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THE RESPONSE OF BURIED CYLINDERS
TO QUASI-STATIC OVERPRESSURES

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Research and Technology Division
AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base
New Mexico

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FOREWORD

This report is based on an experimental investigation conducted by the University of New Mexico at the Air Force Shock Tube Facility. During the research, Captain Jack T. Pantall and Captain Thomas F. Dean of the Air Force Weapons Laboratory were Project Officers for the Air Force at the Shock Tube Facility. Dr. Walter E. Fisher and, recently, Major James O. Putnam were Technical Monitors of all research on buried structures.

Special acknowledgment is made to the Director of the Shock Tube Facility, Dr. Eugene Zwoyer. The writer also wishes to acknowledge the contributions of all his colleagues at the facility. He is particularly appreciative of the assistance of Mr. Dwane Brewer, Research Associate Engineer and head of the electronics department at the facility.

ABSTRACT

An experimental investigation was conducted into the response of small buried aluminum cylinders to quasi-static overpressures. The cylinders were buried with their axes horizontal in dense, dry, 20-30 Ottawa sand.

Cylinders of two stiffnesses were tested at depths ranging from zero to two cylinder diameters. Their behavior was evaluated quantitatively by radial displacement gages and tangential strain gages. Data at five overpressure levels up to 140 psi are presented. This maximum value exceeded the theoretical in-air primary buckling pressure of the cylinders by factors of 9.4 and 99.

Destructive tests were conducted on noninstrumented cylinders of six stiffnesses. This maximum applied overpressure was 160 psi, 470 times the theoretical in-air primary buckling pressure of the most flexible cylinder. The overpressure required to cause collapse of the various cylinders was determined for as many depths of burial as the maximum overpressure would allow.

The destructive tests demonstrate the great resistance to collapse imparted to a cylinder by burial. The nondestructive tests afford a comparison between the behavior of stiff and flexible cylinders as the depth of burial and the overpressure are changed. Two zones of burial, deep and shallow, are defined. These zones depend on the rigidity of the cylinder and the magnitude of the overpressure.

PUBLICATION REVIEW

This report has been reviewed and is approved.

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1. INTRODUCTION.

The soil-structure interaction problem is not new. One aspect of it, that of the culvert and tunnel, has been the subject of much theoretical and experimental study.[1-7] The known high load-carrying capacity of the culvert and tunnel, together with other advantages associated with burial, has attracted the attention of those charged with the design of facilities (so-called protective structures) to resist the effects of nuclear blast environment.

Heretofore, the design of buried structures was concerned mainly with a static gravity stress field. But the criterion that a facility withstand high blast overpressures introduced two new aspects to an already difficult problem. Both concern the applied overpressure. First, it is dynamic in nature; and second, its magnitude is such that at practical depths the effects of gravity are negligible.

A portion of the research effort at the Air Force Shock Tube Facility is directed toward an understanding of the parameters involved in the design of protective structures. These parameters include the structure's shape and stiffness, the engineering properties of the surrounding medium, the depth of burial of the structure, and the peak magnitude and time history of the applied overpressure.

This investigation was concerned with the response to quasi-static overpressures of small cylindrical structures (4-inch ID) buried with their axes horizontal in dense, dry, 20-30 Ottawa sand.

The first phase of the investigation dealt with nondestructive tests on instrumented cylinders. The program allowed variations in the stiffness of the cylinders, the depth of burial, and the overpressure level.

Destructive tests on noninstrumented cylinders were conducted in the second part of the investigation. The intent was to determine the overpressure required (maximum available, 160 psi) to cause collapse of cylinders of various stiffnesses over as great a range in depth of burial as the maximum overpressure would allow.

2. SUMMARY OF PREVIOUS WORK.

It is the writer's opinion that Robinson,[8] Bulson,[9] and Whitman and Luscher[10] have produced the most significant experimental reports on the behavior of small buried cylinders under quasi-static loading.

Robinson[8] describes the results of four tests on steel and two tests on aluminum cylinders. All cylinders were 6 inches in diameter and horizontally oriented in dry Ottawa sand (density 109 lb/cu ft). The diameter/thickness (d/t) values of the steel cylinders were 80 and 120 while the d/t value of the aluminum cylinder was 120. To compare the stiffness of steel cylinders with the stiffness of aluminum cylinders, the writer divided the values for the steel cylinders by three (the ratio of Young's moduli). All tests were conducted in a steel bin (3 feet ID by 3 feet long) at a constant depth of burial of two and one-half cylinder diameters and with a 100-psi maximum overpressure.

The instrumentation on each cylinder consisted of four sets of tangentially mounted back-to-back strain gages and a displacement gage capable of being rotated to give 360° coverage. Vertical displacements at four points on the sand surface were also recorded.

Bulson[9] describes the esults of a series of 56 quasi-static tests on steel cylinders buried in a dense sand. The diameters ranged from 5 to 10 inches. Sheet thickness was in the range of 0.011 to 0.022 inch. Diameter/thickness values of the cylinders varied from 400 to 1,000. Again, for comparison with aluminum cylinders, these d/t values were divided by three. The test bin was 5 feet by 2 feet in plan by 3 feet deep. The depth of burial was either 3/4 or 3/8 of the diameters of the cylinders. The maximum overpressure varied from test to test, but did not exceed 75 psi. The deformations of the cylinders were monitored by a displacement gage which was rotated to give 360° coverage. A high speed movie camera was used to record the collapse.

The program conducted by Whitman and Luscher[10] was of a different nature. By means of three series of tests, they demonstrated the two mechanisms by which a structure increases its resistance to collapse by virtue of its embedment in a medium possessing shear strength. The first series involved the testing of hollow cylinders of sand supported by membranes under pressure on both the internal and external surfaces. Failure was precipitated by increasing the pressure on the external membrane. In the second series, the in-air collapse pressure of a thin flexible tube was determined. The third series determined the uniform radial pressure required to cause collapse of flexible tubes when the tubes were surrounded by sand cylinders. The two components of these composite structures were identical to those tested in the first two series.

The increase in strength of a sand-surrounded tube over its in-air strength was attributed to two effects. One was called the "arching effect." Arching is a stress-transfer phenomenon caused by a modulus mismatch between a structure and the surrounding medium.[3,4,5,6,7,11] The other was called the "deformation-interference effect," to which all other increases in strength over the in-air strength were attributed.

The maximum arching effect was determined in the first series. The deformation-interference effect could be evaluated from the results of the series of tests on the composite structures, with prior knowledge of the strength of unsupported tubes and the arching effect. The arching effect was found to be an important factor for the radially symmetric condition of the tests, but was far outweighed by the deformation-interference effect.

As far as the writer is aware, these results constitute the only qualitative evaluation of the two effects. In a consideration of structures buried in a cohesionless material, regardless of the stress field, this contribution is very significant.

3. EXPERIMENTAL PROGRAM.

a. Scope of investigation.

The experimental program was divided into two parts: (1) nondestructive testing of instrumented cylinders, and (2) destructive testing of noninstrumented cylinders.

The test cylinders described by Robinson[8] and Bulson[9] varied from very stiff to very flexible (the equivalent aluminum d/t values ranged from 27 to 333) Testing outside of this stiffness range would have involved the problems of handling an impracticably flexible cylinder at one end of the scale and eliciting a measurable response in the range of overpressure (140-psi maximum) at the other end of the scale. For the instrumented cylinders, two d/t values (114 and 250) were chosen to fit conveniently between these extremes.

The program was designed to alleviate somewhat the paucity of information on the effects of variation in depth of burial of the test cylinders. Tests were conducted at as many as eleven different depths, ranging from zero to two cylinder diameters. The maximum overpressure in the nondestructive tests was 140 psi.

The primary goal of the destructive tests was to determine the collapse overpressure for cylinders of as many stiffnesses and over as great a range in depth of burial as the maximum overpressure would allow. However, the practical limitation on the maximum overpressure (160 psi) and the great increase in resistance to collapse imparted to a cylinder by burial combined to curtail the extent of destructive testing.

Dense Ottawa sand was used as the surrounding medium in all tests.

b. <u>Description of cylinders</u>.

All the structures tested were aluminum cylinders, 4 inches ID by 16 inches long. The ends of each cylinder were sealed by tight-fitting plates which were held apart by an axial rod so that the axial forces on the plates were borne by the rod and not by the cylinder (fig. 1).

Instrumented cylinders of two stiffnesses were used. The stiffer cylinder was a commercially available drawn tube of 6061-T4 aluminum with 0.035-inch wall thickness. The more flexible cylinder was fabricated at the Shock Tube Facility from 2024-0 aluminum sheet of 0.016-inch thickness, using a 1/4-inch epoxied lap joint. The d/t values of the two types of cylinders were 114 and 250, respectively. The theoretical in-air primary buckling pressure ($p_{cr} = \frac{2E}{1 - \nu^2} \left(\frac{t}{d}\right)^3$, Timoshenko)[12] for these two cylinders is 14.9 and 1.41 psi, respectively. The maximum overpressure exceeded these theoretical values by factors of 9.4 and 99.

The cylinders used in the destructive tests were also manufactured from 2024-0 aluminum sheet with thicknesses of 0.010, 0.012, 0.016, 0.020, and 0.025 inch, giving d/t values of 400, 333, 250, 200, and 160, respectively. The theoretical in-air primary buckling pressures for these cylinders are presented in table 1. These pressures range from 0.34 to 5.37 psi.

Young's modulus for both alloys is 10×10^6 psi. The yield strength, based on 0.2-percent permanent strain, is 16,000 psi for 6061-T4 aluminum and 8,000 psi for the 2024-0 aluminum.[13]

c. <u>Test technique</u>.

The cylinders were tested in a horizontal orientation in a bin, 30 inches in diameter and 16 inches deep, containing dense, dry, 20-30 Ottawa sand. The sand was sieved into position by

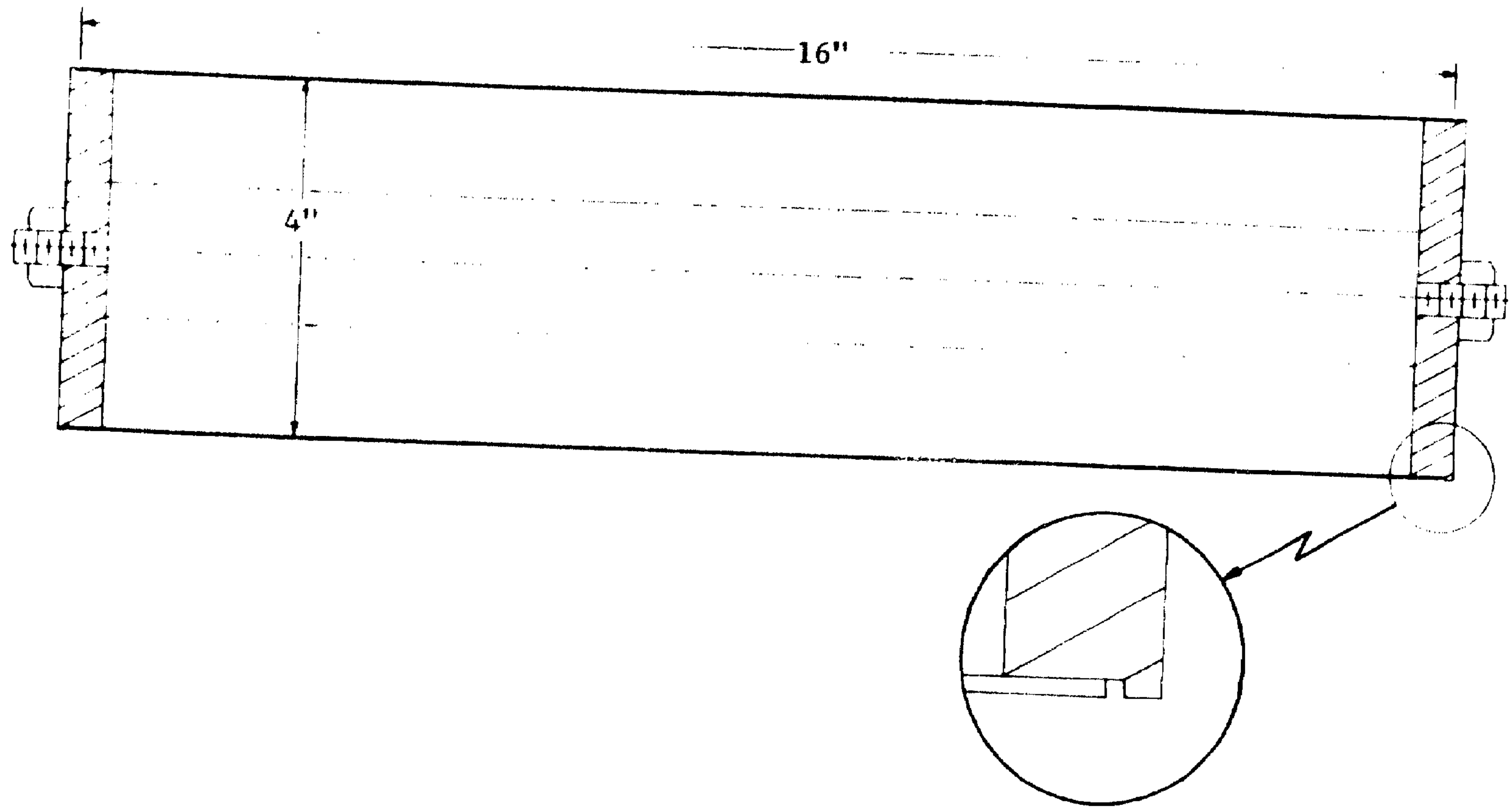


Figure 1. Longitudinal section of 4-inch-ID aluminum cylinder

Table 1

RESULTS OF DESTRUCTIVE TESTS

Cylinder stiffness (d/t)	Theoretical in-air primary buckling pressure, $p_{cr} = \frac{2E}{1 - v^2} \left(\frac{t}{d}\right)^3$ (psi)	Experimental collapse overpressure (psi)			
		c/d = zero	c/d = 1/16	c/d = 1/8	c/d = 1/4
400	0.34	12 (35 p_{cr})	42 (124 p_{cr})	90 (265 p_{cr})	--
333	0.59	18 (31 p_{cr})	84 (142 p_{cr})	152 (257 p_{cr})	--
250	1.41	28 (20 p_{cr})	133 (94 p_{cr})	137 (97 p_{cr})	--
200	2.75	40 (15 p_{cr})	140 (51 p_{cr})	--	--
160	5.37	--	--	--	--

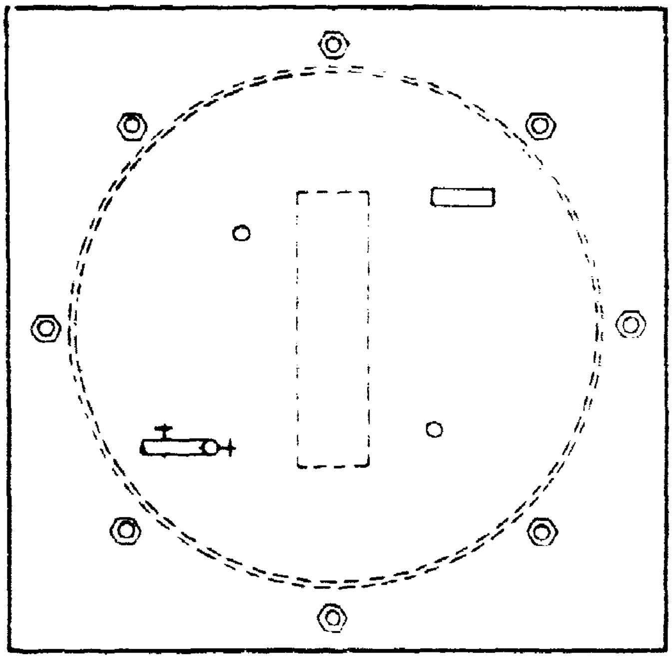
allowing it to fall free through a flexible hose, funnel, and screen.[14] The height of fall from the end of the hose to the surface of the sand varied from 12 to 18 inches.

