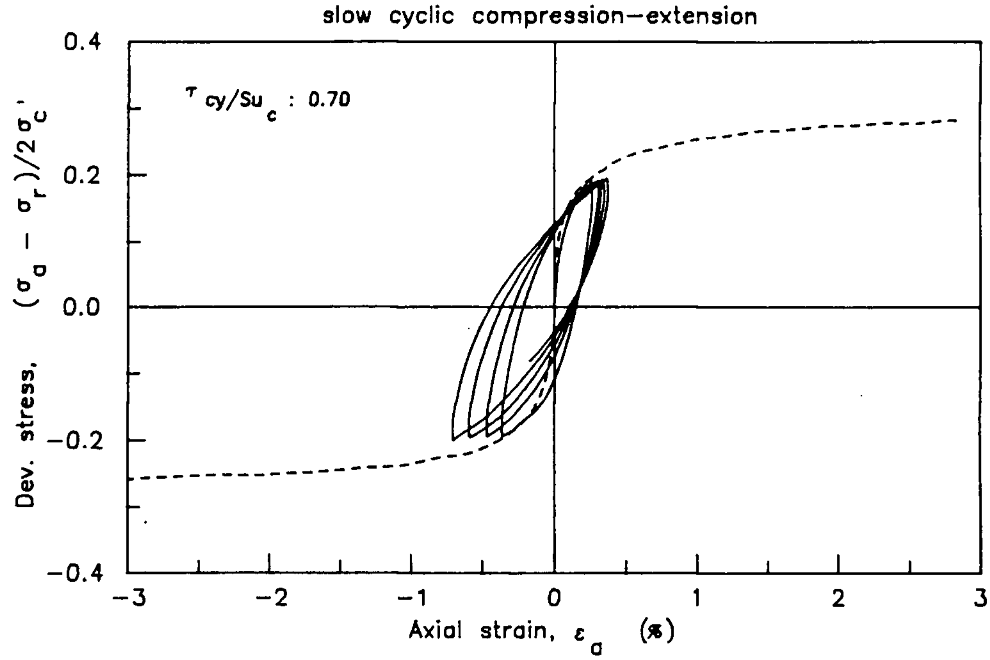


Fig 4.29 Effect of initial direction of loading on relationship between principal effective stress ratio and axial strain at peak of cyclic stress in slow two-way undrained cyclic loading.



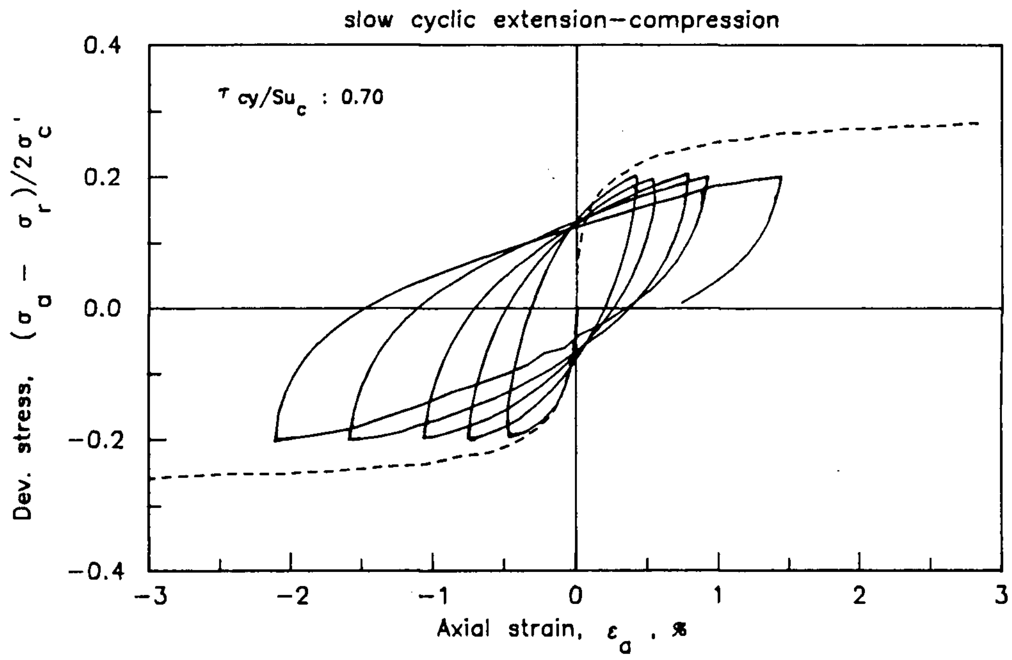
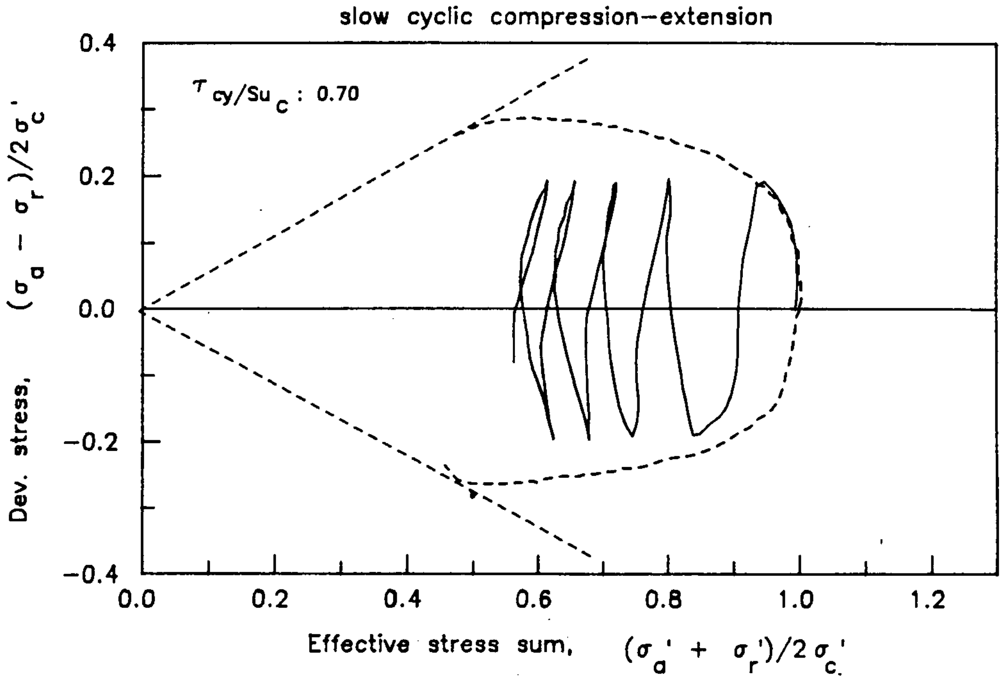


Fig 4.30 Effect of initial loading direction on stress–strain hysteresis loops in two-way undrained cyclic loading to a constant cyclic stress level.



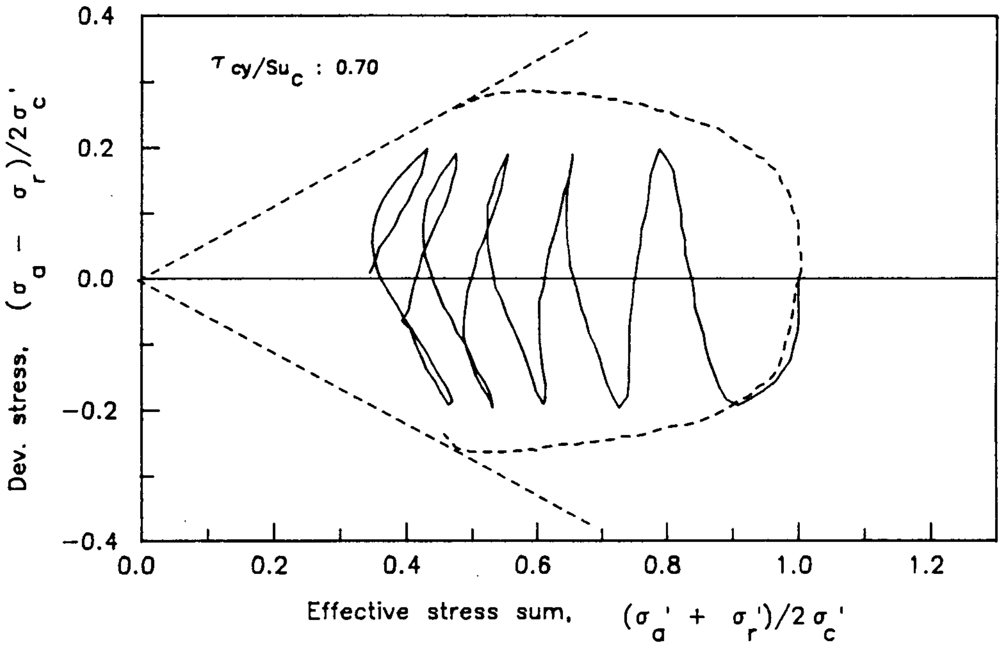


Fig 4.31 Effect of initial loading direction on effective stress path in slow two–way undrained cyclic loading to a constant cyclic stress level.

loading. Two-way undrained cyclic loading initiated in the compression mode would be less conservative than cyclic loading initiated in extension.

The effect of initial direction of cyclic loading on clay response is most apparent in the relationship between principal effective stress ratio and axial strain at peak of cyclic stress. The principal effective stress ratio also constitutes an effective stress stability criterion against large strain development during cyclic loading. Therefore, principal effective stress ratio plays an important role in strain development due to undrained cyclic loading. The role of this parameter is further emphasized in the following series of tests where symmetrical cyclic loading is applied under a constant amplitude of pincipal effective stress ratio.

4.4 Response to slow undrained cyclic loading with constant stress ratio amplitude

This section describes the response of Cloverdale clay to slow two-way undrained cyclic loading under various constant amplitudes of principal effective stress ratio. The range of effective stress ratios was selected to allow direct comparisons with the response to constant deviatoric stress amplitude cyclic loading. In these test series cyclic loading is also initiated in compression for comparison with previous results.

The stress-strain response of Cloverdale clay is considered at two particular points in each loading cycle:

. at maximum cyclic stress (peak); and,

. at completion of the cycle (residual).

The complete stress-strain response of the clay to undrained cyclic loading is also considered to obtain further information on the clay behaviour.

As before, the stress-strain response of the clay to undrained monotonic loading is used as reference in the effective stress interpretation of response to undrained cyclic loading.

4.4.1 Peak stress-strain response

Figure 4.32 shows the development of peak axial strain in the compression phase during undrained cyclic compression-extension loading of Cloverdale clay to various principal effective stress ratio amplitudes. The associated decrease in deviatoric stress amplitude with number of cycles is also shown in figure 4.32.

For all amplitudes of the effective stress ratio the peak axial strain decreases rapidly in the few initial cycles and reaches an equilibrium plateau with further cyclic loading. The level of equilibrium peak strain decreases with decreasing amplitude of cyclic effective stress ratio. A similar trend is followed by the peak axial strain in the extension phase. However, the equilibrium peak strains in extension are smaller than in compression for the same number of cycles under a given effective stress ratio amplitude.

The variation of deviatoric stress amplitude during cyclic loading follows a pattern similar to the development of peak strain with number of cycles. The plateau of cyclic stress levels lies within a narrow band ranging from 0.55 to 0.6. The number of cycles required to reach the equilibrium plateau is about 10 to 15, the larger number of cycles corresponding to the higher initial cyclic stress levels.

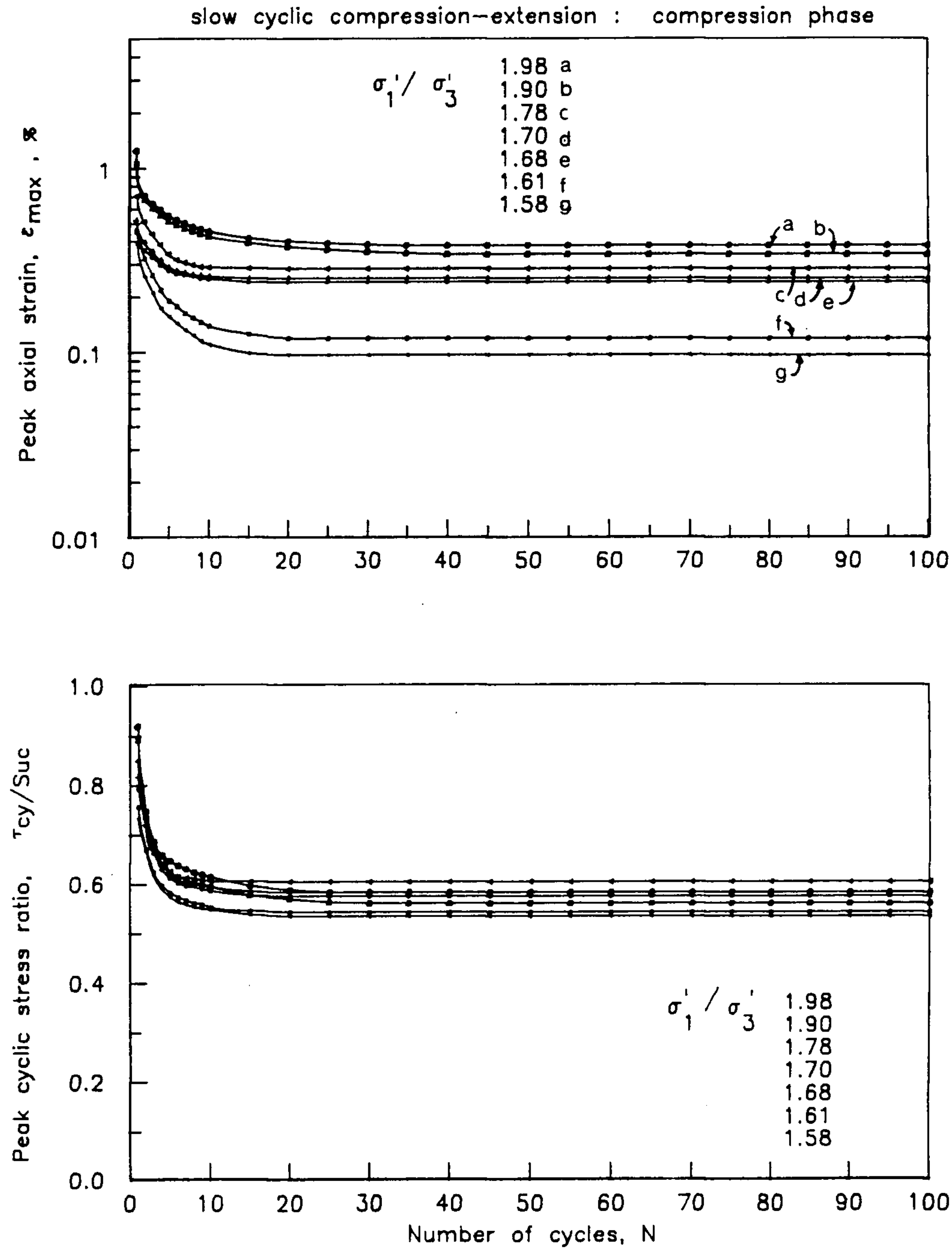


Fig 4.32 Variation of peak axial strain and cyclic stress in slow two-way undrained cyclic loading to various amplitudes of principal effective stress ratio.

A comparable behaviour was reported for Newfield clay under slow one-way cyclic loading to a constant principal effective stress ratio amplitude of approximately 2 (96).

These observations confirm that the generation of strains during undrained cyclic loading is closely related to the change in principal effective stress ratio.

4.4.2 Residual stress-strain response

Figure 4.33 shows the variation of residual strain and pore water pressure during two-way undrained cyclic loading of Cloverdale clay to various levels of principal effective stress ratio. Invariably, the residual pore water pressure tends toward an equilibrium plateau after a marked rise in the few initial cycles. The equilibrium pore water pressure ranges from 40 to 60 percent of the consolidation stress and increases with increasing principal effective stress ratio level.

A similar pattern is followed in the development of residual axial strain with number of cycles. Figure 4.33 shows that the equilibrium residual strains develop in extension and increase with increasing principal effective stress ratio amplitude. Under all cyclic stress ratio amplitudes considered the residual strain remains limited to values less than 0.5 percent.

The above observations suggest that the principal effective stress ratio controls also the residual clay stress-strain response to cyclic loading.

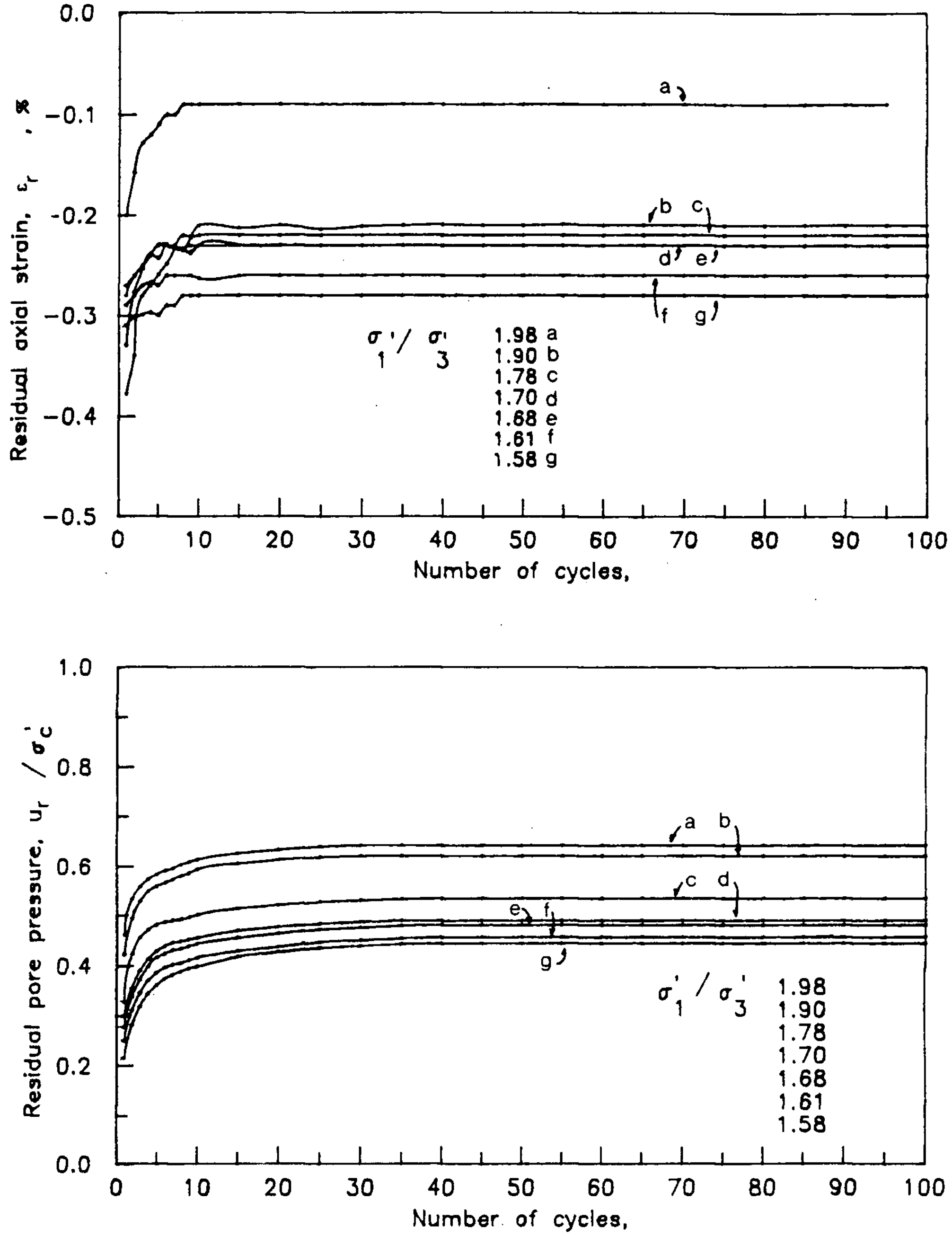


Fig 4.33 Development of residual strain and pore pressure during slow tow-way undrained cyclic loading to various constant principal effective stress ratio amplitudes.

4.4.3 Comparison with constant stress amplitude response

A direct comparison between figure 4.32 and figure 4.8 shows that the equilibrium peak axial strain during constant principal effective stress ratio cyclic loading is similar to the plateau of peak strain approached during cyclic loading at constant cyclic stress levels smaller than about 0.55. Therefore, the cyclic stress level delineating clay response leading to an equilibrium condition from the response resulting in accelerated strain increase per cycle may be identifed from constant principal effective stress ratio amplitude cyclic loading. Constant effective stress ratio amplitude tests eliminate the interpolation used in constant deviatoric stress amplitude tests to define the cyclic stress level below which equilibrium conditions would prevail. In addition to fewer tests required, the duration of each test is significantly reduced because in constant principal effective stress ratio amplitude cyclic loading equilibrium conditions are promptly established.

Figure 4.34 shows the locus of peak points during constant principal effective stress ratio cyclic loading on the effective stress path plane. The contours of equal number of cycles from cyclic loading to various constant cyclic stress levels is also shown for comparison. An interesting observation emerges: the collapsing stable state boundary surface identified in constant stress amplitude cyclic loading corresponds to the equilibrium condition in constant stress ratio amplitude cyclic loading. Therefore, the collapsed stable state boundary surface may be located based on cyclic loading under constant principal effective stress ratio amplitude.

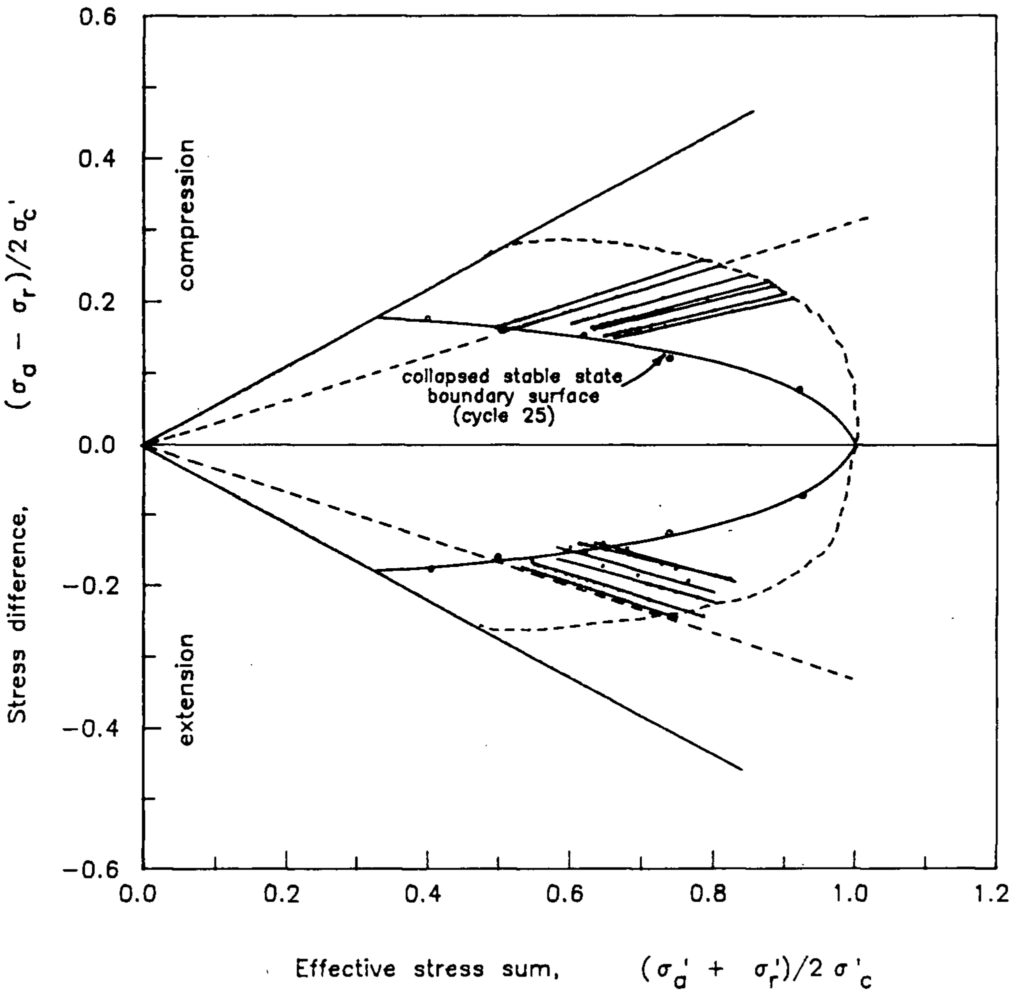


Fig 4.34 Comparison between peaks in constant principal effective stress ratio amplitude and equal number of cycles in constant deviatoric stress amplitude during slow two-way undrained cyclic loading.

The above conclusions are limited to cyclic loading conditions where the amplitude of cyclic deviatoric stress or cyclic principal effective stress ratio is maintained constant. It would be of interest to examine the clay response to cyclic loading condition where the cyclic stress level changes during the loading event and find its possible relationship to behaviour under constant stress amplitude loading. However a controlled change in cyclic stress level is preferred in an attempt to study behaviour under random cyclic loading conditions. The undrained stress-strain response of Cloverdale clay to a step increase in cyclic stress level is now considered.

4.5 Effect of a step increase in cyclic stress level

To extend the results of constant stress amplitude cyclic loading tests to a variable stress amplitude loading event, the effect of a controlled step increase in cyclic stress level on undrained behaviour should be assessed. The response of Cloverdale clay to slow two-way undrained cyclic loading with a step increase in stress level was studied in both constant deviatoric stress amplitude and constant principal effective stress ratio amplitude tests. The cyclic stress level in these special tests was selected to allow direct comparison with the clay response to cyclic loading without step loading.

4.5.1 Constant stress amplitude

Figure 4.35 shows strain and effective stress ratio development with number of cycles at peak compression in slow two-way undrained cyclic loading with constant deviatoric stress level. In the step loading test the cyclic stress level

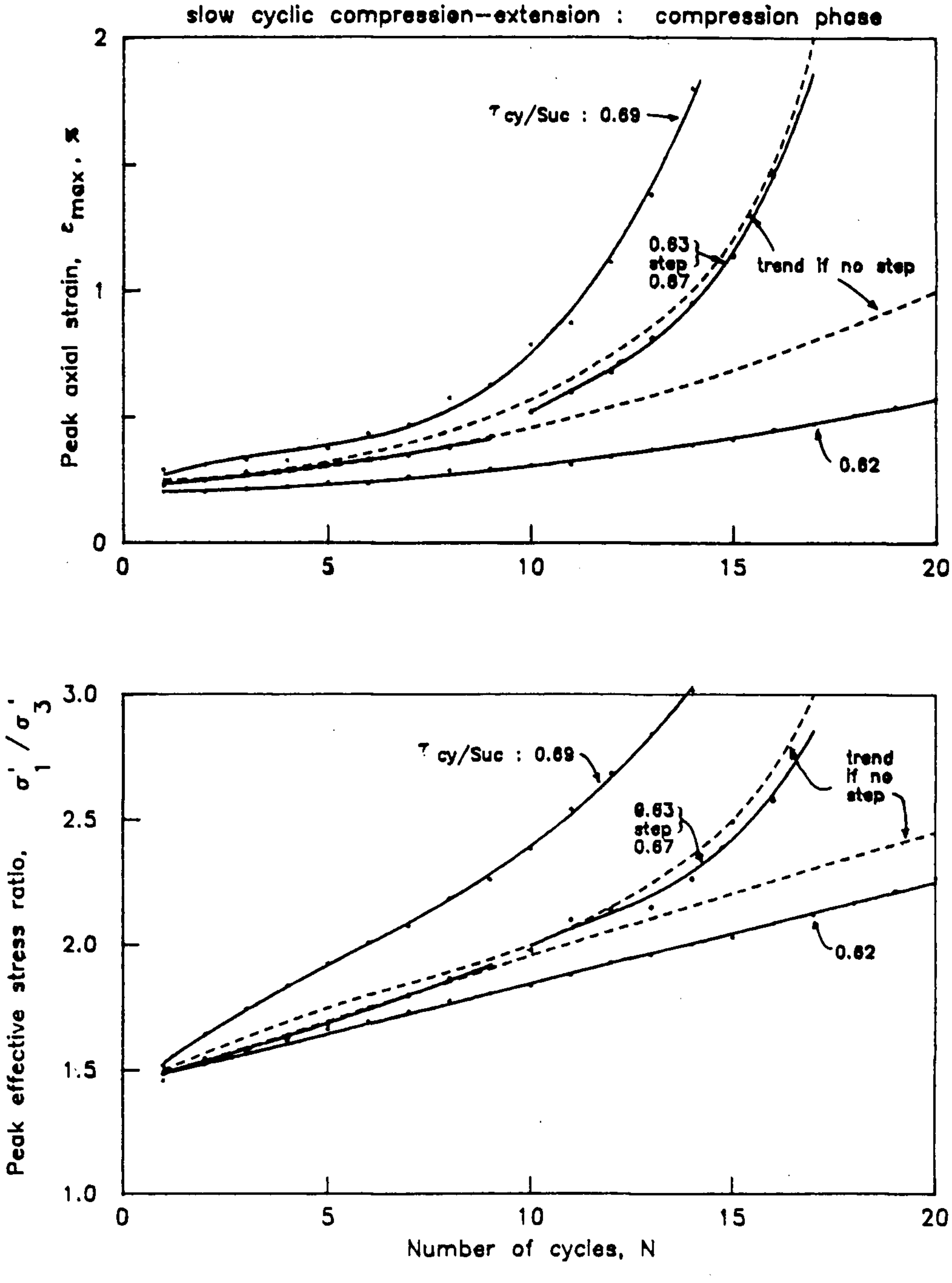


Fig 4.35 Effect of a step increase in cyclic stress level on clay response to slow two-way undrained cyclic loading with constant deviatoric stress amplitudes. Compression phase.