The surface of the sand was maintained as close to horizontal as possible during placement. When the sand reached a required level in the bin, the cylinder to be tested was placed on the sand surface. Care was taken to minimize the generation of failure zones in the sand. The sieving continued until the surface of the sand reached a level 1/4 inch below the top of the bin. The sand adjacent to the invert of the cylinder was deflected into place in order to maintain a horizontal surface and thus avoid the formation of local shear failures.

An air-tight rubber membrane which extended over the rim of the bin was placed carefully on top of the sand surface. The top cover plate was then put in position and tightened down. The surcharge, in the form of air pressure on top of the membrane, was applied at the rate of about 5 psi per second and then released. The maximum pressure was 160 psi for destructive tests and 140 psi for nondestructive tests. Lower values were used in the testing of the more flexible, instrumented cylinder to avoid its collapse and the destruction of the displacement gages. The purpose of the membrane was to transfer the applied overpressure to the sand skeleton and thereby duplicate the effective stress condition which would prevail in a dry, cohesionless material in the field as a result of an in-air nuclear detonation.

Figure 2 shows a plan and elevation of the test bin.

The method of placing a dense sand around a flexible cylinder proved satisfactory. The average unit weight throughout the bin was 113 lb/cu ft (void ratio 0.47). In about half the tests the variation in average unit weight was less than 0.4 lb/cu ft, and in only about ten percent of the tests did it exceed 1 lb/cu ft.



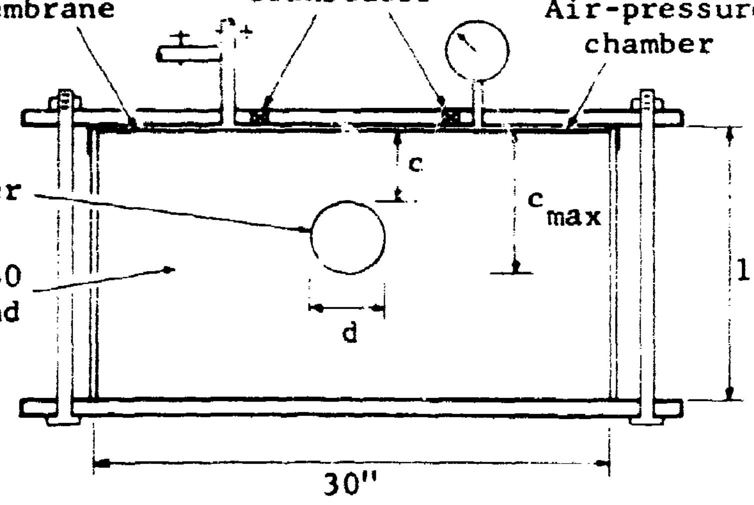


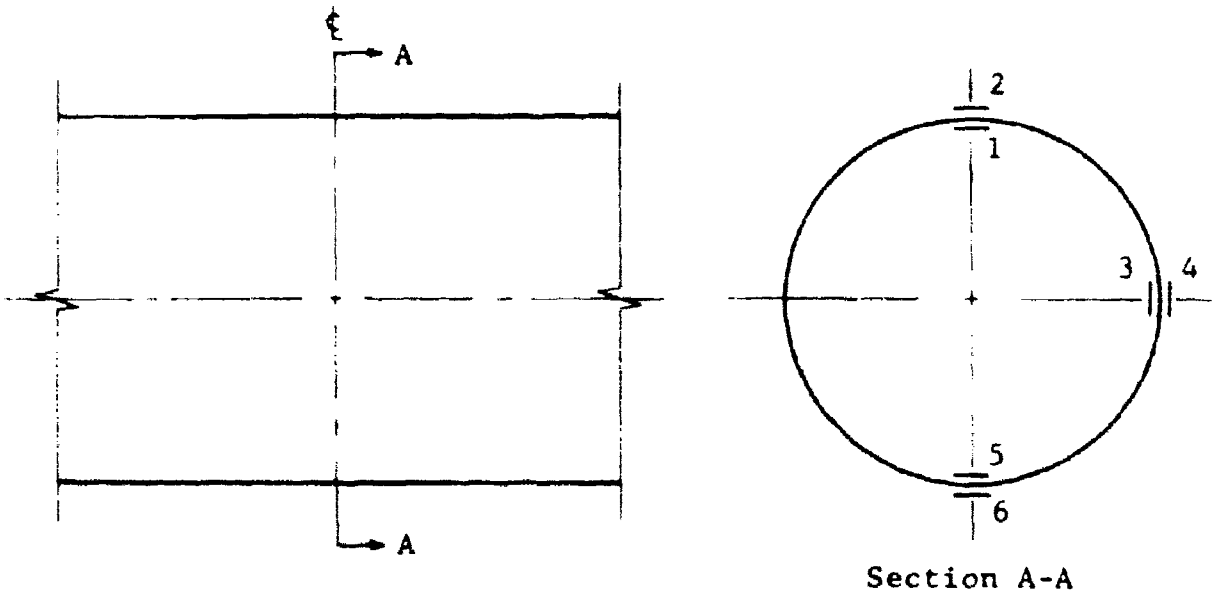
Figure 2. Plan and elevation of test bin

Due to the reproducibility of the average unit weight it seems reasonable to suppose that a uniformly dense condition was obtained, with the possible exception of the small volume of sand adjacent to the invert of the cylinder which was deflected into place. It is not known what, if any, variations occur in the density of this deflected sand.

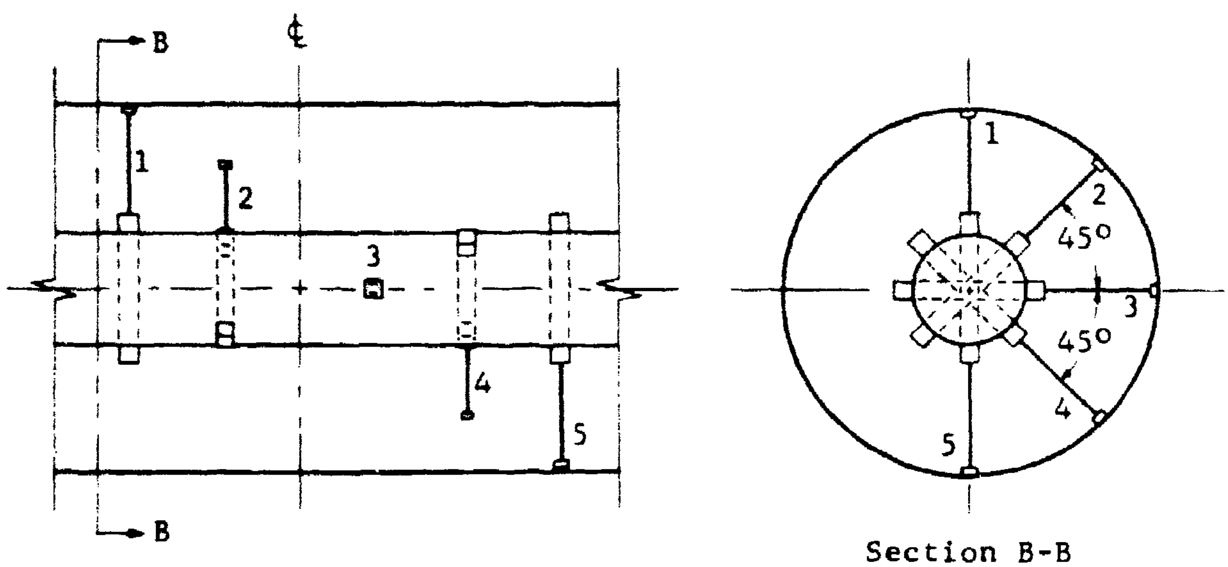
d. Instrumentation.

The response of each instrumented cylinder throughout the loading and unloading cycles was monitored continuously by means of six electric strain gages and five electric displacement gages. Type A-14, wire-wound, paper-back strain gages manufactured by the Baldwin-Lima-Hamilton Corporation were used. Linear potentiometers manufactured by both Computer Instruments Corporation and Bourns, Incorporated were used as displacement gages. The strain gages were mounted circumferentially at mid-length of the cylinders on both the inner and outer surfaces at the crown, springline, and invert (fig. 3a). The readings from each set of back-to-back gages enabled the strain in the wall of the cylinder to be broken into the direct and flexural components. The displacement gages were installed to register the relative displacement between the cylinder wall and the stiff axial rod supported by the end plates (fig. 3b). Two Dynisco model 25-1C linear pressure transducers were installed in the cover plate to monitor the overpressure in the nondestructive tests.

The collapse overpressures of the noninstrumented cylinders in the destructive tests were read on a Bourdon gage. The moment of collapse was marked by a sudden reduction in overpressure and a sharp report. The locations of the pressure transducers and the Bourdon gage are shown in figure 2.



(a) Strain gages



(b) Displacement gages

Figure 3. Arrangement of gages

e. Cautionary remarks.

In the testing of small buried structures, there are many sources of error. These include shortcomings in the test technique itself and inevitable errors in the recording and reduction of data.

There is a definite possibility that silo-type arching* in the test bin itself may have influenced the behavior of the buried cylinders. In a carefully built apparatus in which total loads at both ends of a rigidly contained column of dense, 20-30 Ottawa sand were measured hydraulically, Abbott[15] reported measuring only about 85 percent of the applied load when the height/diameter value of the sand was 0.315. In the writer's investigation, the ratio between the maximum cover over the test cylinders and the diameter of the test bin was only 0.267. Hence, it is unlikely that silo effects distorted the trends in the data.

It is recognized that a cylinder length/diameter value of four would inhibit the development of the in-air primary buckling mode. However, the end restraints play a smaller and smaller role as the order of the buckling mode increases.

In addition, there are inevitable errors in the calibration of gages and in the processing of data. Reduced data, from tests conducted under supposedly identical conditions, which differ by less than 20 percent are considered satisfactory. The reader should bear this in mind when terms such as "constant" and "linear" are used in connection with the data.

*Silo-type arching is the mechanism by which load is transferred by shear from the contained material to the sides of the container. The phenomenon is observed in grain silos.

4. PRESENTATION OF DATA.

The data from the tests on instrumented cylinders were obtained in the form of traces of gage output versus time on Polaroid pictures. The sweep speed was 5 sec/cm. The vertical grid lines on the pictures corresponded to the same times in any one test. No time lag between the application or release of pressure, as recorded by the pressure gage, and the response of any displacement or strain gage could be determined. It was thus possible to line up the pressure-time traces with the gage output-time traces and read the output of the gages at any desired overpressure level. Overpressure levels of 10, 30, 50, 100, and 140 psi (the maximum value) were chosen arbitrarily for the portrayal of the data. Figure 4 shows the manner in which the gage data were correlated with the pressure-time traces.

For purposes of plotting and analysis, the deflections (δ) and the depths of cover (c) were normalized by dividing by the diameter of the structure (d). The normalized deflection was then expressed as a percentage. In the majority of cases at least three tests were conducted at each depth of burial. Only the average value from each level was plotted.

For the stiffer structure ($d/t = 114$), the displacement-gage data are presented in figures 5-9. The upper plot in each of these figures shows the relationship between the normalized deflection, expressed as a percentage ($100\ \delta/d$), and the normalized cover (c/d) for each of five overpressure levels. The lower plot in figures 5-9 shows the variation in the normalized deflection with overpressure for various c/d values. For clarity, the curves corresponding to many c/d values were omitted.

The data from each of the three sets of back-to-back strain gages for the same cylinder were plotted in figures 10-15. For strain gages 1 and 2 at the crown, the total strains were plotted

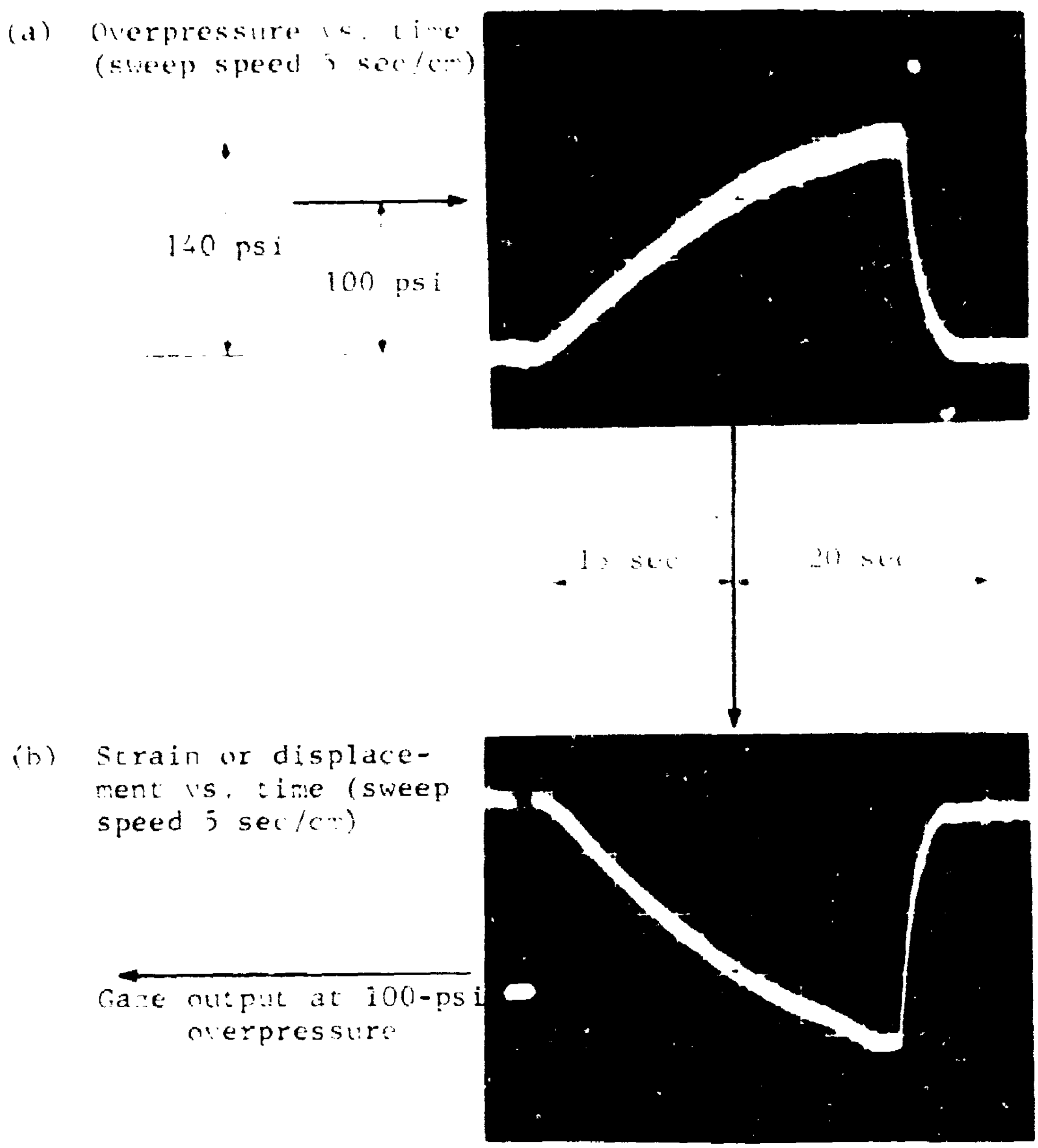


Figure 4. Correlation of gage output with overpressure

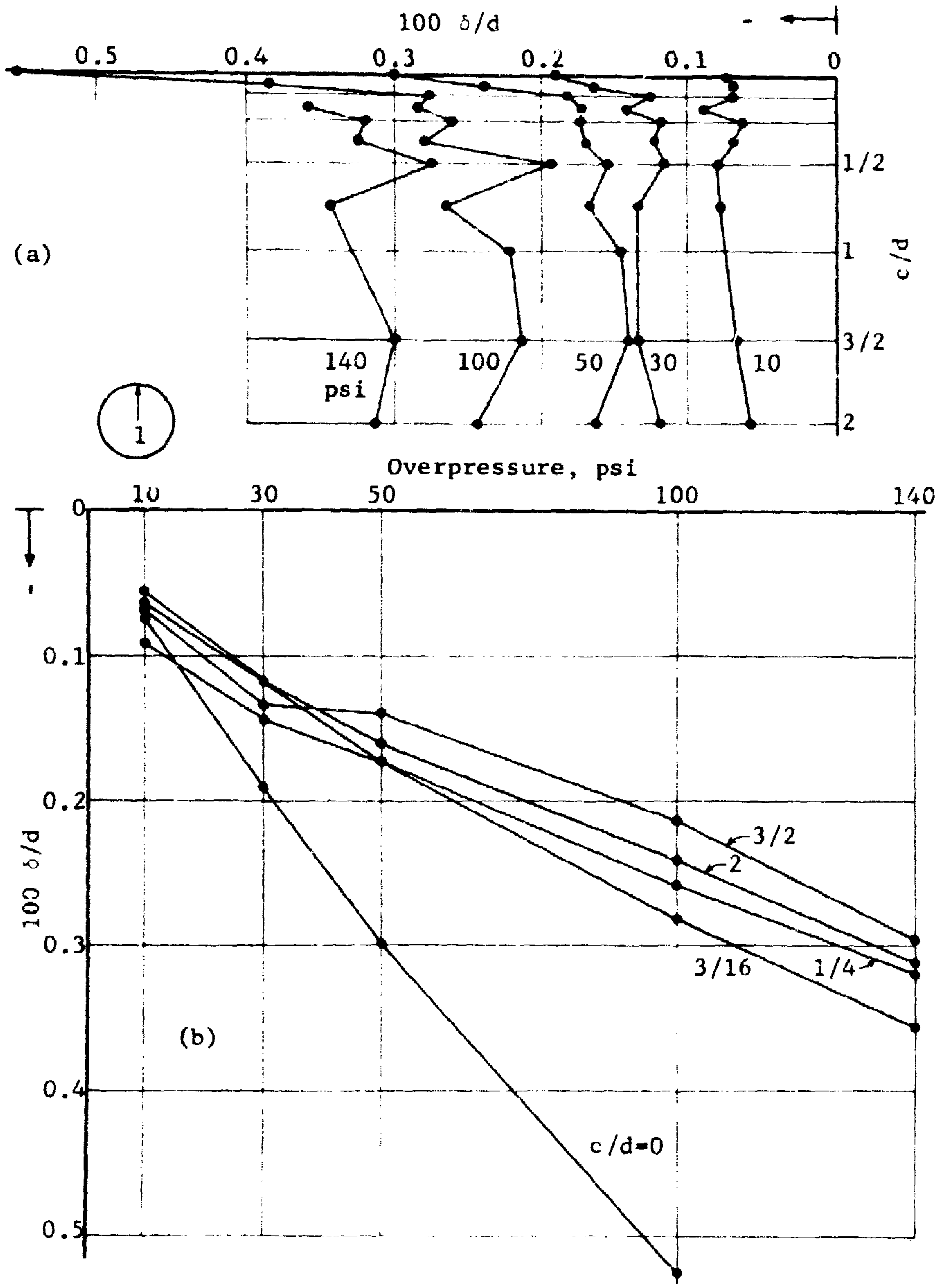


Figure 5. Normalized radial displacements at crown (d/t = 114)

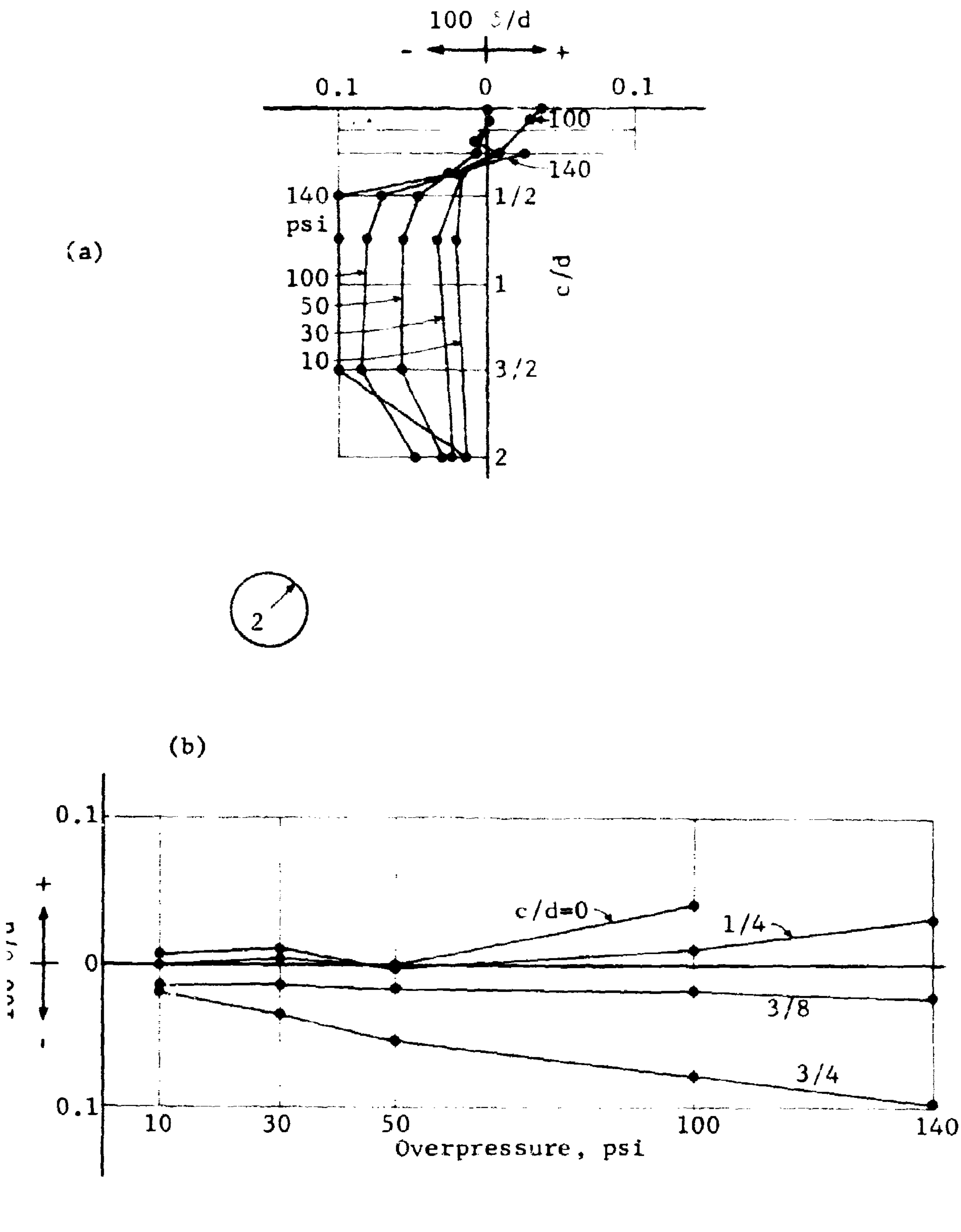


Figure 6. Normalized radial displacements, 45° above springline (d/t = 114)

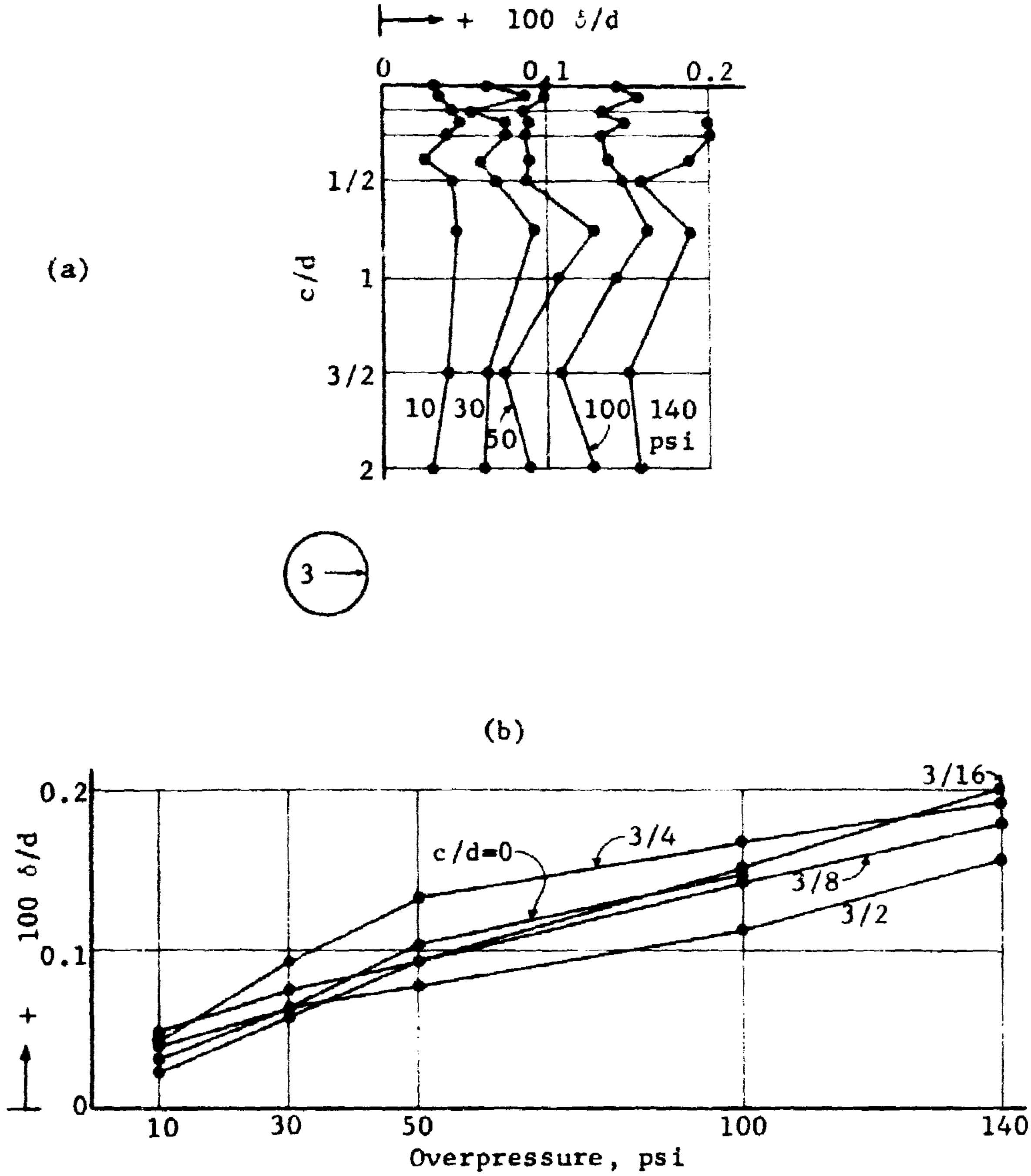


Figure 7. Normalized radial displacements at springline (d/t = 114)