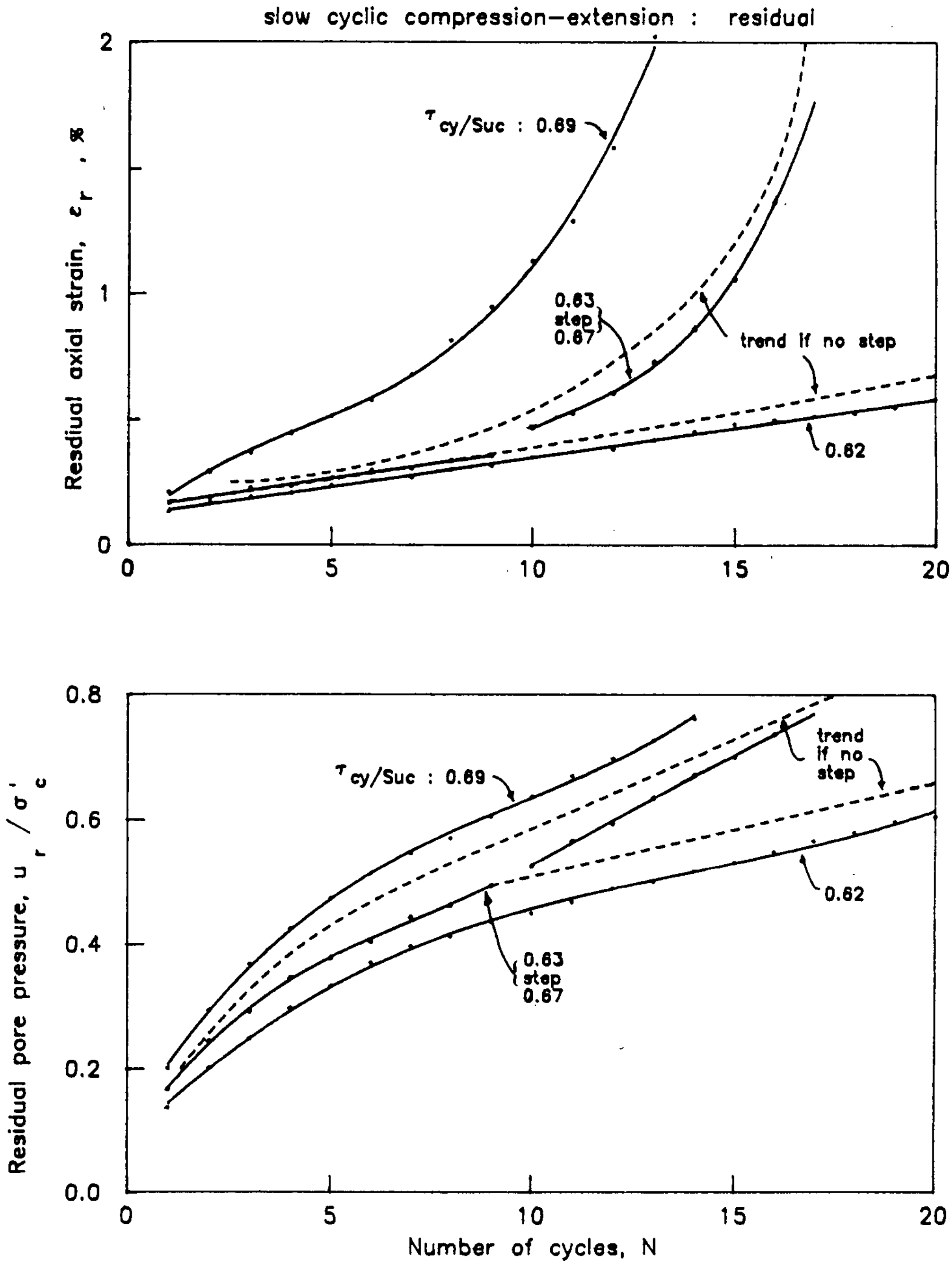


Fig 4.36 Effect of a step increase in cyclic stress level on clay response to slow two–way undrained cyclic loading with constant deviatoric stress amplitudes. Residual phase.

is suddenly increased from 0.63 to 0.67 after ten cycles. The clay response would follow the trend shown in dashed lines in the absence of step loading. The response trends under constant cyclic stress amplitudes were obtained by interpolation from the contours of equal number of cycles in figure 4.15 for the peak response and in figure 4.21 for the residual response. The sudden increase in cyclic stress level results in a response similar to the one obtained if loading were initiated with the higher cyclic stress level. Similar comments apply in terms of residual strain and residual pore water pressure as shown in figure 4.36. If this behaviour holds for all cyclic stress levels then the development of strain and pore water pressure in undrained cyclic loading would depend only on the current cyclic stress level and current number of cycles regardless of past cyclic loading history within the same event.

This observation would allow prediction of undrained clay response under increasing cyclic stress amplitude from the results of constant stress level cyclic loading. This observation would also imply that a step increase in cyclic stress level may shift the clay response from a low cyclic stress level trend to a high cyclic stress level pattern. In the low cyclic stress trend strain development tends toward an equilibrium plateau with number of cycles, whereas in the high cyclic stress level pattern strains may develop at an accelerated rate per cycle with cyclic loading.

4.5.2 Constant stress ratio amplitude

Figures 4.37 and 4.38 show the effect a step increase in principal effective stress ratio amplitude on the response of Cloverdale clay to slow two-way

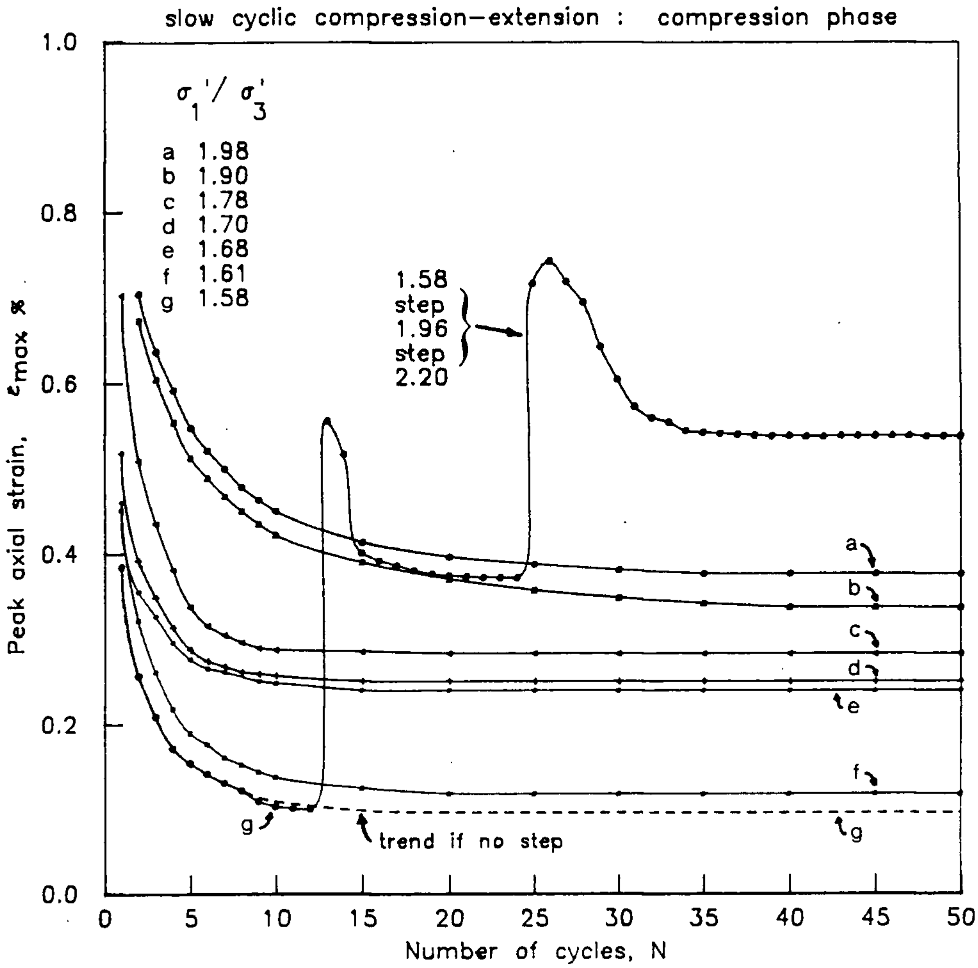


Fig 4.37 Effect of step increase in cyclic stress level on clay response to slow two–way undrained cyclic loading with constant principal effective stress ratio amplitudes. Compression phase.

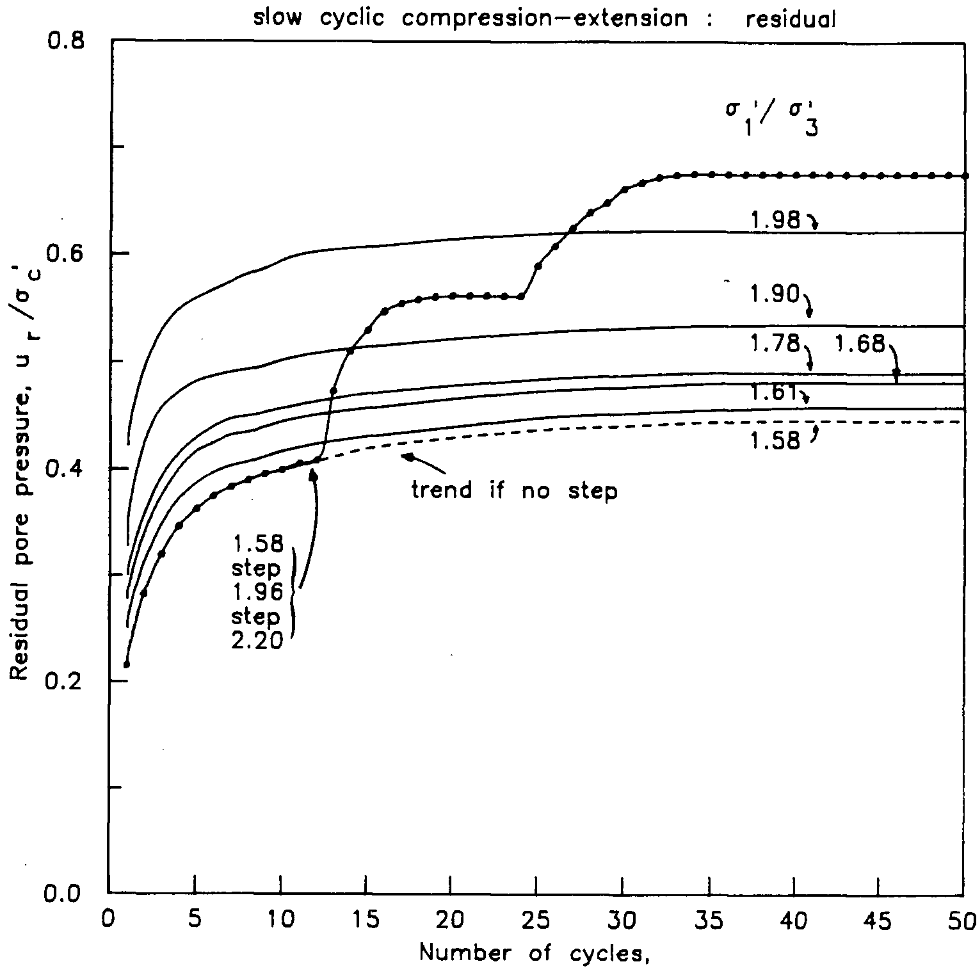


Fig 4.38 Effect of step increase in cyclic stress level on clay response to slow two–way undrained cyclic loading with constant principal effective stress ratio amplitudes. Residual phase.

undrained cyclic loading. Upon the step increase in the effective stress ratio amplitude, the strain and pore water pressure developed correspond to the response that would be followed if the higher stress level were applied initially. Hence, in this loading mode also the clay response depends only on the current cyclic effective stress level and the current number of cycles. However, the extrapolation of clay response from constant principal effective stress ratio amplitude to variable effective stress ratio level is limited to increasing cyclic stress level.

The results of undrained cyclic loading with a step increase in cyclic stress level show that the clay response is a function of cyclic stress level, current rate of strain increase per cycle and cumulative strain level regardless of past cyclic loading history within the same event. A similar state function relates residual pore water pressure, cyclic stress level and rate of pore water pressure increase per cycle. Consequently, a random cyclic loading event may be reorganized in packets of constant cyclic stress levels with increasing amplitudes based on Miner's rule (13) and the strain development may be predicted following the method suggested for Drammen clay (6, 7).