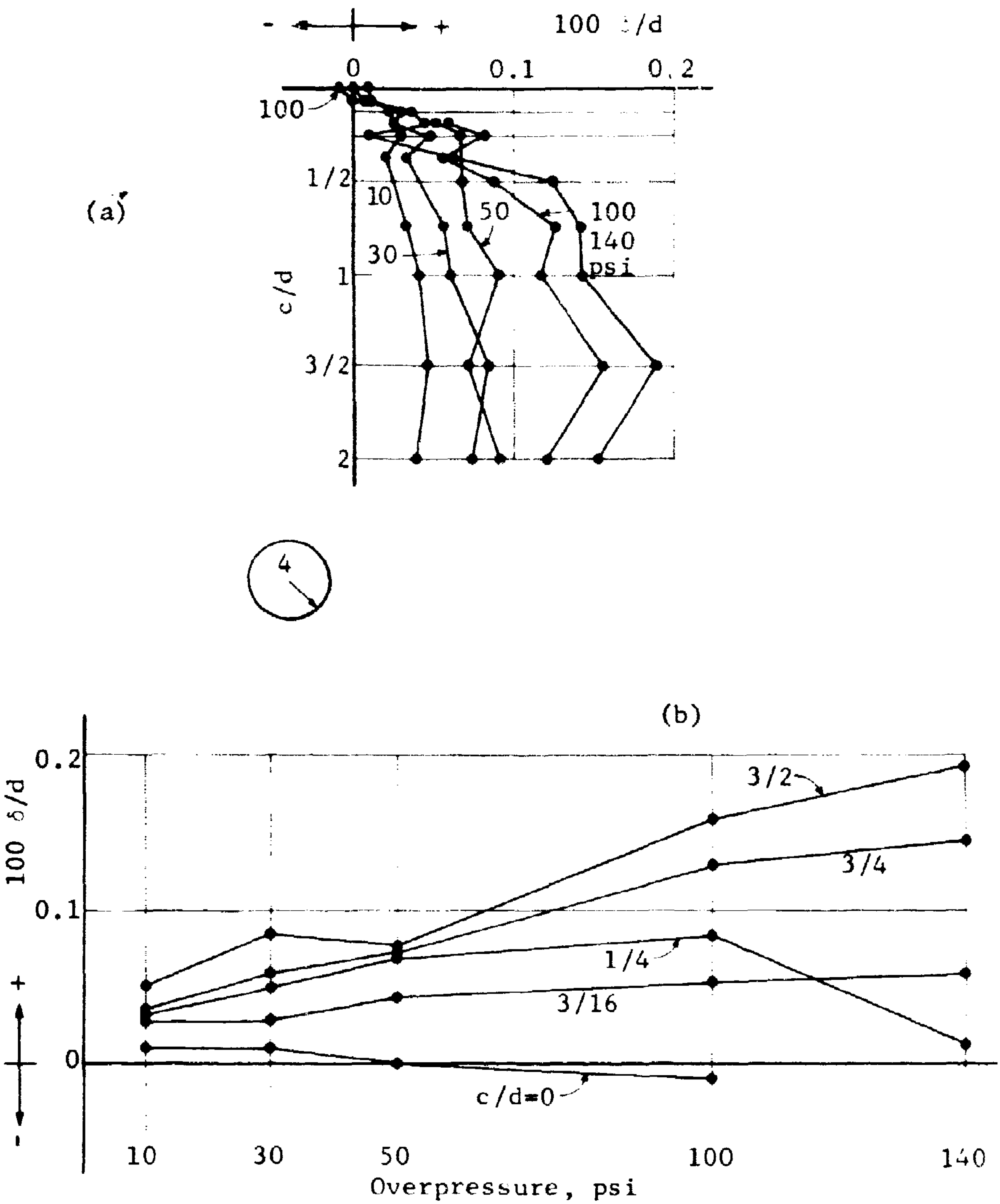


Figure 8. Normalized radial displacements, 45° below springline (d/t = 114)

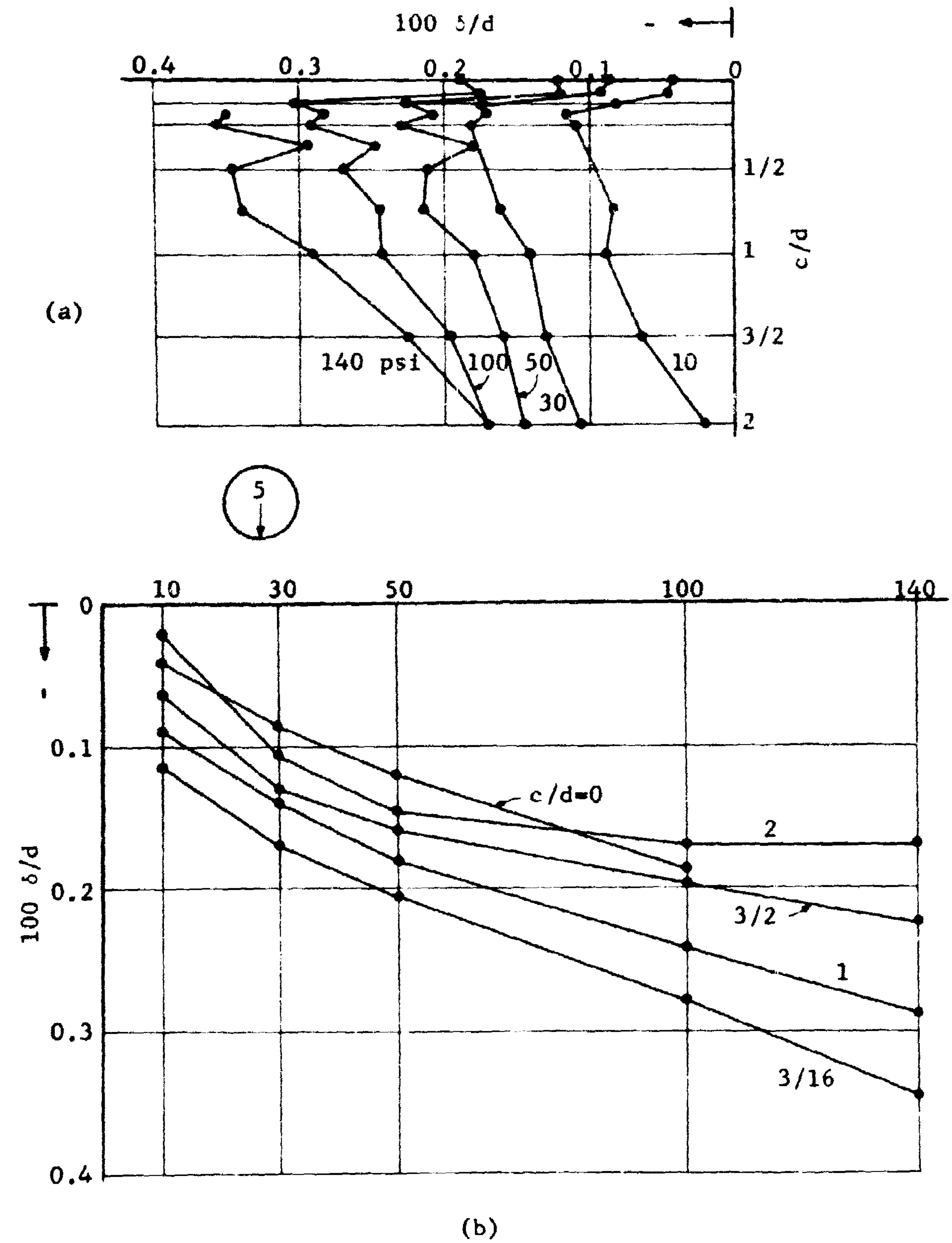


Figure 9. Normalized radial displacements at invert (d/t = 114)

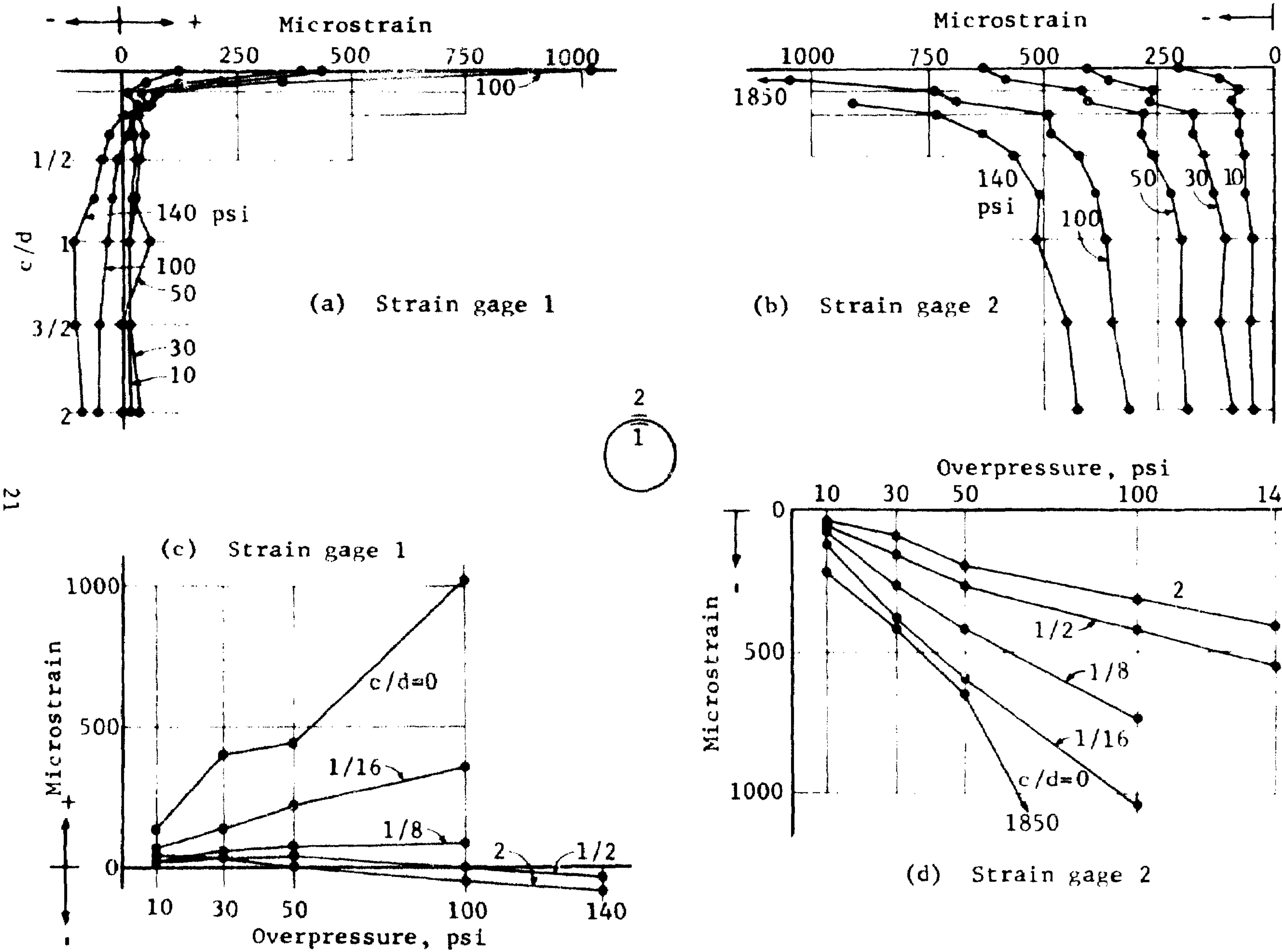
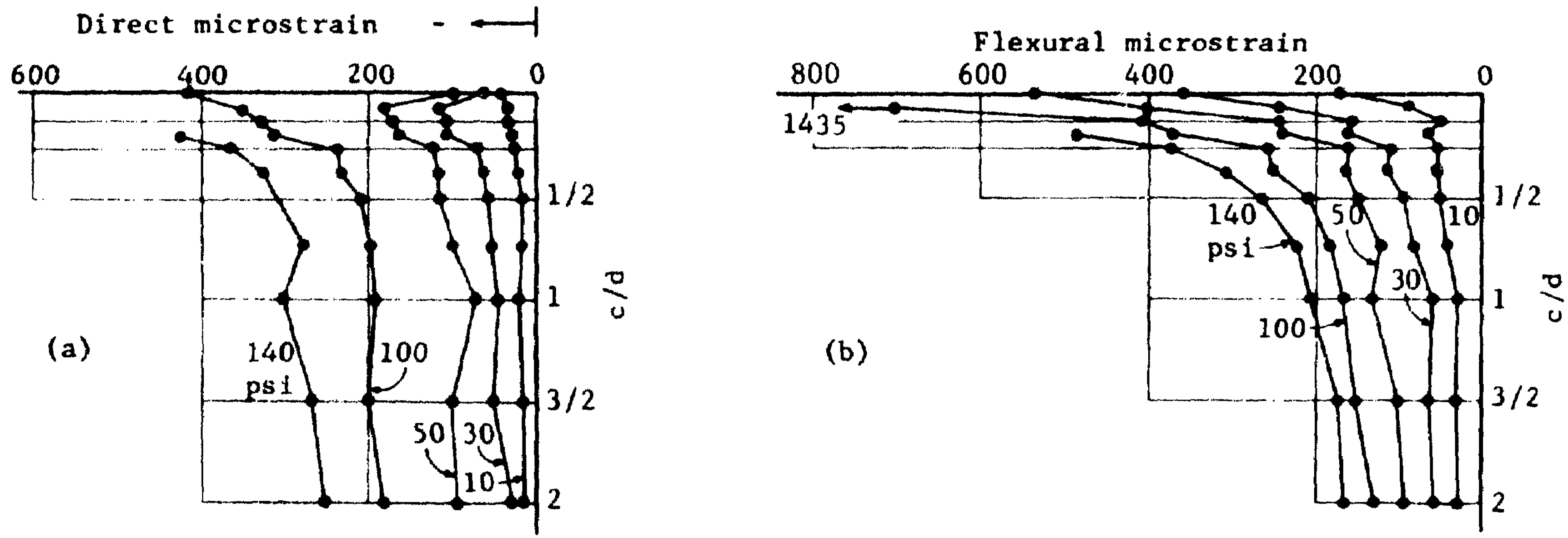


Figure 10 Strai

Figure 12. Strains at springline (d/t = 1[illegible])



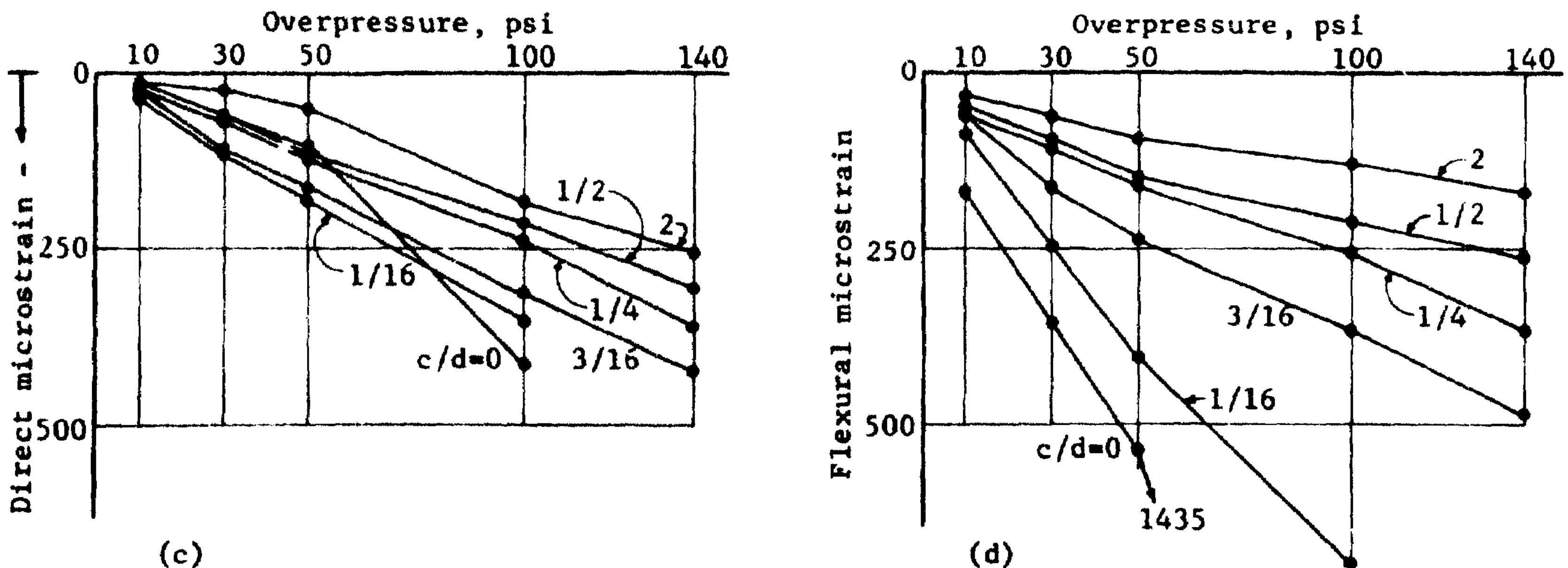
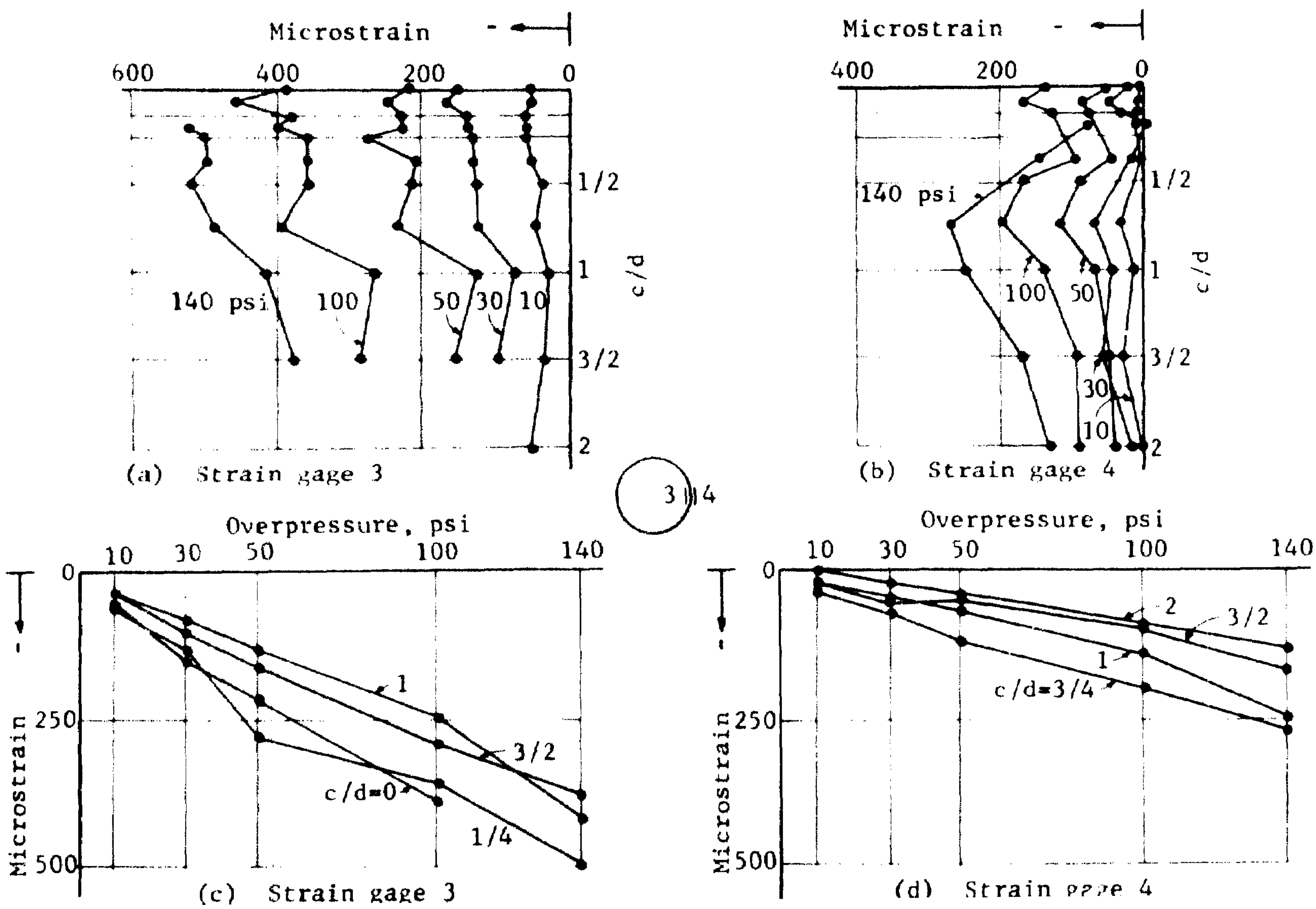


Figure 11. Direct and flexural strains at crown (d/t = 114)



(a) Strain gage 3

(b) Strain gage 4

(c) Strain gage 3

(d) Strain gage 4

(c) Strain gage 5

(d) Strain gage 6

Figure 14. Strains at invert (d/t = 114)

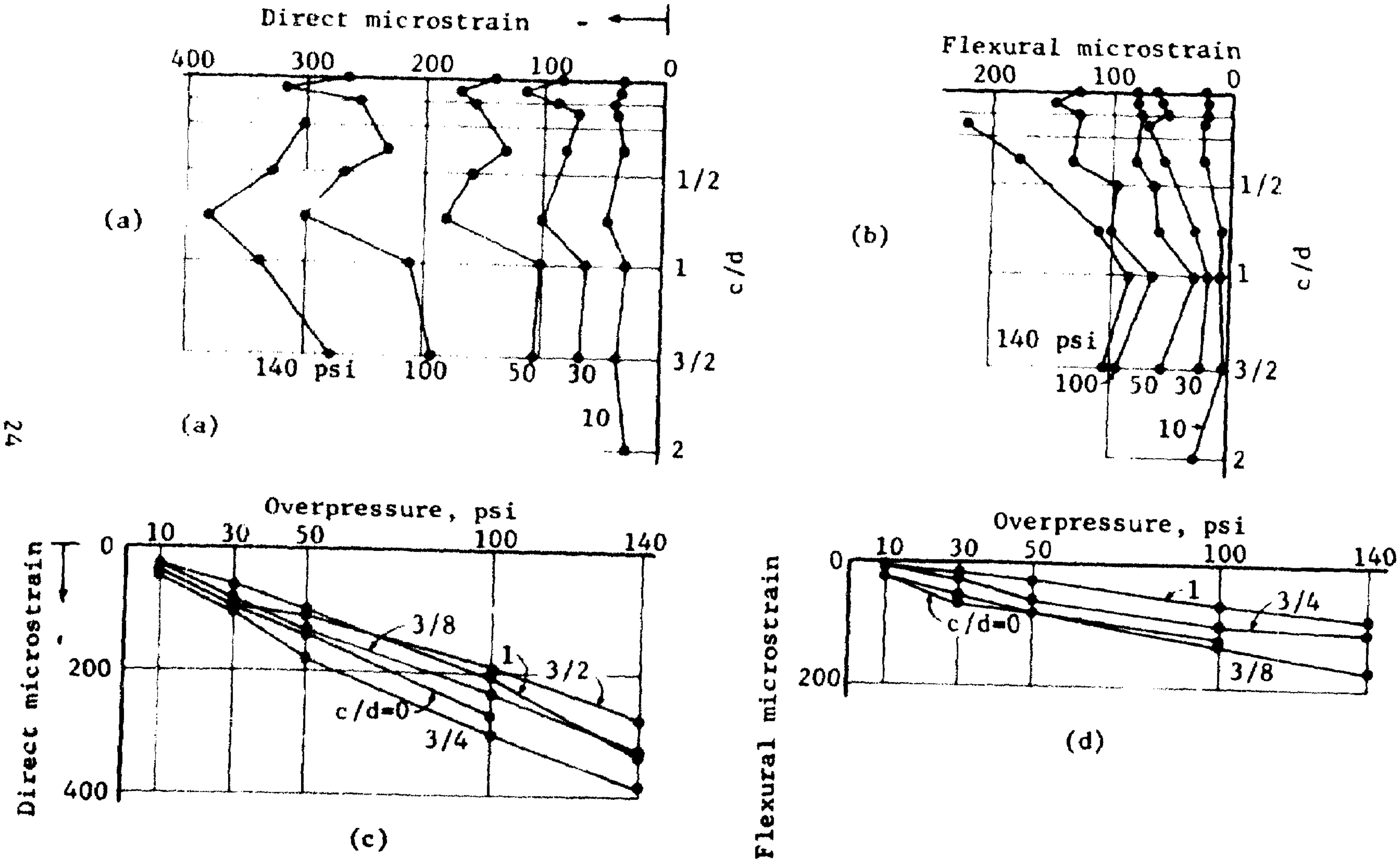
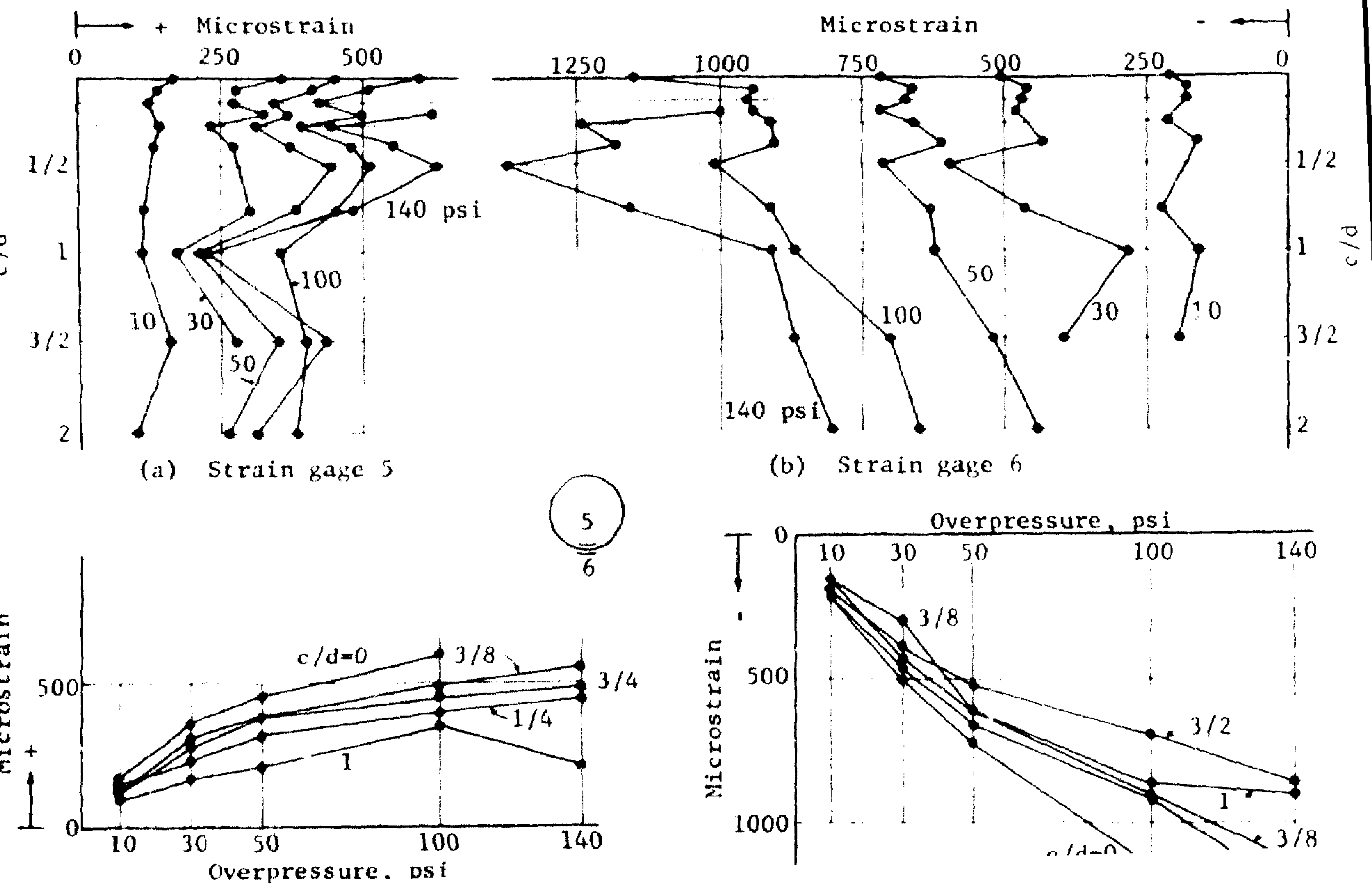


Figure 13. Direct and flexural strains at springline (d/t = 114)


+ Microstrain
0
250
500
Microstrain
1250
1000
750
500
250
0
c/d
1/2
1
3/2
2
140 psi
100
50
30
10
(a) Strain gage 5
(b) Strain gage 6
5
6
Microstrain
500
0
10
30
50
100
140
Overpressure, psi
c/d=0
3/8
3/4
1/4
1
Overpressure, psi
Microstrain
500
1000
3/2
1
3/8
c/d=0