4.6 Clay response to postcyclic undrained monotonic loading

Most cyclically loaded specimens were subjected to an undrained monotonic loading stage immediately following the last cycle of loading. Changes in undrained strength and stiffness are then related to cyclic loading paramters such as maximum strain, hysteretic work and peak principal effective stress ratio developed during cyclic loading. The relationship of postcyclic loading response

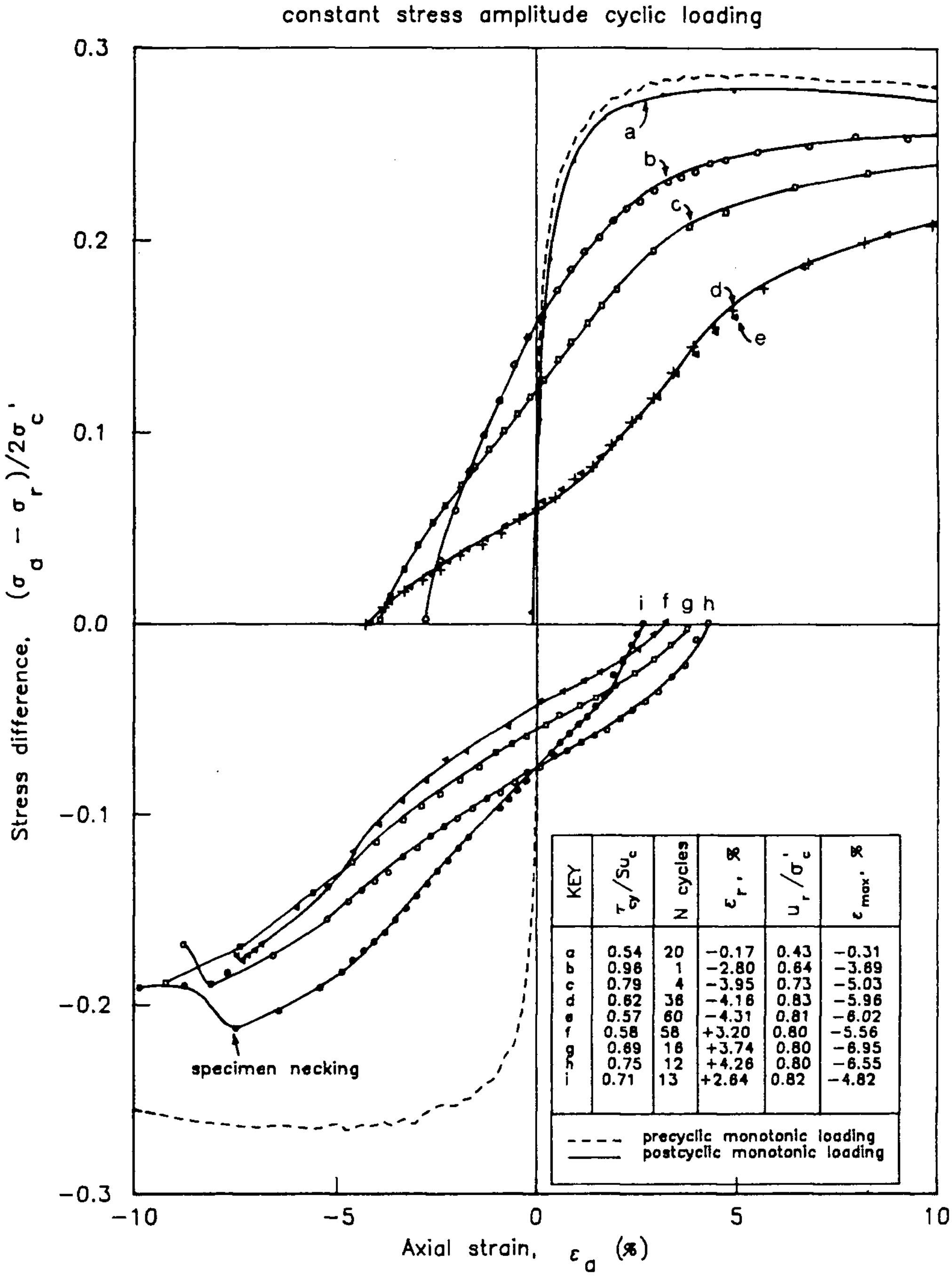
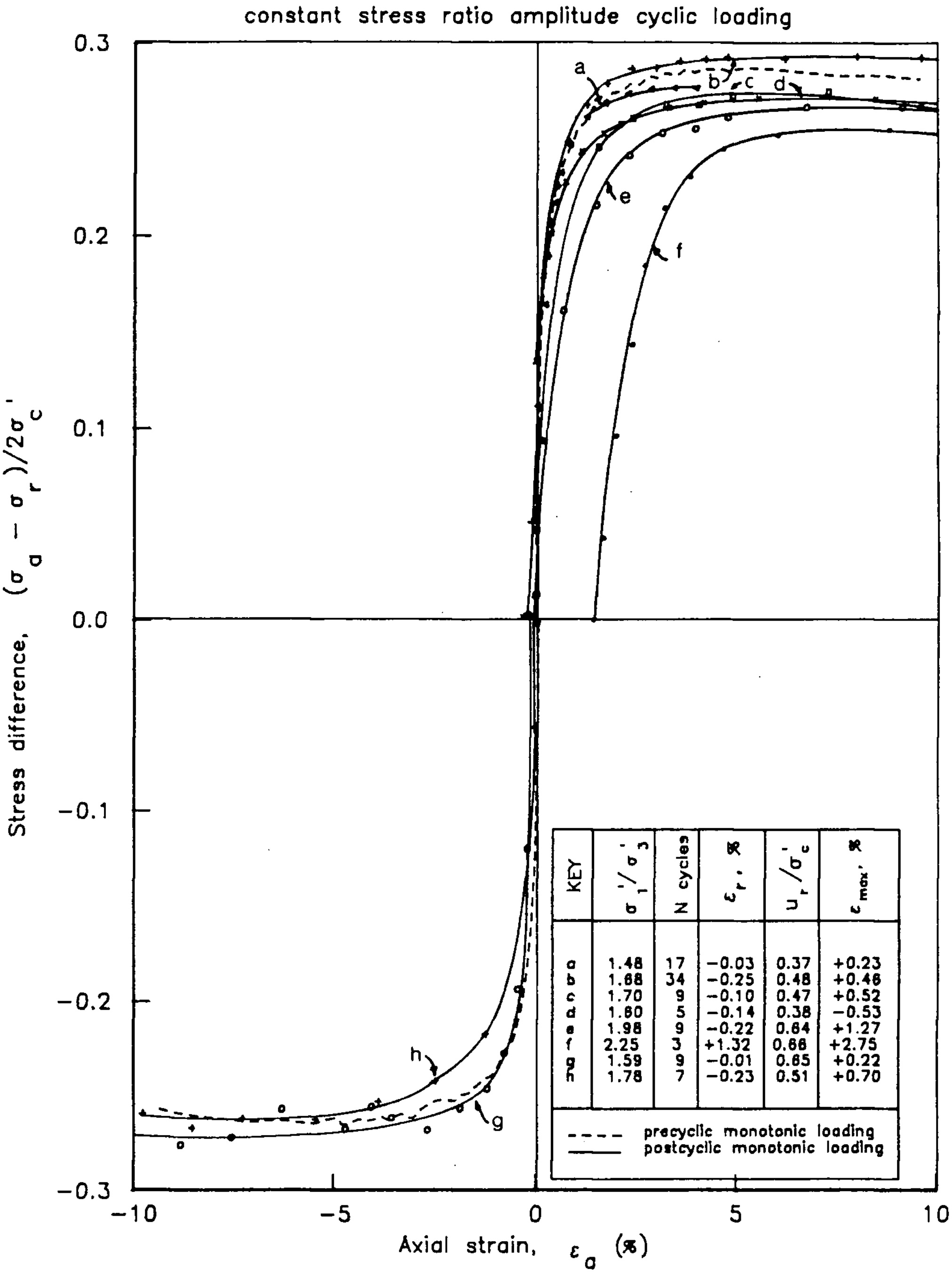


Fig 4.39 Effect of slow two–way undrained cyclic loading to various cyclic stress levels on response to undrained monotonic loading.



KEY	σ_1'/σ_3'	N cycles	ε_r, %	u_r/σ_c'	ε_{max}, %
a	1.48	17	−0.03	0.37	+0.23
b	1.68	34	−0.25	0.48	+0.46
c	1.70	9	−0.10	0.47	+0.52
d	1.60	5	−0.14	0.38	−0.53
e	1.98	9	−0.22	0.64	+1.27
f	2.25	3	+1.32	0.66	+2.75
g	1.59	9	−0.01	0.65	+0.22
h	1.78	7	−0.23	0.51	+0.70

Fig 4.40 Effect of slow two-way undrained cyclic loading to various cyclic stress ratios on response to undrained monotonic loading.

to the effective stress state at end of cyclic loading is of particular interest because slow cyclic loading enabled confident measurement of pore pressures. This relationship encompasses postcyclic compression and extension loading following cyclic compression-extension and extension-compression cyclic loading under both constant stress and constant stress ratio amplitudes.

4.6.1 Effect of maximum strain due to cyclic loading

Postcyclic compression and extension response after constant stress amplitude cyclic loading is shown in figure 4.39 and after constant stress ratio amplitude in figure 4.40. Results from only a selected number of specimens are presented. For clarity, no data is shown at cyclic stress level less than 0.54, as the response of these specimens was essentially identical to that at a stress level equal to 0.54. For comparison, the behaviour of clay before cyclic loading is also shown by dashed lines.

A general degradation of strength and stiffness may be noted as a result of cyclic loading which seems to increase with the magnitude of maximum strain during cyclic loading. The relationship of postcyclic strength and stiffness to maximum strain is shown in figures 4.41 and 4.42. The postcyclic undrained strength is normalized by the reference undrained strength in compression and the stiffness is expressed by the secant modulus E_{50} at 50 percent of undrained strength normalized by the consolidation stress. Little reduction in postcyclic strength occurs until maximum strain due to cyclic loading exceeds about half the strain (4 percent) to mobilize the reference undrained strength. A comparable postcyclic response was reported by other researchers (57, 58, 82, 113, 114).

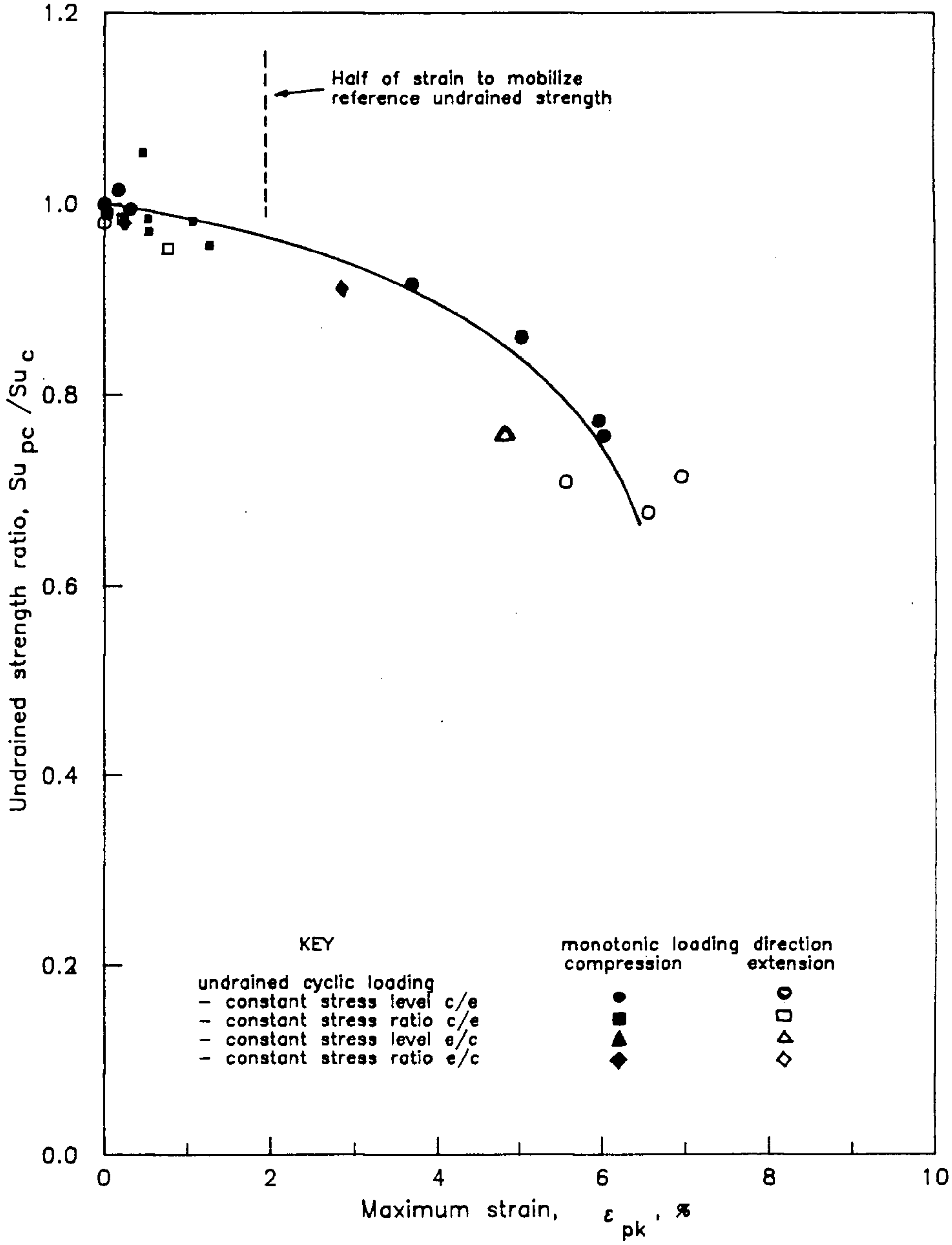


Fig. 4.41 Relationship between maximum strain due to two-way undrained cyclic loading and postcyclic undrained strength.

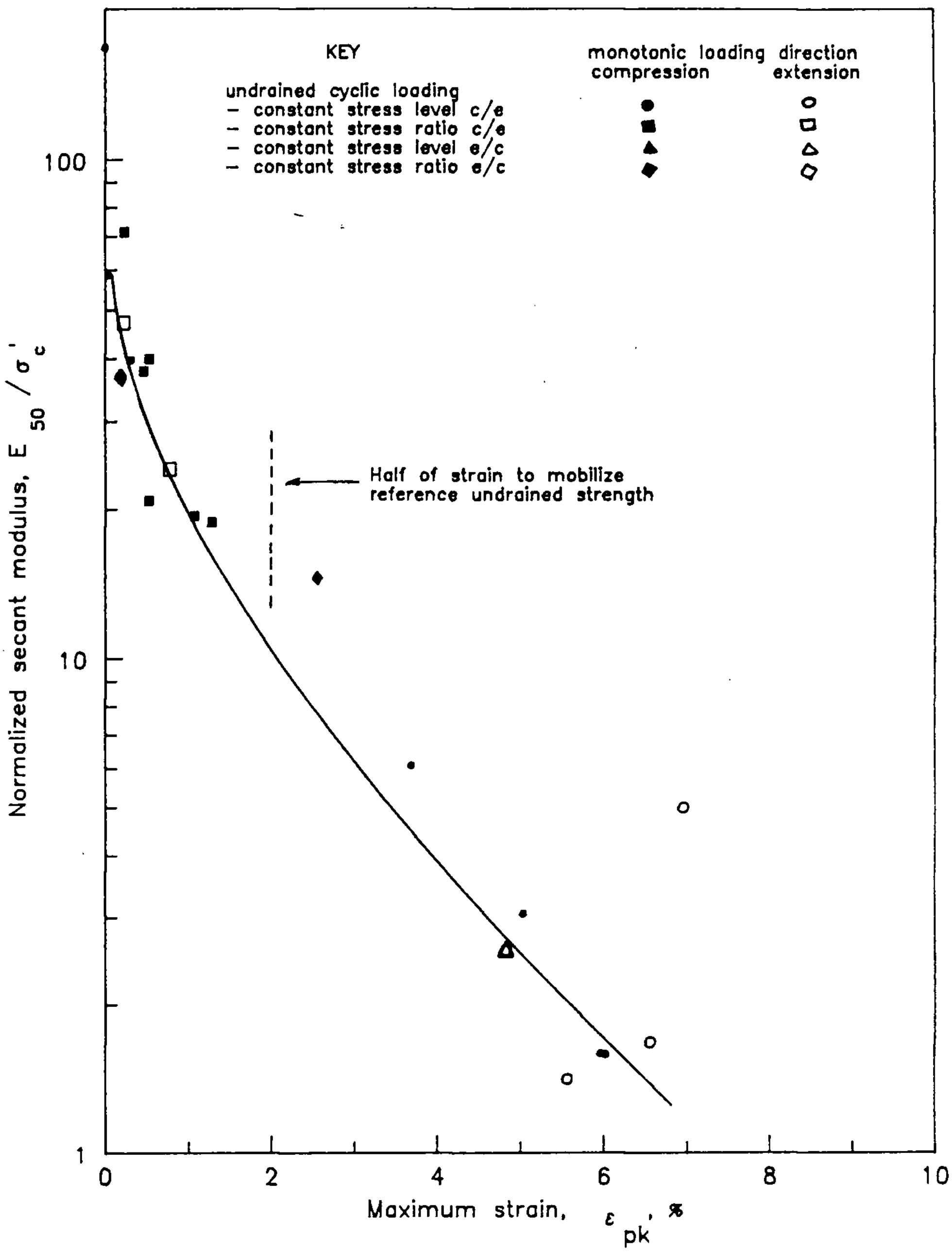


Fig. 4.42 Relationship between maximum strain due to two-way undrained cyclic loading and postcyclic normalized secant modulus.

Their results were, however, confined to postcyclic compression behaviour following compression-extension constant stress level cyclic loading only. The data in figures 4.41 and 4.42 encompass, in addition, cyclic loading under constant stress ratio amplitude, extension-compression and postcyclic extension loading. This implies that the relationship of postcyclic strength to maximum strain during cyclic loading is applicable regardless of the manner in which this strain was accumulated. It also shows that the low degree of undrained strength anisotropy noted in precyclic monotonic loading remains essentially unaltered even after cyclic loading. However, a different behaviour may result from constant strain amplitude cyclic loading because of the larger hysteretic work involved (57).

Unlike the small undrained strength reduction, large degradation in stiffness occurs even at small maximum strains induced by cyclic loading (see figure 4.42). In fact, the steepest degradation in stiffness is associated with the range of maximum strain where strength reduction is the least.

4.6.2 Effect of cumulative hysteretic work

The maximum strain developed during cyclic loading includes implicitly the effect of cyclic stress level and number of loading cycles. As discussed previously, hysteretic work also includes the effect of cyclic stress level and number of cycles and may thus constitute an alternative parameter that controls postcyclic response to undrained monotonic loading. Figure 4.43 shows correlation between postcyclic undrained strength and hysteretic work for Cloverdale clay. No relationship between postcyclic undrained strength and hysteretic work is apparent. Several data points indicate that a given postcyclic

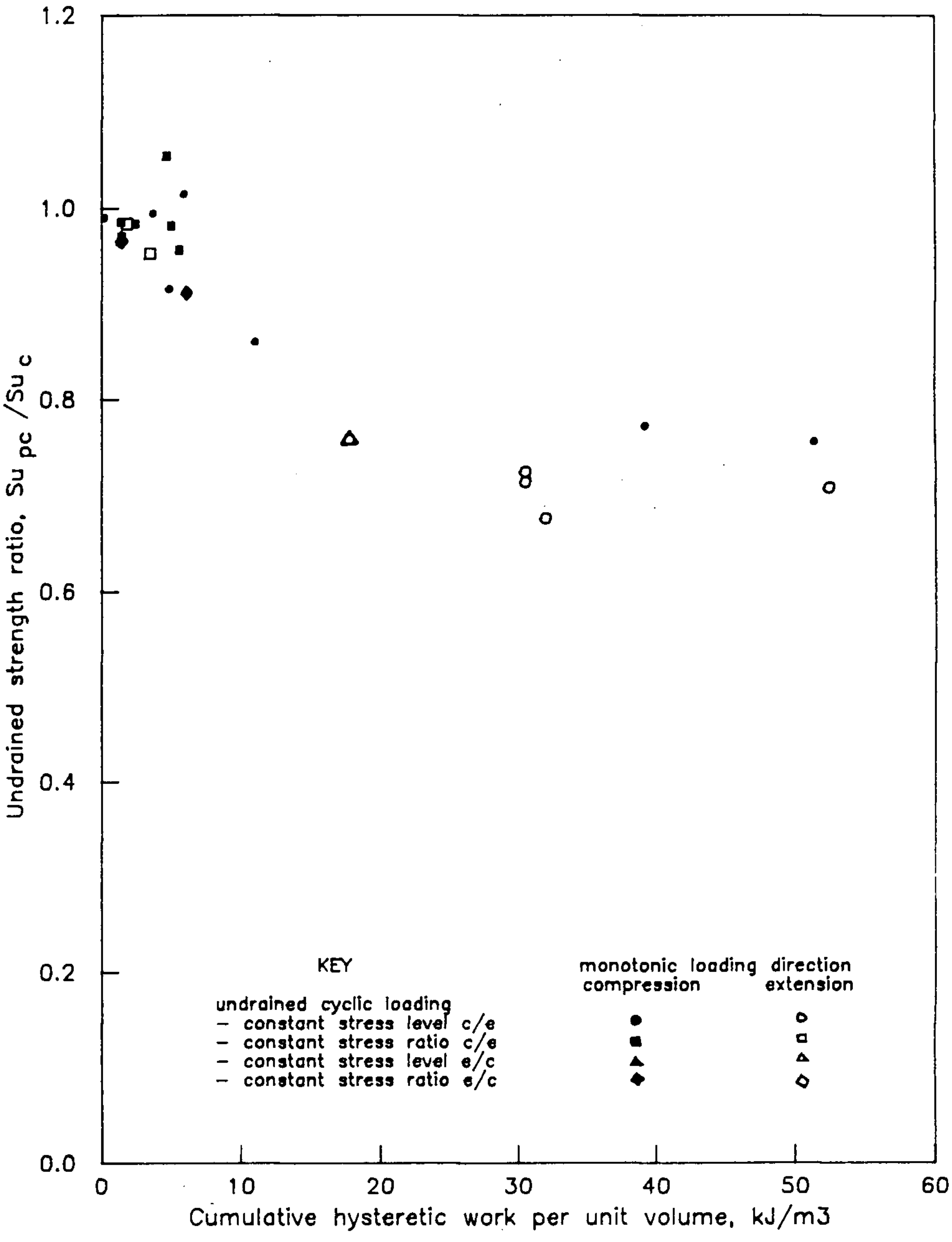


Fig. 4.43 Relationship between cumulative hysteretic work and postcyclic undrained strength.

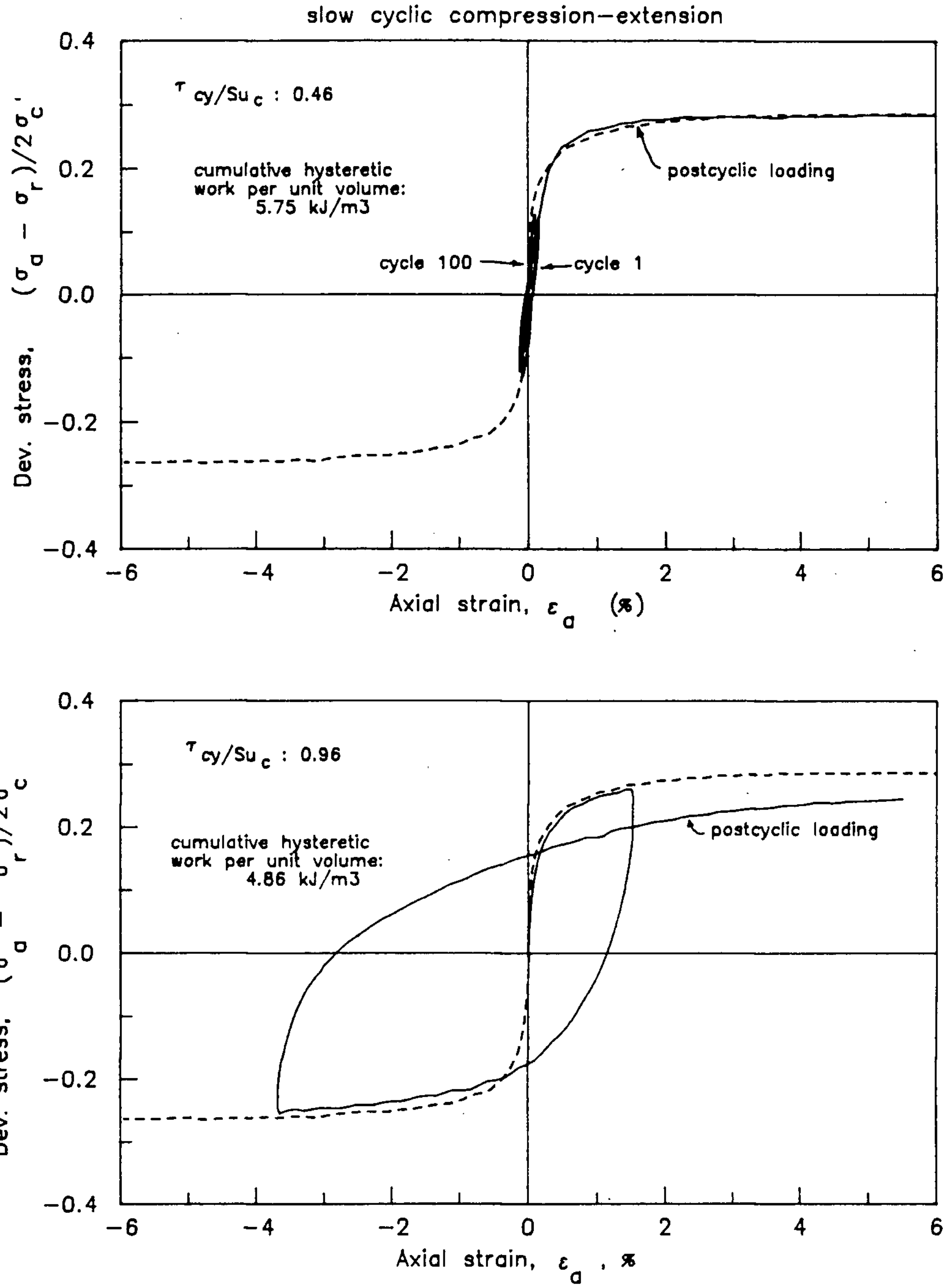


Fig 4.44 Stress–strain hysteresis loops in slow two–way undrained cyclic loading to two cyclic stress levels resulting in same cumulative hysteretic work per unit volume.