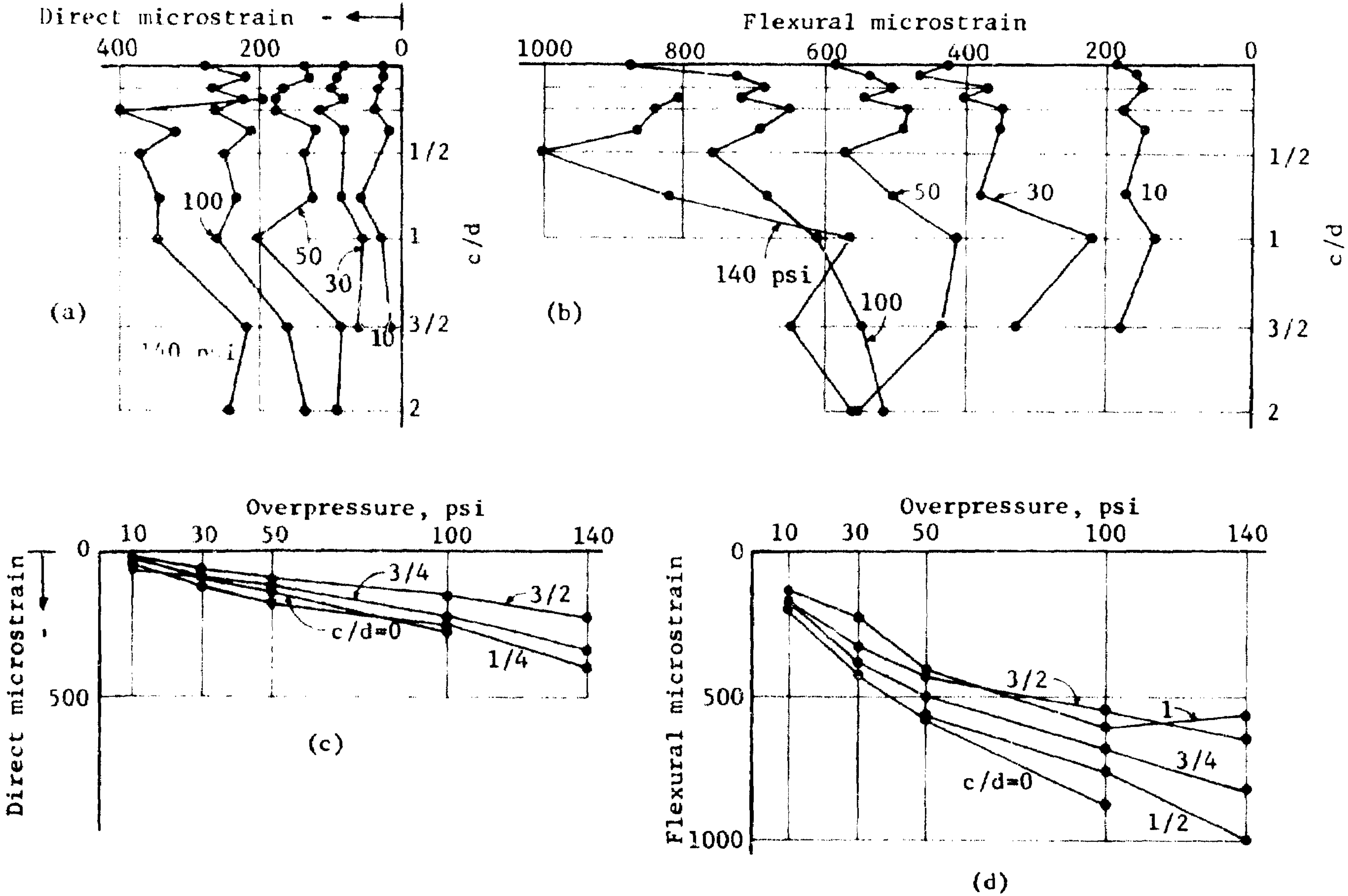


Figure 15. Direct and flexural strains at invert (d/t = 114)

versus c/d for five overpressure levels in figures 10a and 10b.*
The same data were plotted versus overpressure for various c/d values in figures 10c and 10d. The direct and flexural strains were plotted versus c/d in figures 11a and 11b and versus overpressure in figures 11c and 11d. Similar plots of the data from the other two sets of back-to-back strain gages were drawn in figures 12 and 13 for the springline and in figures 14 and 15 for the invert.

Figures 16 and 17 show the variations in displacement and the two components of strain around the structure at two c/d values. No pretense is made that the curves connecting the data points are even qualitatively correct, especially since Bulson[9] has found modes of high order in the vicinity of the invert. However, the writer is of the opinion that this was due to the high flexibility of the cylinders used by Bulson.

An effort was made to avoid the inclusion of many similar plots; those presented were selected to illustrate behavior of cylinders at both deep and shallow burial. In this report, a cylinder is considered to be deeply buried when the phenomena observed are independent of or, at least, vary little with c/d in the overpressure range tested. A cylinder is considered to be shallow buried when the observed phenomena vary considerably with c/d in the overpressure range tested. These definitions proved satisfactory, as the distinction was quite sharp. It was best exemplified by the displacements and strains at the crown (figs. 5, 10, and 11). An examination of these figures shows that the cylinder in question (d/t = 114) can be considered deeply buried for the conditions of this test series when c/d equals 3/4. Figure 16 shows the normalized radial displacement, direct strain, and flexural strain corresponding to this c/d value.

*In figure 10 and in subsequent figures, microstrain = strain, in./in.

Figure 15. Normalized radial displacement, direct strain, and flexural strain (d/t = 114, c/d = 1/16)

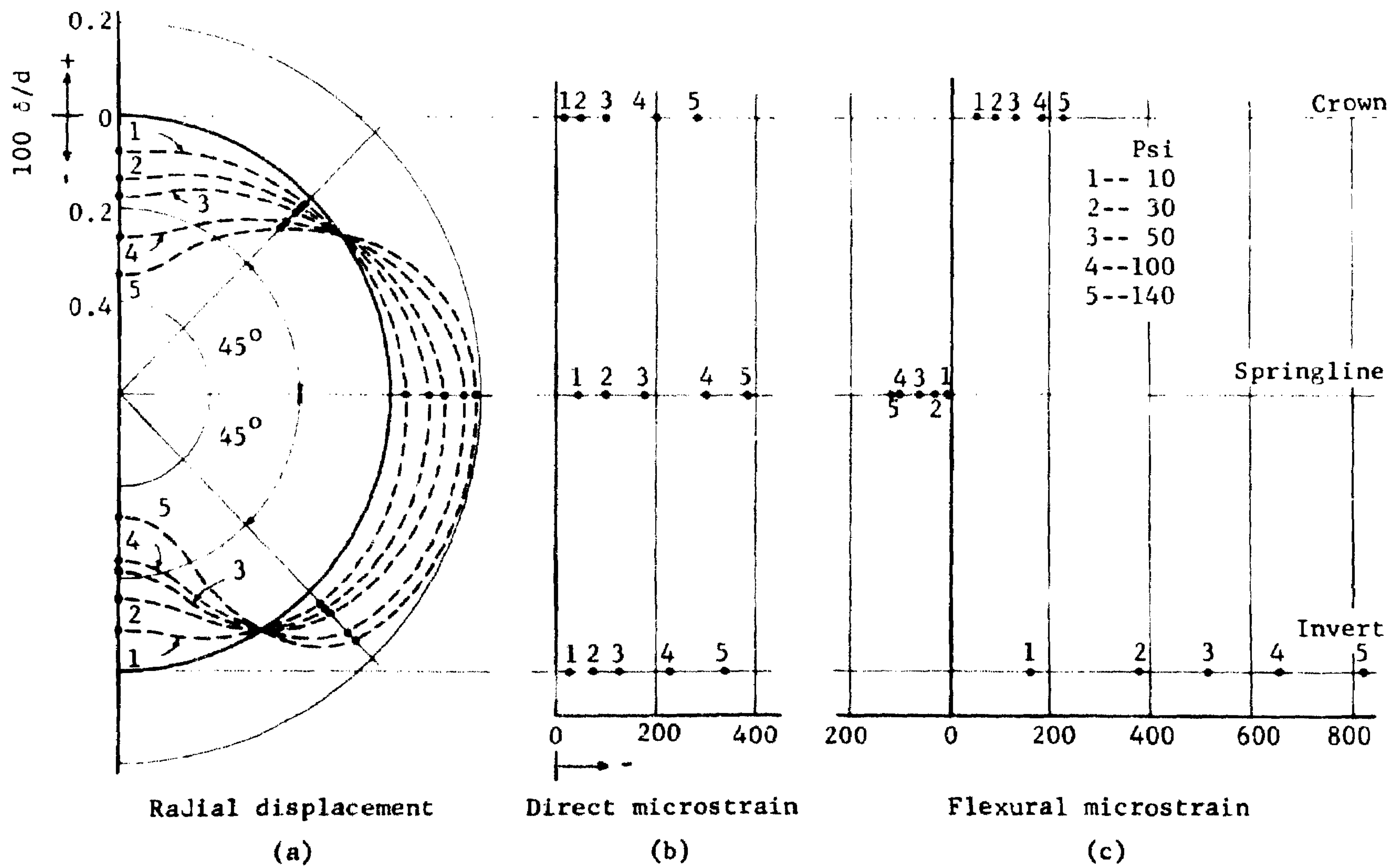
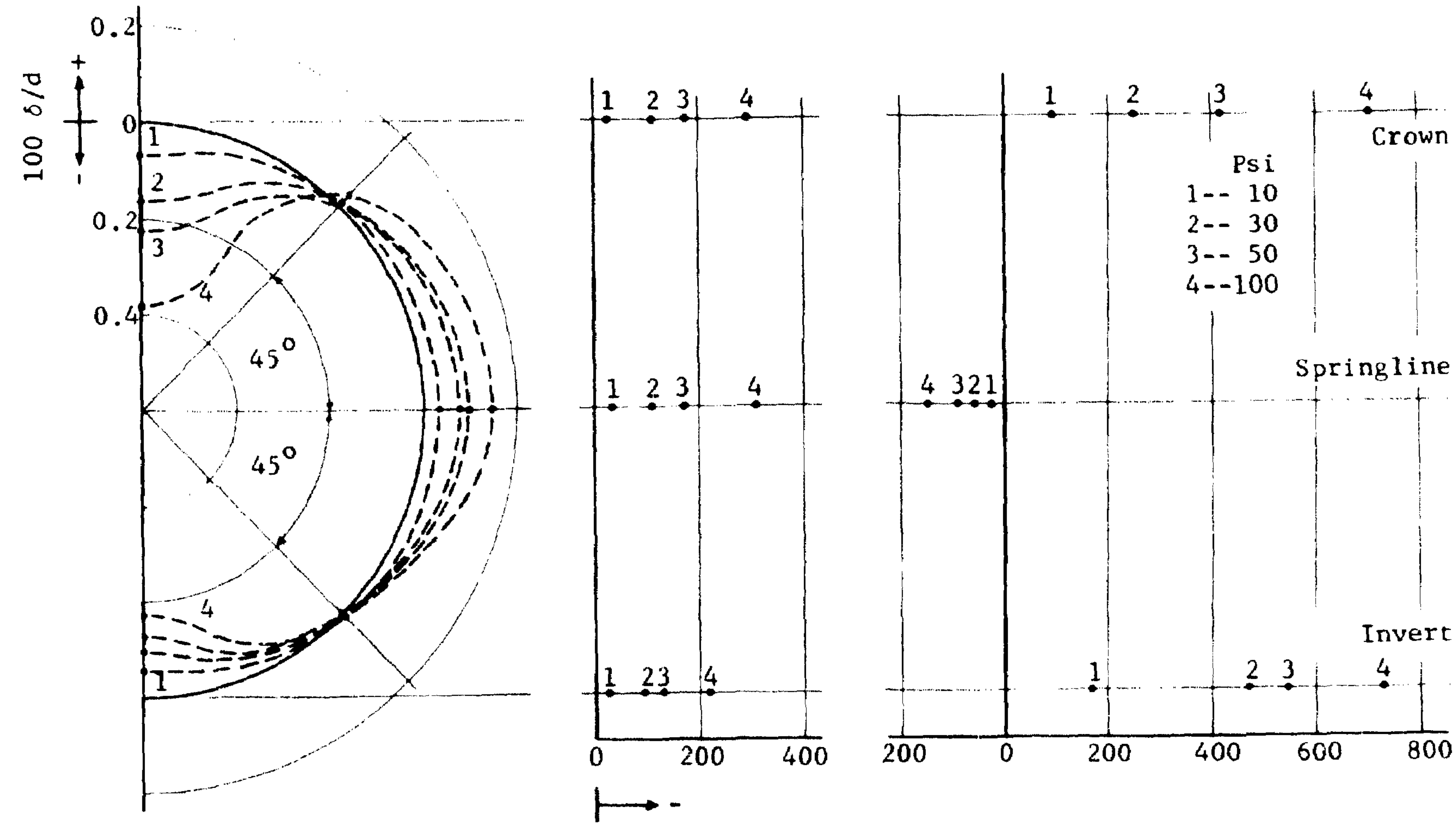


Figure 16. Normalized radial displacement, direct strain, and flexural strain (d/t = 114, c/d = 3/4)



Radial displacement
(a)

Direct microstrain
(b)

Flexural microstrain
(c)

Many c/d values could have been selected to illustrate the behavior of the cylinder at shallow burial. But none could be regarded as typical since most of the observed phenomena, particularly the displacements and strains at the crown, proved very sensitive to small changes in c/d. The normalized displacements, direct strains, and flexural strains for four overpressure values and a c/d value of 1/16 were plotted in figure 17.

Figure 18 affords a comparison between the behavior of a cylinder at deep burial (c/d = 3/4) and one at shallow burial (c/d = 1/16). The overpressure was 100 psi in both cases.

The data for the more flexible, instrumented cylinder (d/t = 250) were plotted in figures 19-30. The method of presentation is similar to that used for the stiffer, instrumented cylinder. Tests were not conducted at small c/d values lest collapse of the cylinder and damage to the displacement gages occur.

In figure 31 a comparison is made between the deflections of stiff and flexible cylinders for deep and shallow burial at 50-psi overpressure.

It will be observed that occasionally some data points are missing from the figures. This is due to the fact that the signals on the Polaroid pictures, for some reason, were unintelligible.

Table 1 presents the data from the destructive tests on non-instrumented cylinders.