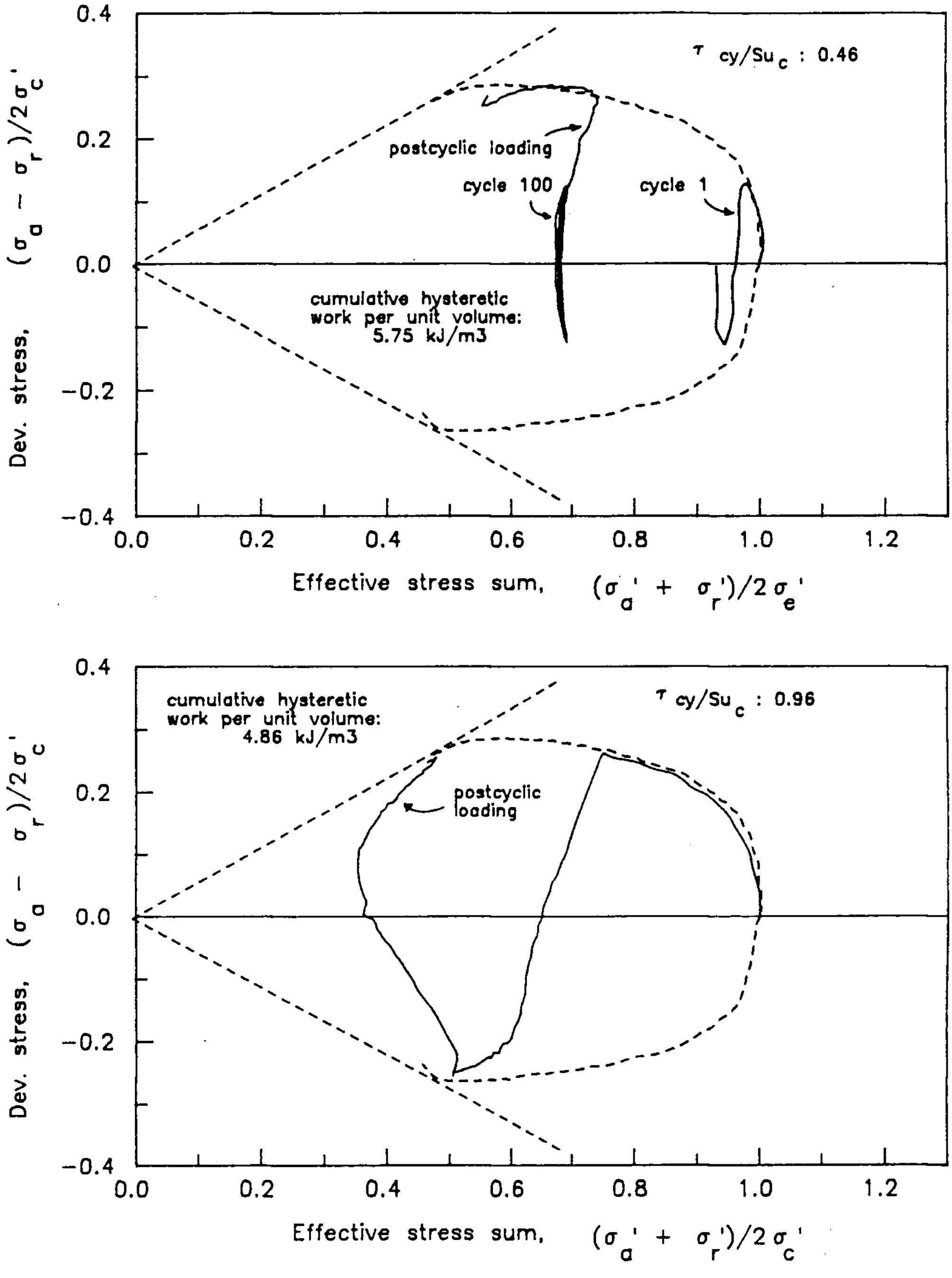


Fig 4.45 Effective stress path in slow two-way undrained cyclic loading to two-cyclic stress levels resulting in same cumulative hysteretic work per unit volume.

undrained strength is associated with widely different values of hysteretic work. Conversely, a given amount of hysteretic work is associated with different values of postcyclic undrained strength. Therefore, the relationship between postcyclic undrained strength and cumulative hysteretic work is not unique as suggested earlier (57).

Figure 4.44 shows clay behaviour under two different cyclic stress levels. Cyclic loading was terminated after the completion of 100 cycles at the low stress level but only one cycle at the higher stress level. Although the amount of hysteretic work dissipated is essentially the same for the two cases, strain response and undrained strength are very different. Major differences in postcyclic effective stress response of the two specimens are further emphasized in figure 4.45. Under a cyclic stress level of 0.96, only one cycle of loading generates a residual pore water pressure twice as large as caused by 100 cycles at stress level of 0.46; even though the cumulative hysteretic work is almost identical in both cases. It appears therefore that attempts to relate postcyclic response to cyclic loading parameters which do not include the effect of change in effective stress due to cyclic loading are not likely to be successful.

4.6.3 Effect of effective stress change due to cyclic loading

The effective stress paths followed by Cloverdale clay during postcyclic loading are shown in figure 4.46 for constant stress amplitude loading and in figure 4.47 for constant stress ratio amplitude loading. The effective stress paths of the overconsolidated clay under monotonic loading without cyclic loading are also shown by dashed lines. Because of the difference in void ratio between

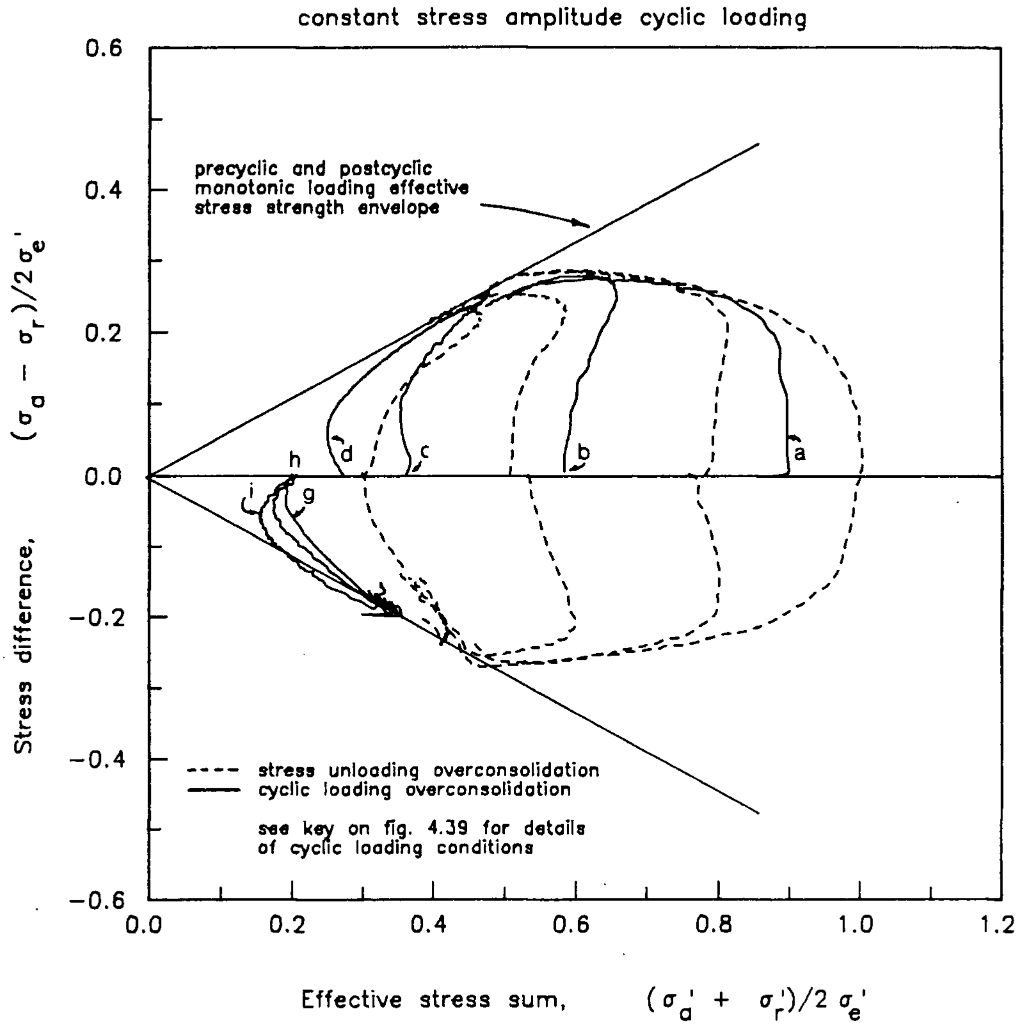


Fig 4.46 Comparison between undrained cyclic loading overconsolidation and drained stress unloading overconsolidation.

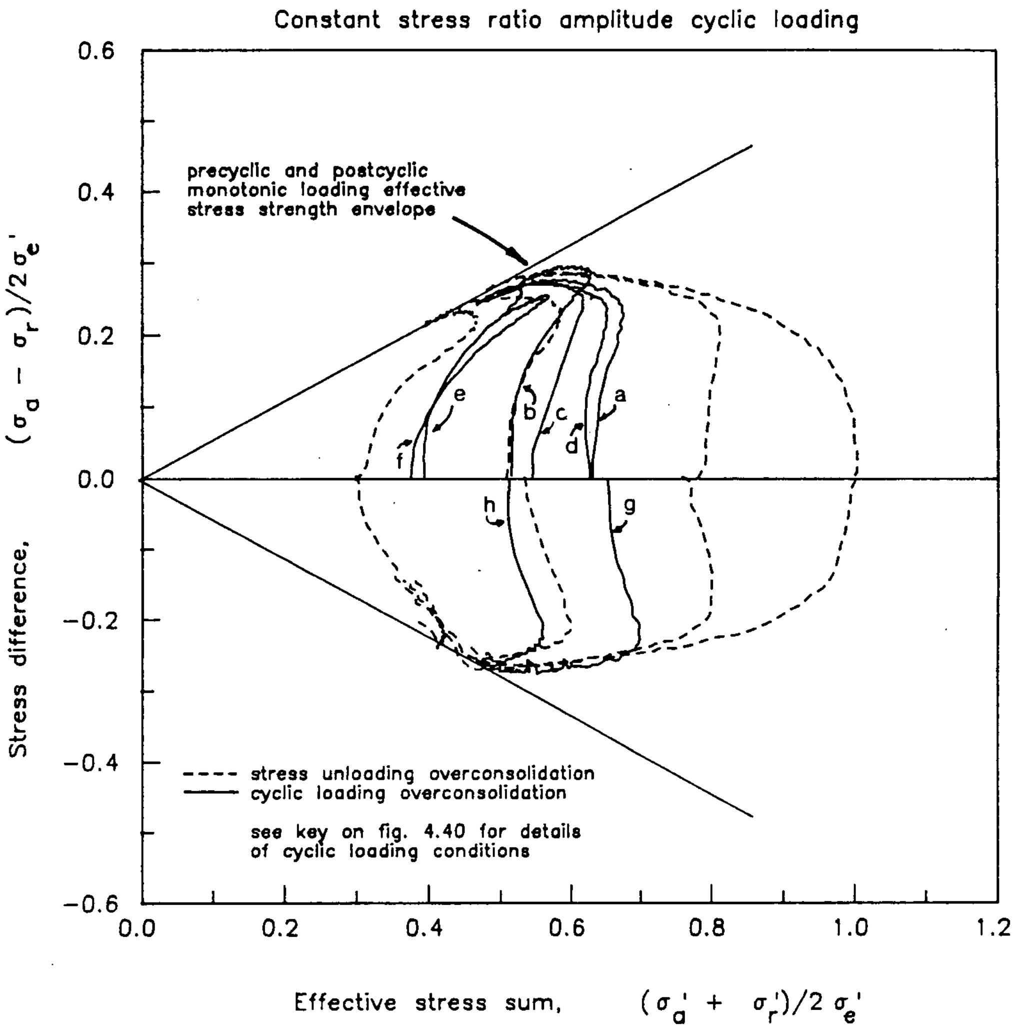


Fig 4.47 Comparison between undrained cyclic loading overconsolidation and drained stress unloading overconsolidation.

overconsolidated and cyclically loaded specimens, the equivalent consolidation stress is used as the normalizing parameter for stresses. The similarity between the postcyclic and the monotonic loading effective stress path of the stress overconsolidated clay suggests that undrained cyclic loading may be regarded as inducing an equivalent overconsolidation effect on the clay. Thus the effect of a positive residual pore water pressure on the postcyclic loading behaviour of normally consolidated clays may be interpreted as an equivalent overconsolidation due to cyclic loading. It may also be noted that the effective stress strength envelopes established under monotonic loading also define failure in postcyclic loading in both compression and extension. For clarity, data from only a limited number of postcyclic tests is illustrated in figures 4.46 and 4.47.

Figure 4.48a shows a comparison between the two types of overconsolidation on the relationship between normalized undrained strength and equivalent OCR. The data include stress overconsolidated clay subjected only to monotonic loading as well as clay overconsolidated by two-way cyclic loading and then subjected to postcyclic monotonic loading. Cyclic loading data include both constant stress and constant stress ratio amplitudes. The relationship between normalized undrained strength and logarithm of OCR may be noted to be unique. This unique relationship suggests that postcyclic undrained strength may be estimated from the undrained strength of stress overconsolidated clay provided that the equivalent consolidation stress is used to define OCR. Previous results reported by other investigators (49, 50, 58, 60, 82) show distinctly different relationships for the two types of overconsolidation histories. Failure to define OCR using equivalent and not the maximum consolidation stress was apparently