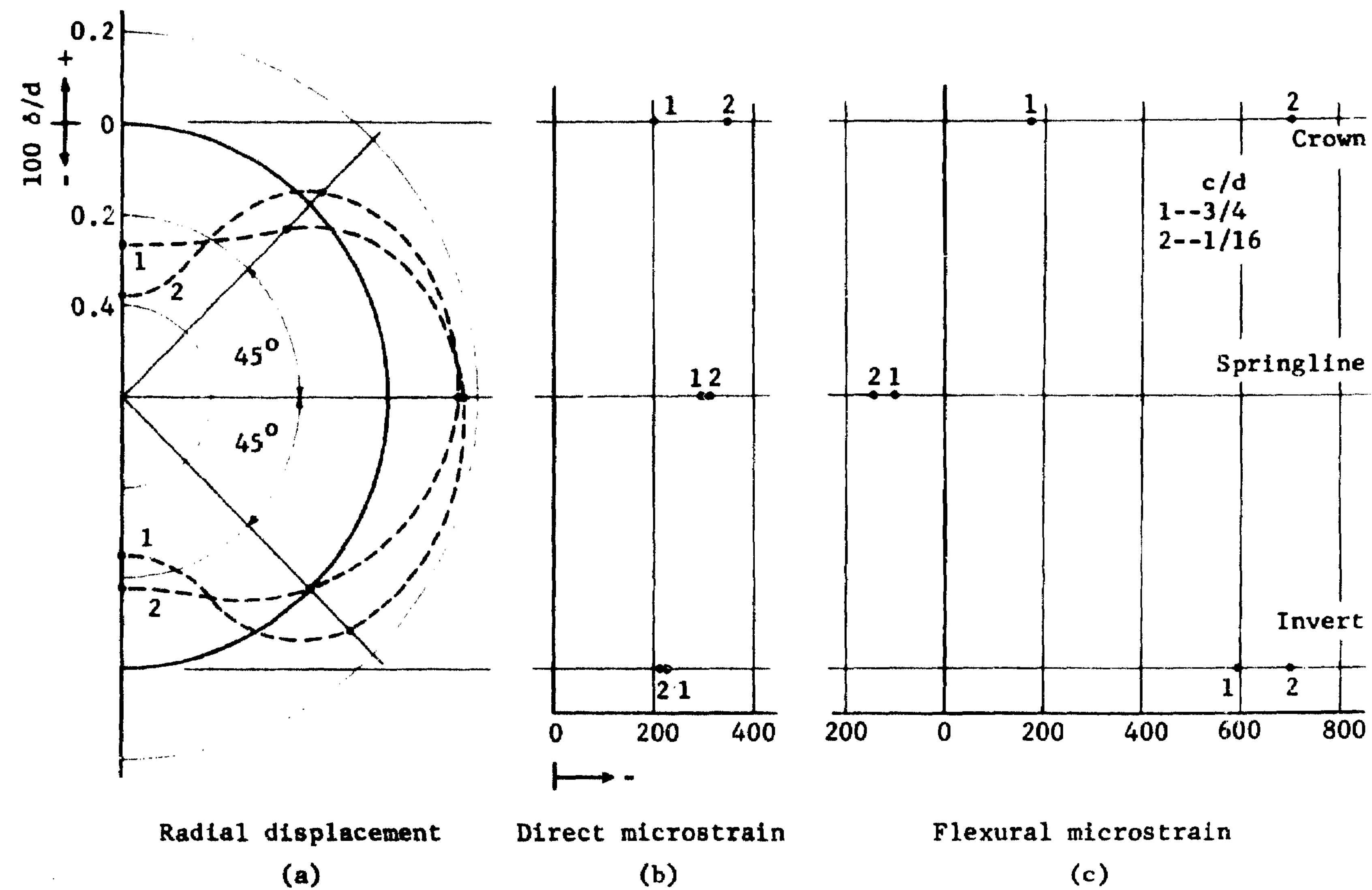


Figure 18. Normalized radial displacement, direct strain, and flexural strain at 100-psi overpressure (d/t = 114)

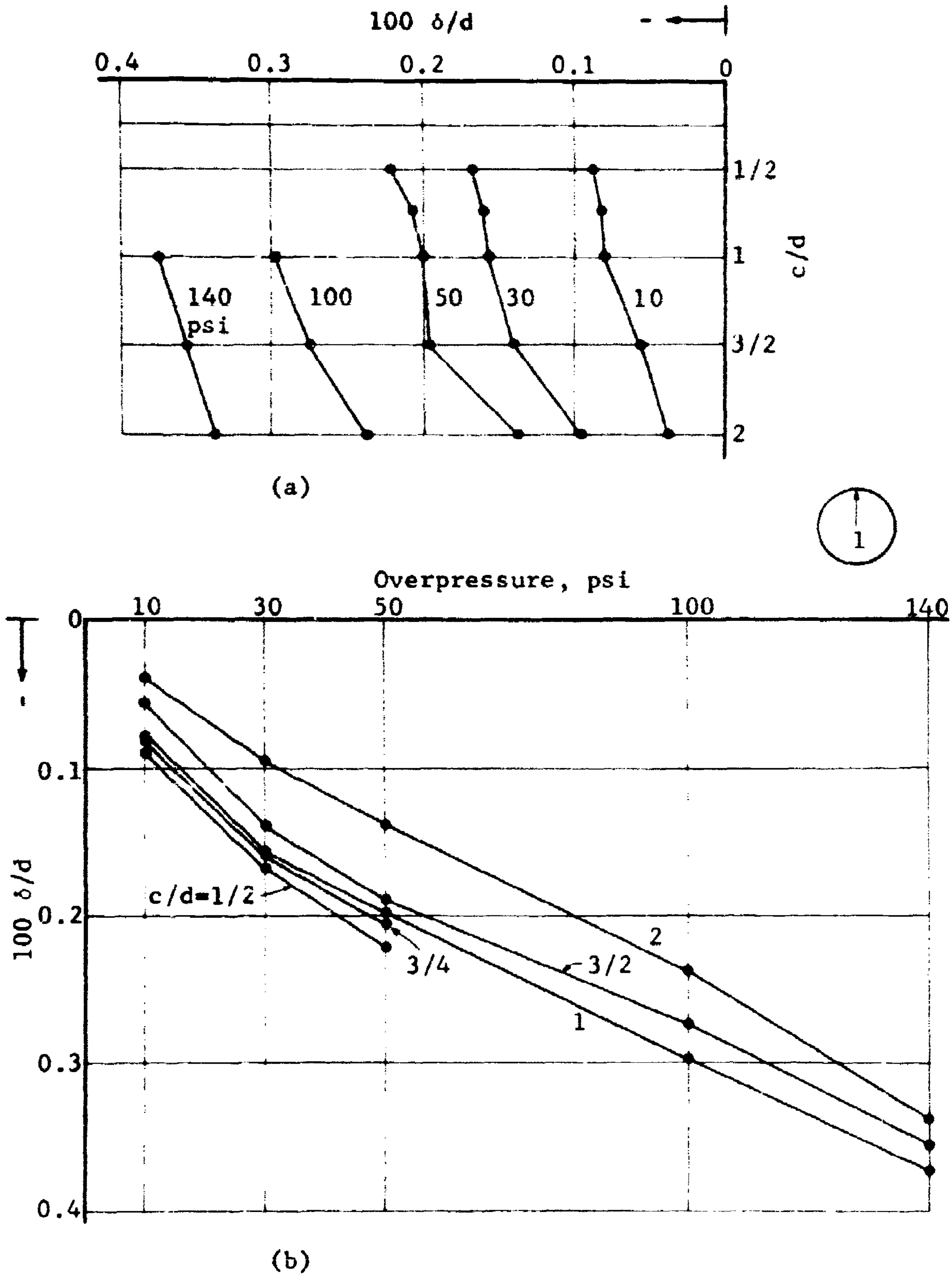


Figure 19. Normalized radial displacements at crown (d/t = 250)

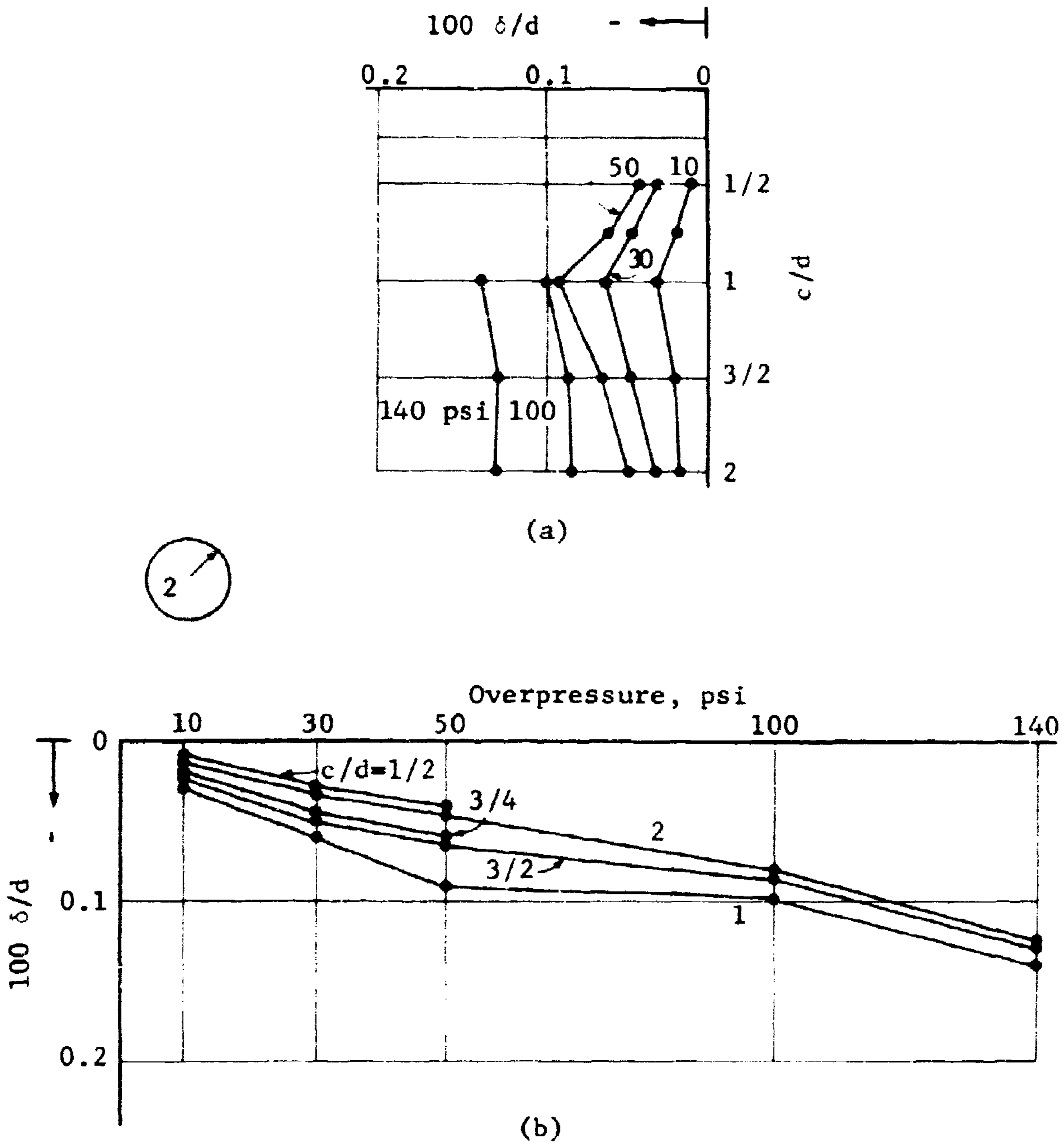


Figure 20. Normalized radial displacements, 45° above springline (d/t = 250)

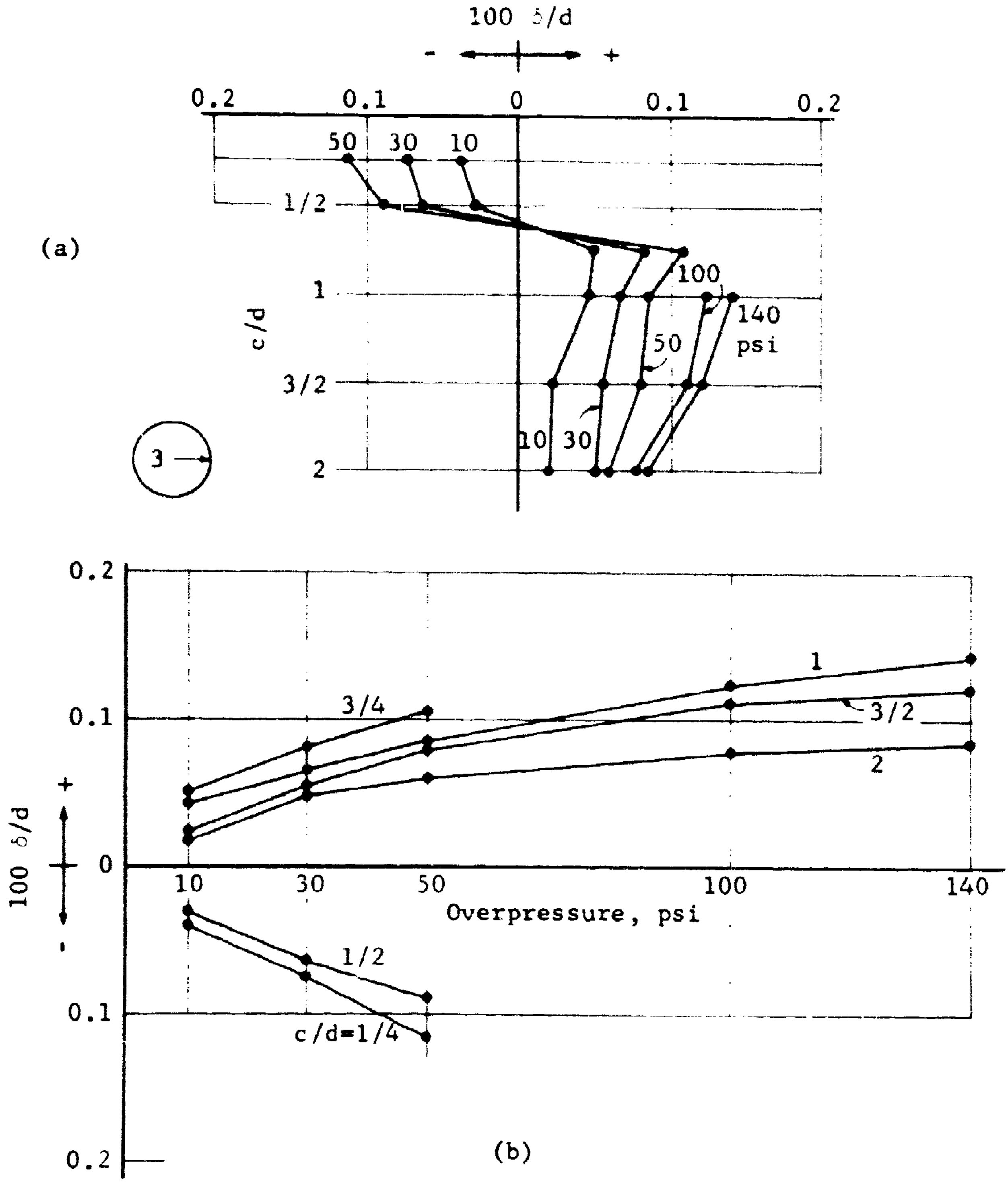


Figure 21. Normalized radial displacements at springline (d/t = 250)