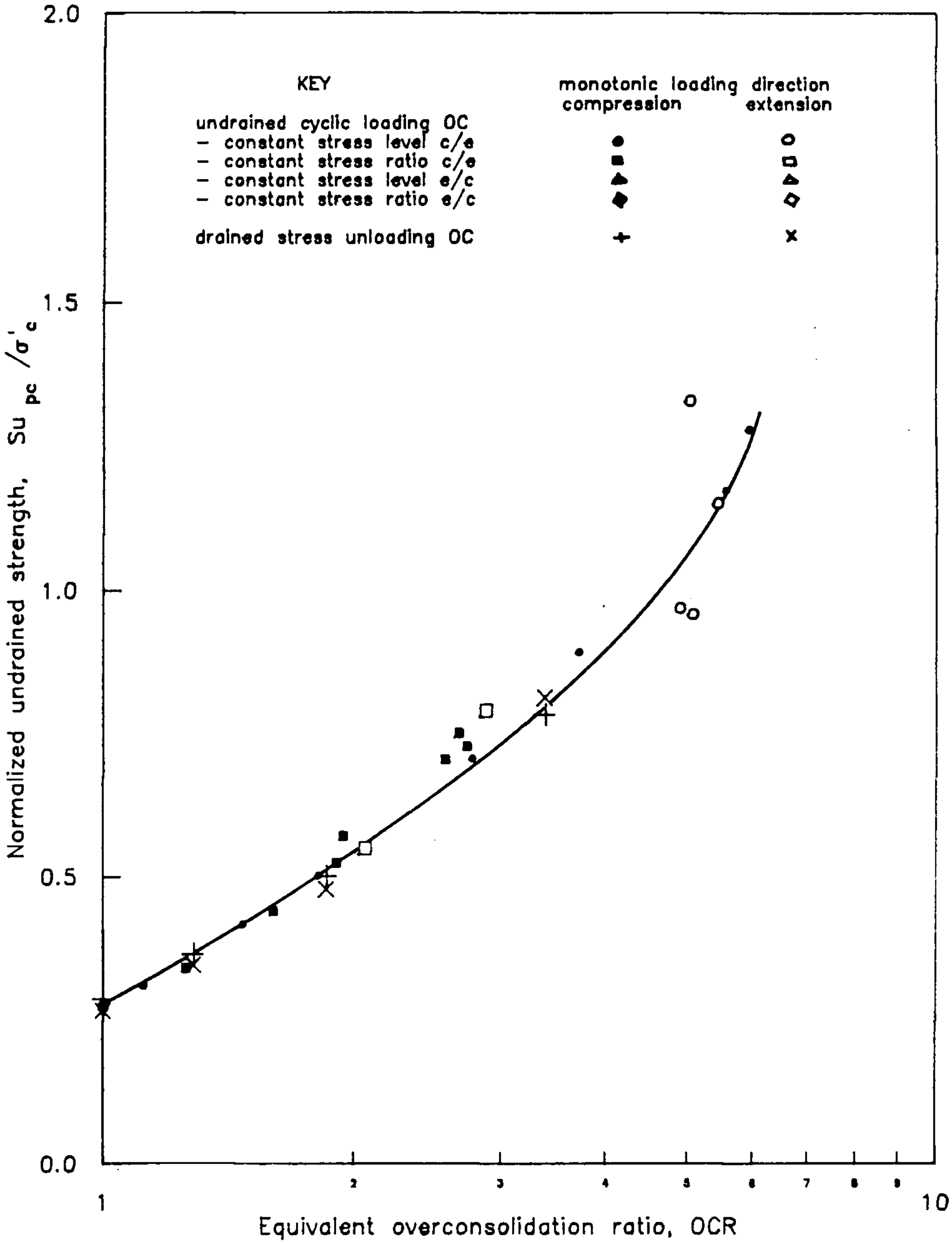


Fig. 4.48a Comparison between effect of overconsolidation due to undrained cyclic loading and overconsolidation by drained stress unloading on normalized undrained strength.

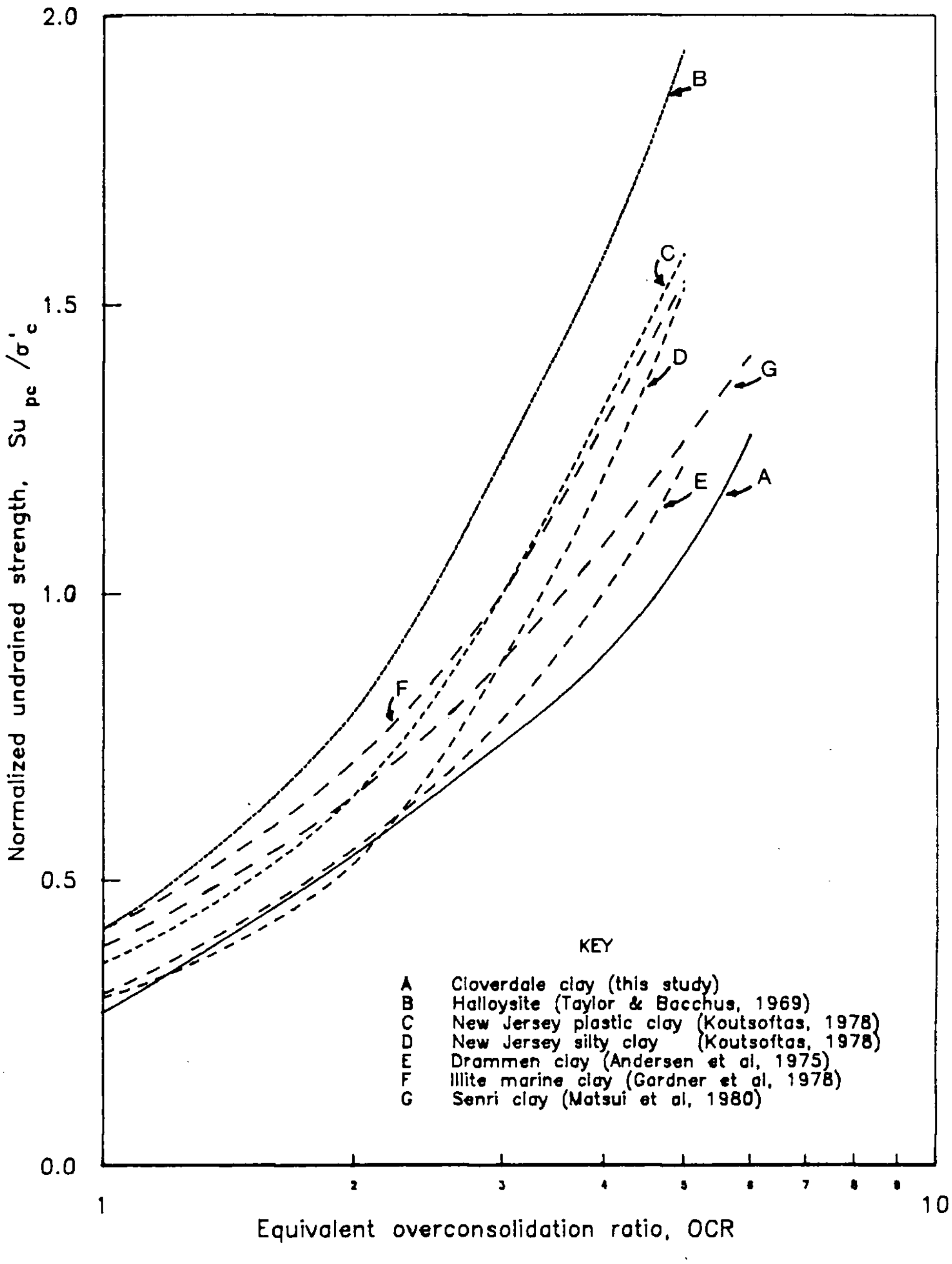


Fig. 4.48b Correlation between postcyclic normalized undrained strength and equivalent overconsolidation ratio due to undrained cyclic loading. Comparison between Cloverdale clay and various clays.

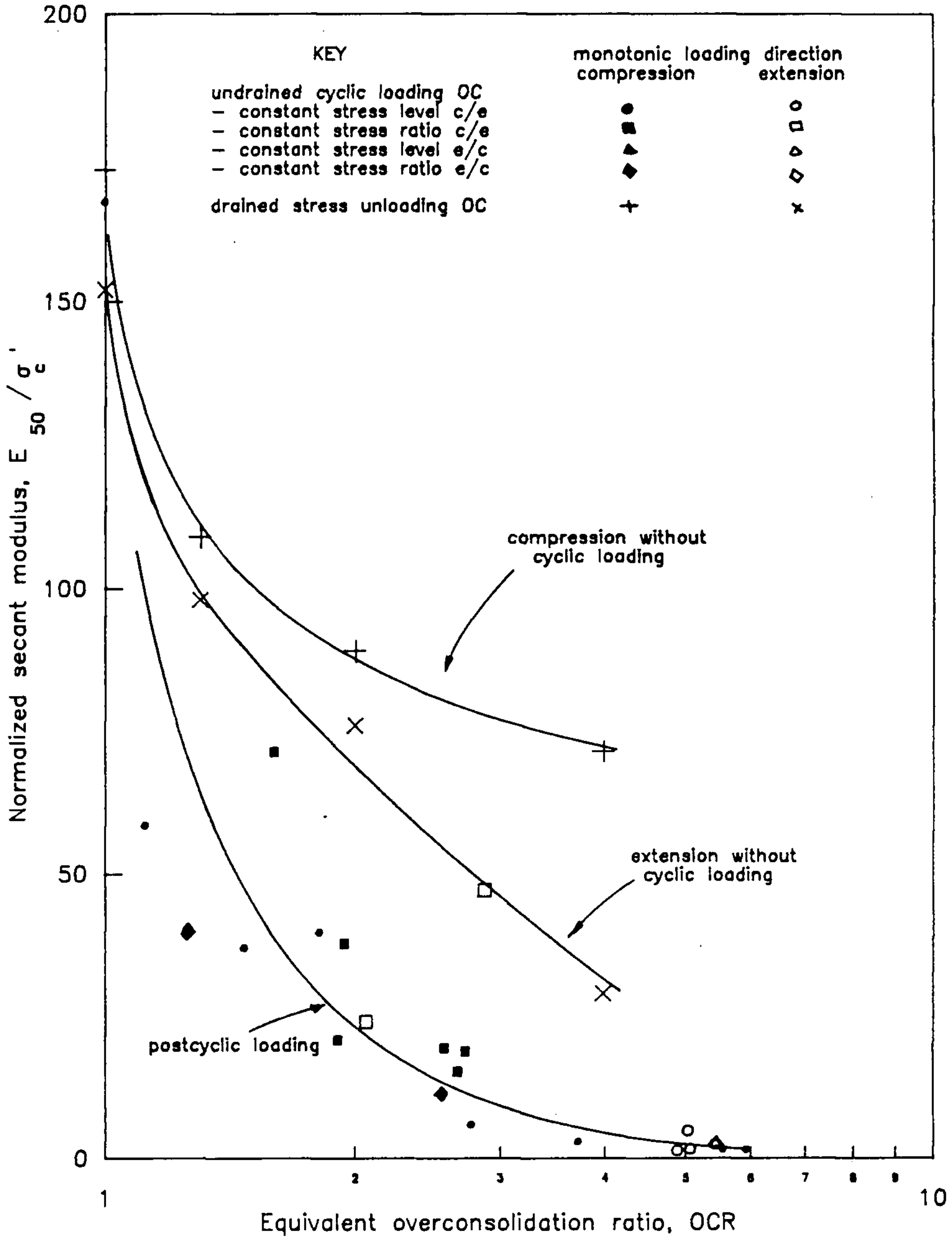


Fig. 4.49 Comparison between effect of overconsolidation due to undrained cyclic loading and overconsolidation by drained stress unloading on normalized secant modulus.

the cause for different and not a unique relationship. Figure 4.48b shows a comparison between Cloverdale clay and various other clays reported in the literature in terms of postcyclic undrained strength versus equivalent overconsolidation ratio. It may be seen that all clays follow a trend similar to the unique relationship observed for Cloverdale clay. Drammen clay, in particular, follows a trend almost identical to Cloverdale clay due to the similarity between the types of soils. This may imply that the difference between the trend followed by Cloverdale clay and that of other clays may be related to the type of clay.

However, the similarity between stress overconsolidation and cyclic loading induced overconsolidation does not hold for the variation of clay stiffness with OCR as shown in figure 4.49. Undrained cyclic loading causes a more pronounced degradation in stiffness than drained stress overconsolidation.

4.6.4 Effect of peak effective stress ratio developed in cyclic loading

Postcyclic loading response may also be related to the peak principal effective stress ratio mobilized during cyclic loading. Such relationships may be regarded as effective stress interpretations of the correlation between postcyclic loading response and maximum strain developed in cyclic loading shown in figure 4.41 and 4.42.

Figure 4.50 shows that the postcyclic undrained strength is indeed closely related to the peak principal effective stress ratio developed in compression during undrained two-way cyclic loading. The decrease in postcyclic undrained strength becomes pronounced when the peak effective stress ratio equals or exceeds appoximately 2. This value corresponds to the threshold effective stress

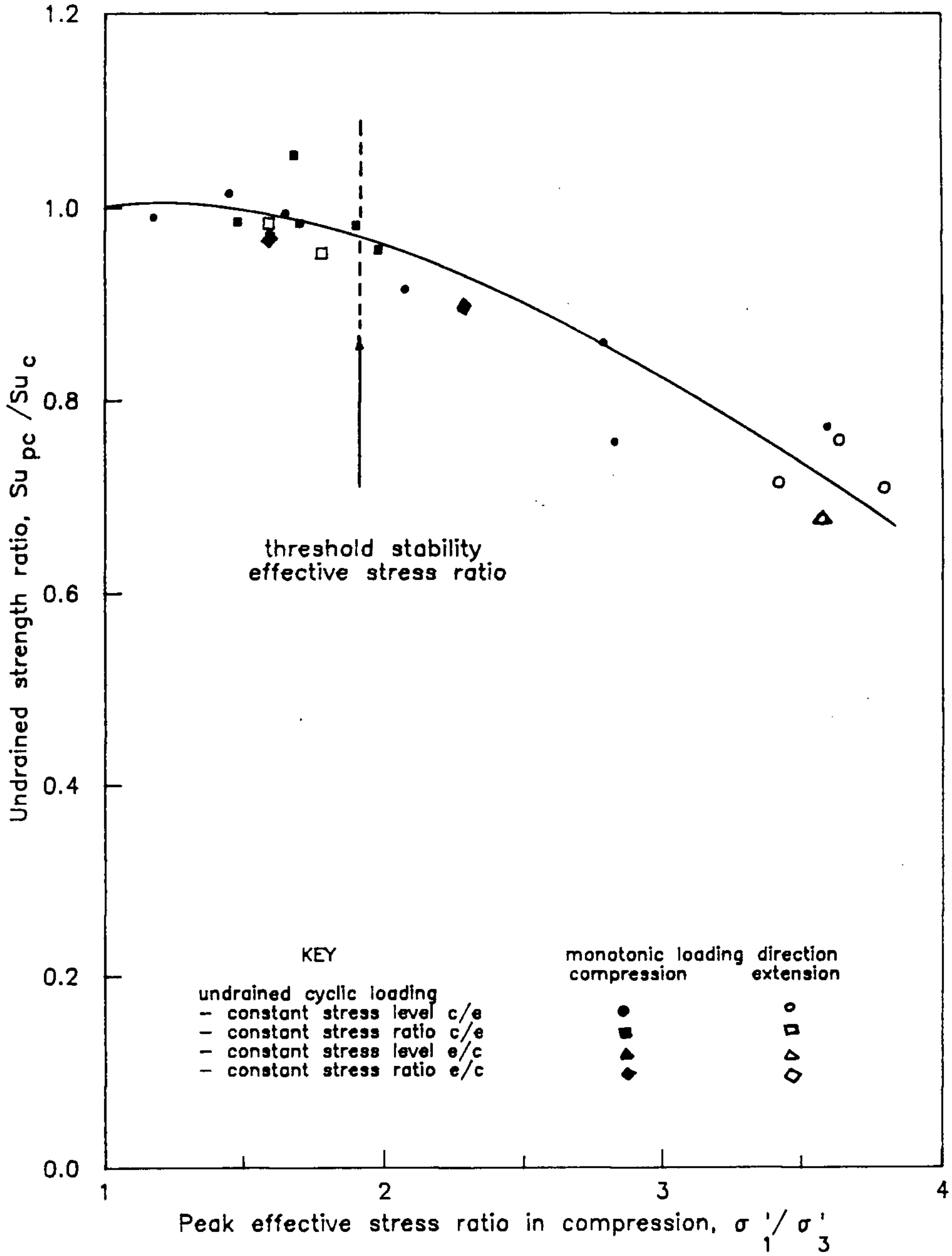


Fig. 4.50 Relationship between peak effective stress ratio in two-way undrained cyclic loading and postcyclic undrained strength.

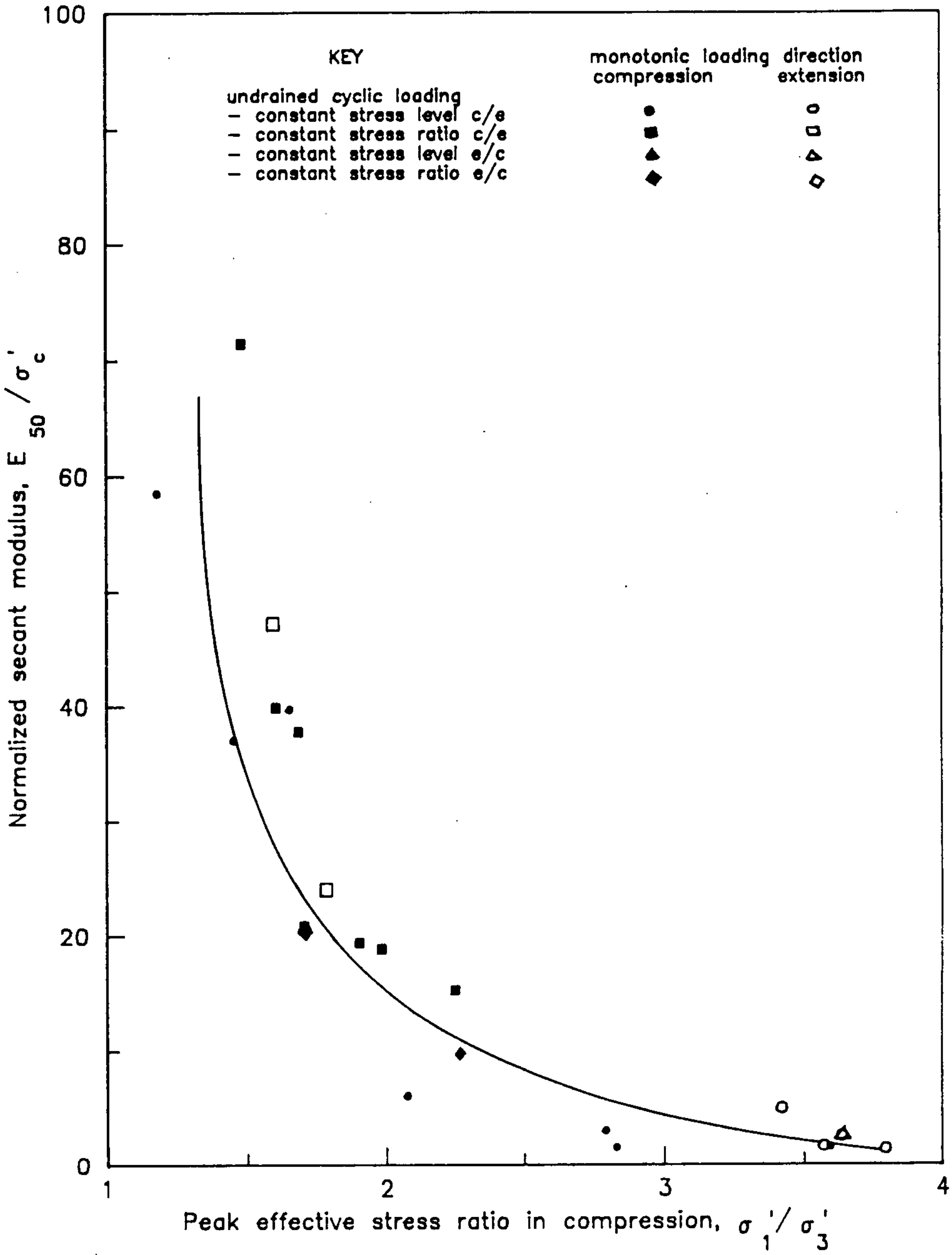


Fig. 4.51 Relationship between peak effective stress ratio in two-way undrained cyclic loading and postcyclic secant modulus.

ratio triggering accelerated strain increase per cycle defined earlier for constant stress amplitude two-way cyclic loading. Therefore, the effective stress ratio threshold that delineates clay stability in undrained cyclic loading also defines the limits of competent clay behaviour in postcyclic undrained monotonic loading. The variation in postcyclic loading secant modulus is also related to the peak effective stress ratio developed during cyclic loading as shown in figure 4.51. Unlike the undrained strength, a large decrease in clay stiffness occurs even before the threshold stability effective stress ratio is mobilized.

The decrease in postcyclic undrained strength and stiffness of normally consolidated clays implies that allowance must be made in design of engineering structures for such reduction in strength and deformation parameters by cyclic loading. The estimate of the reduction in the design parameters may be based on the correlation of the postcyclic undrained strength and stiffness to maximum strain or residual pore pressure (or equivalent overconsolidation ratio) predicted from undrained loading laboratory tests. For postcyclic undrained strength evaluation, undrained monotonic loading on overconsolidated clay specimens would be sufficient based on the equivalent overconsolidation ratio concept. For postcyclic deformation modulus evaluation, constant stress amplitude undrained cyclic loading tests followed by undrained monotonic loading would be necessary. The reduction in undrained deformation modulus caused by cyclic loading is dramatic even at relatively small cyclic or residual strains. Therefore, the evaluation of clay stiffness degradation with cyclic loading could have a more practical significance than the reduction in undrained strength.

Based on the foregoing observations the following conclusions may be formulated on the response of Cloverdale clay to undrained postcyclic loading:

1. The postcyclic strength reduction is small (less than 5 percent) until the maximum strain due to cyclic loading exceeds about half the strain (4 percent) required to mobilize the precyclic reference undrained strength.
2. A large degradation in stiffness occurs even at small maximum strains (less than 0.5 percent) induced by cyclic loading.
3. No relationship between postcyclic undrained strength and hysteretic work is apparent.
4. The relationship between normalized undrained strength and logarithm of OCR is unique. This unique relationship suggests that postcylic undrained strength may be estimated from the undrained strength of stress overconsolidated clay provided that the equivalent consolidation stress is used to define OCR.
5. The similarity between stress overconsolidation and cyclic loading rinduced overconsolidation does not hold for the variation of clay stiffness with OCR. Undrained cyclic loading causes a more pronounced degradation in stiffness than drained stress overconsolidation.
6. The effective stress strength envelopes established under monotonic loading also defines failure in postcyclic loading in both compression and extension.

7. The effective stress ratio threshold that delineates clay stability in undrained cyclic loading also defines the limits of competent clay behaviour in postcyclic undrained monotonic loading.
8. A large decrease in clay stiffness occurs even before the threshold stability effective stress ratio is mobilized.
9. The conclusions outlined above are based on postcyclic compression and extension loading following cyclic compression-extension and extension-compression cyclic loading under both constant stress and constant stress ratio amplitudes. Therefore they suggest that postcyclic loading response may be independent of the manner in which strains and effective stress changes are caused.

SUMMARY AND CONCLUSIONS

The response of isotropically consolidated Cloverdale clay to undrained monotonic and cyclic loading in the conventional triaxial apparatus was described. In monotonic tests the effect of both loading direction and overconsolidation were considered. In cyclic tests a slow rate of loading was preferred to fast cyclic loading to obtain a reliable pore water pressure measurement and carry out an effective stress interpretation of the results. Symmetrical compression-extension and extension-compression stress cycles were imposed to the clay to induce strains and pore water pressure under undrained cyclic loading. Postcyclic monotonic loading was carried out on most specimens to assess the effect of cyclic loading on clay behavior. Test results were analyzed in order to:

- Show the effect of cyclic stress level and initial loading direction on clay behaviour during cyclic reversal in stress and strain; and,
- Define an effective stress threshold stability criterion for both cyclic loading and postcyclic monotonic loading.

This study fills a gap in our knowledge of clay behaviour because previous studies either were limited to slow cyclic tests without stress reversal or suffered from nonreliable pore water pressure measurement in fast cyclic tests with stress reversal. The undrained response of Cloverdale clay to monotonic and fast cyclic loading was similar to that of the extensively studied Drammen clay. Hence, the behaviour of Cloverdale clay would be typical of various marine clays comparable to Drammen clay.

The results of monotonic loading tests led to the following conclusions on the effects of loading direction and overconsolidation ratio (OCR) on the clay behaviour:

1. A strain hardening stress-strain relationship is followed before reaching a plateau at a given axial strain. The axial strain at peak deviatoric stress plateau increases slightly with OCR.
2. When the equivalent normal consolidation stress is used as normalizing parameter, the normalized undrained strength decreases with increasing OCR.
3. The clay stiffness and normalized undrained strength are lower in extension than in compression. The degree of anisotropic stress-strain response is small in comparison with other soft clays but it increases with increasing OCR.
4. The effective stress path followed is typical of soft clays and changes with increasing OCR to reflect the lower pore water pressure development with strain during shear loading.
5. A unique effective stress failure envelope is defined at peak principal effective stress ratio with a mobilized friction angle equal to 32 degrees and no cohesion intercept.

SUMMARY AND CONCLUSIONS

The direct comparison between fast and slow two-way cyclic loading tests on normally consolidated Cloverdale clay specimens with end restraint led to the following conclusions:

1. The degree of pore water pressure nonequalization within the specimens during fast cyclic loading is severe.
2. The degree of pore water pressure nonequalization is not minimized with longer test durations or lower cyclic stress levels.
3. Reliable pore water pressure measurements are obtained only in slow cyclic loading tests.

Slow undrained cyclic test results on normally consolidated Cloverdale clay led to the following conclusions on the effect of cyclic stress level on the clay behaviour:

1. A given cyclic stress level separates the clay response into two distinct patterns. In low cyclic stress levels (less than 0.55) strains and pore water pressure tend toward an equilibrium plateau following a power function with number of cycles. In high cyclic stress levels (higher than 0.55) three stages are distinguished:

   . a primary stage characterized by strain development at a decreasing rate

   per cycle;

   . a secondary stage characterized by strain development at a constant rate per cycle; and,

   . a tertiary stage characterized by strain development at an accelerating rate per cycle.

2. The onset of tertiary stage of cyclic loading response occurs at a given threshold effective stress ratio for all cyclicstress levels higher than 0.55.
3. The envelope formed by the threshold peak effective stress ratio is proposed as an effective stress stability criterion against large strain development during undrained cyclic loading.
4. The effective stress strength envelope in monotonic loading is also the bounding failure line during cyclic loading. However there is no similarity whatsoever between the strain response of Cloverdale clay to two-way undrained cyclic loading and to undrained monotonic loading.
5. For a given number of cycles to various cyclic stress levels, the effective stress state of the clay lies on a unique curve comparable to the stable state boundary surface in monotonic loading.
6. The relationship between principal effective stress ratio and peak axial strain depends both on the cyclic stress level and the loading phase considered.
7. The correlation between cumulative hysteretic work and residual pore water pressure depends on cyclic stress level.
8. Damping ratio is essentially constant for all cyclic stress level.
9. Two-way undrained cyclic loading initiated in extension is more damaging than cyclic loading initiated in compression.

Based on slow undrained cyclic compression-extension test results on normally consolidated Cloverdale clay the following conclusions were derived on the effect of principal effective stress ratio amplitude:

SUMMARY AND CONCLUSIONS

1. A nonfailure equilibrium strain and residual pore water pressure is reached within few cycles.
2. The cyclic stress level delineating clay response leading to an equilibrium condition from the clay response resulting in accelerated strain increase per cycle may be identifed from constant principal effective stress ratio amplitude cyclic loading.
3. The collapsed stable state boundary surface may be located based on constant principal effective stress ratio amplitude tests.
4. A step increase in cyclic stress level shows that the clay behaviour is a function of cyclic stress level, current rate of strain or pore water pressure increase per cycle and cumulative strain or pore water pressure regardless of past cyclic loading history within the same event.

The response of Cloverdale clay to postcyclic undrained monotonic loading indicates that:

1. The postcyclic strength reduction is small (less than 5 percent) until the maximum strain due to cyclic loading exceeds about half the strain (4 percent) to mobilize the precyclic reference undrained strength.
2. A large degradation in stiffness occurs even at small maximum strains (less than 0.5 percent) induced by cyclic loading.
3. No relationship between postcyclic undrained strength and hysteretic work is apparent.

4. The relationship between normalized undrained strength and logarithm of OCR is unique. This unique relationship suggests that postcylic undrained strength may be estimated from the undrained strength of stress overconsolidated clay provided that the equivalent consolidation stress is used to define OCR.
5. The similarity between stress overconsolidation and cyclic loading induced overconsolidation does not hold for the variation of clay stiffness with OCR. Undrained cyclic loading causes a more pronounced degradation in stiffness than drained stress overconsolidation.
6. The effective stress strength envelopes established under monotonic loading also defines failure in postcyclic loading in both compression and extension.
7. The effective stress ratio threshold that delineates clay stability in undrained cyclic loading also defines the limits of competent clay behaviour in postcyclic undrained monotonic loading.
8. A large decrease in clay stiffness occurs even before the threshold stability effective stress ratio is mobilized.
9. Postcyclic loading response may be independent of the manner in which strains and effective stress changes are caused.

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