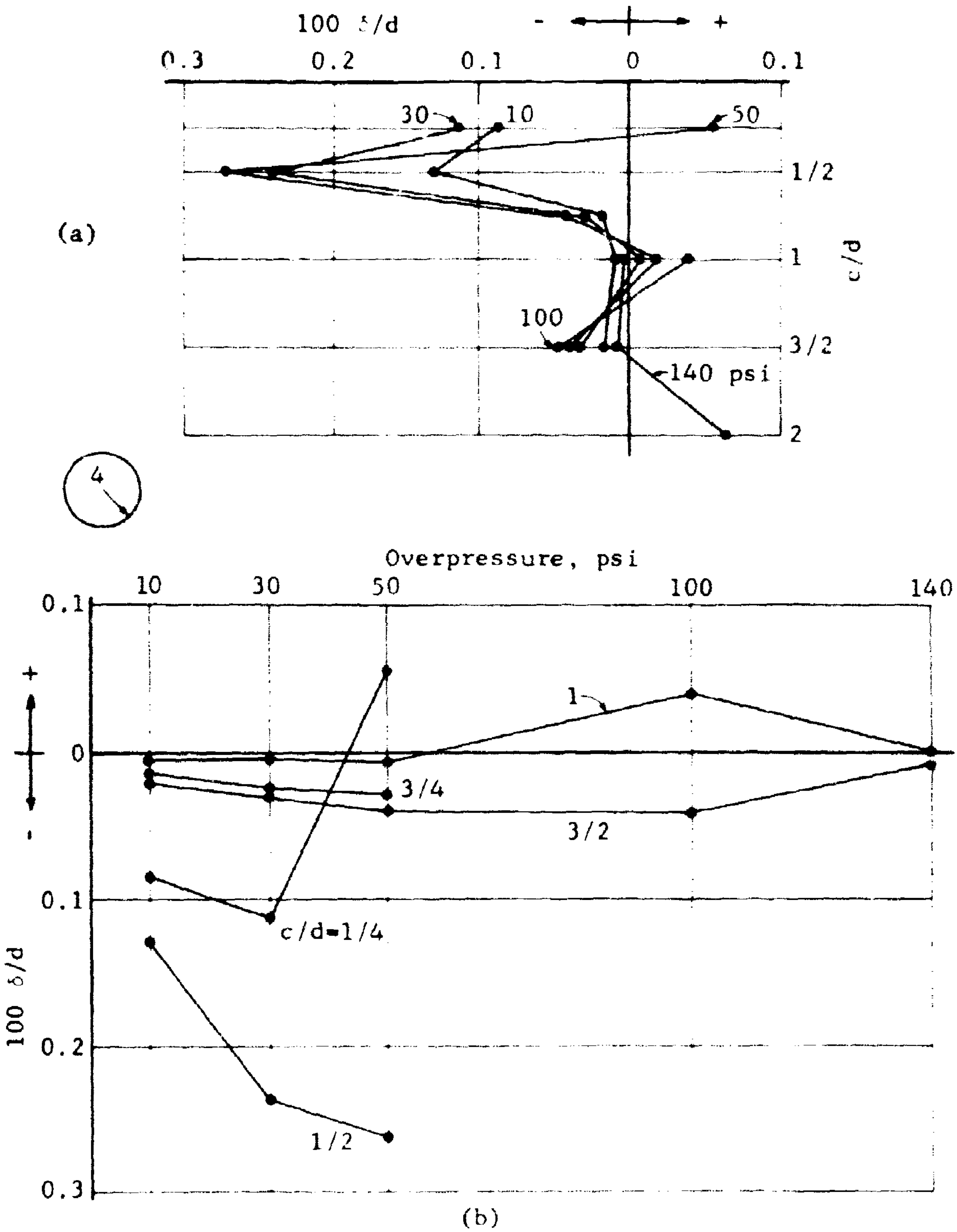


Figure 22. Normalized radial displacements, 45° below springline
(d/t = 250)

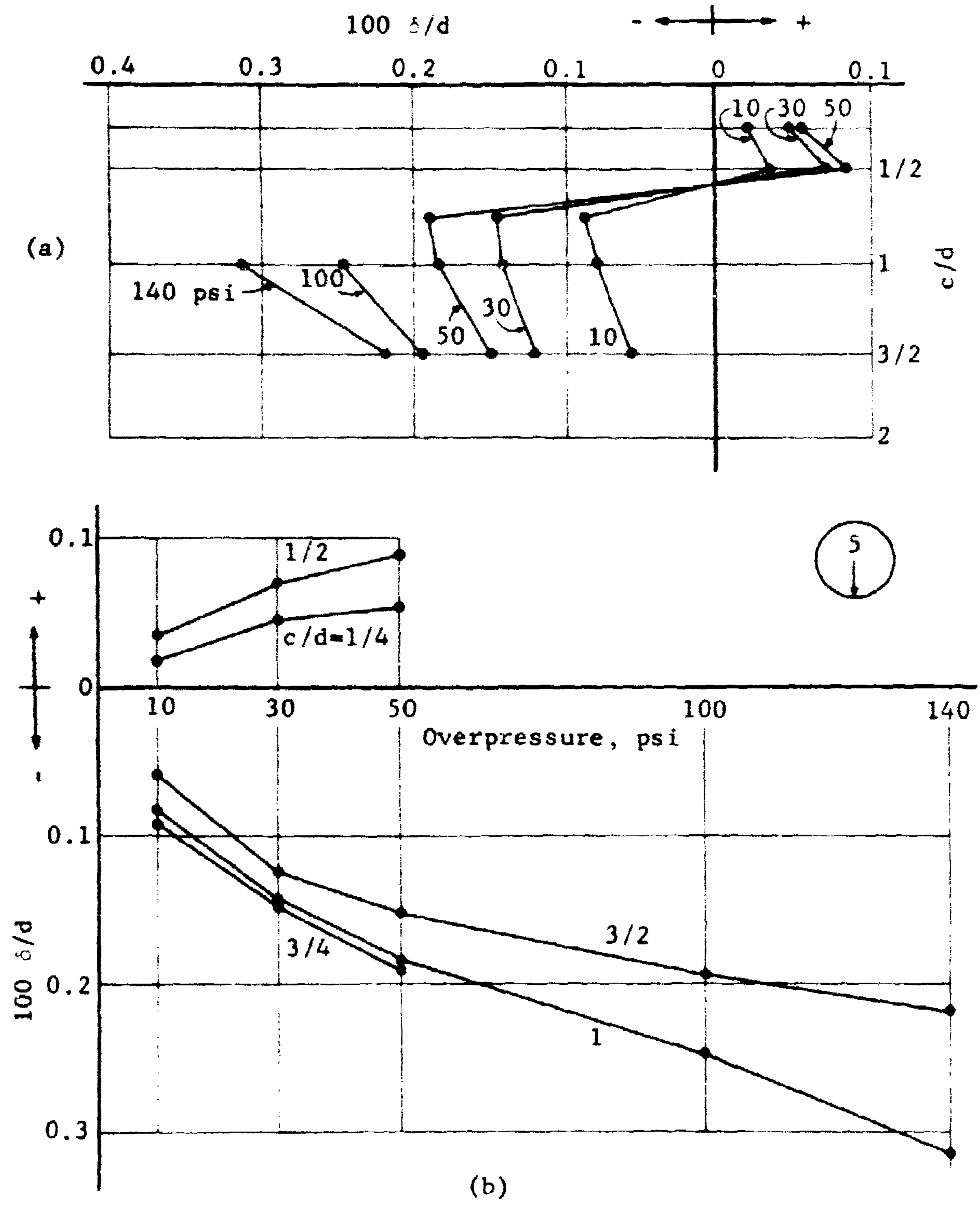
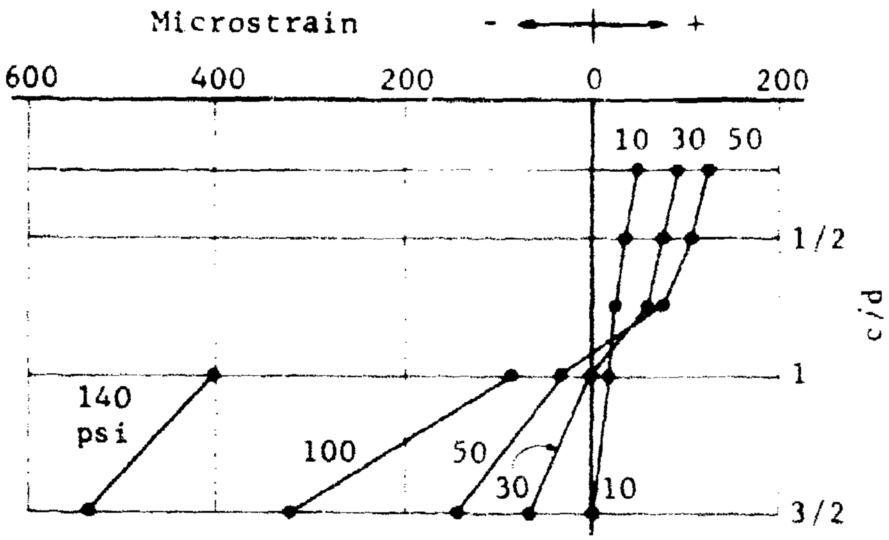
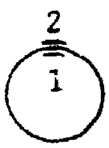
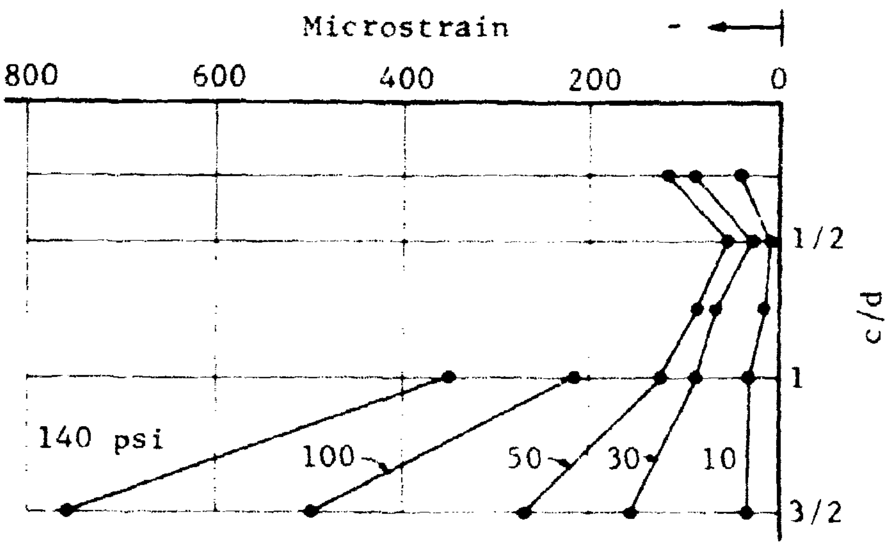


Figure 23. Normalized radial displacements at invert (d/t = 250)



(a) Strain gage 1





(b) Strain gage 2

Figure 24. Strains at crown (d/t = 250)

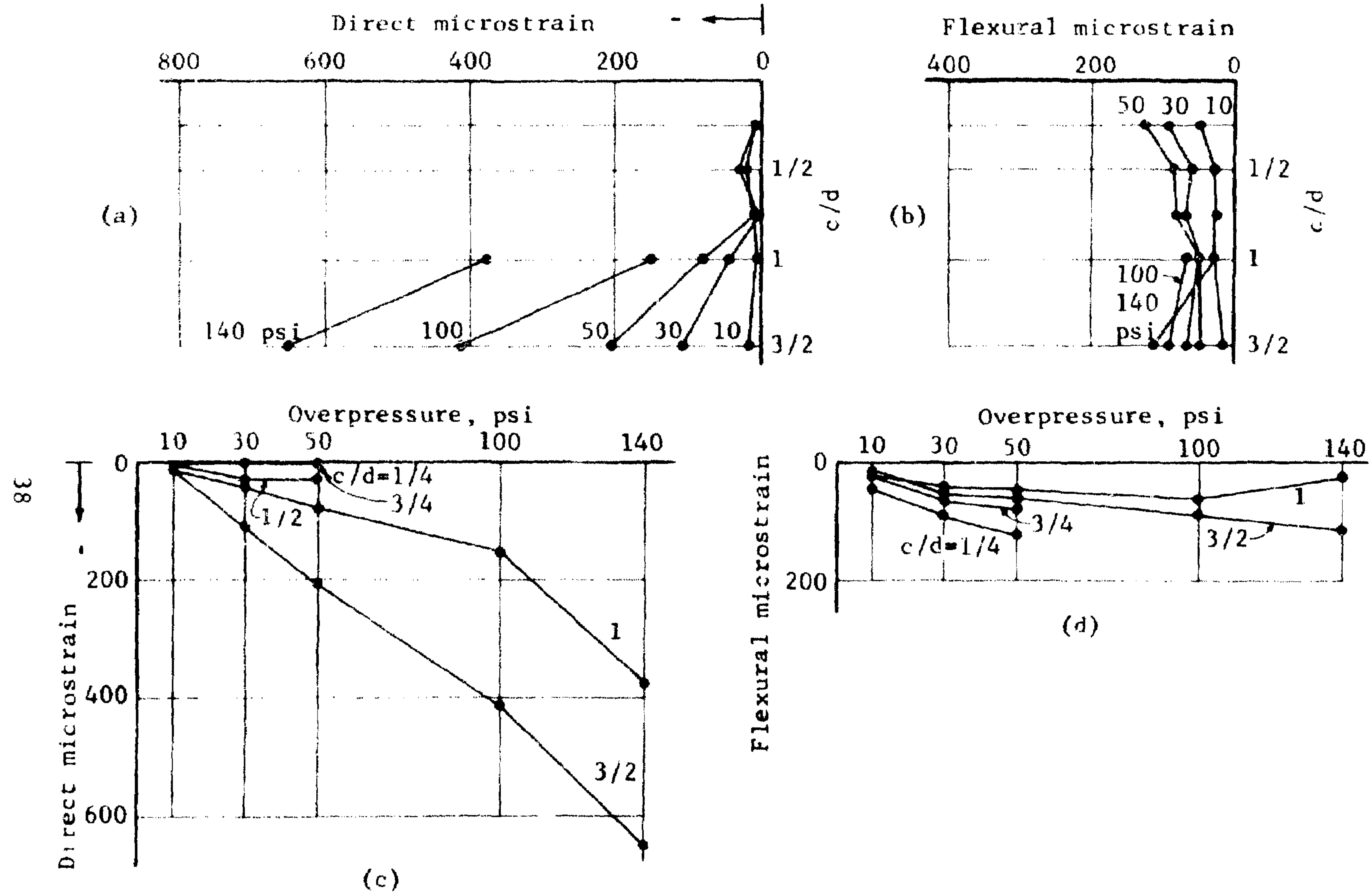
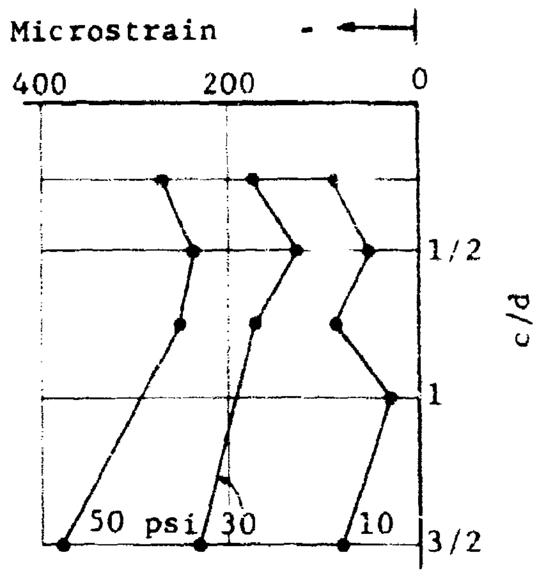
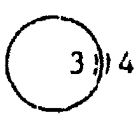
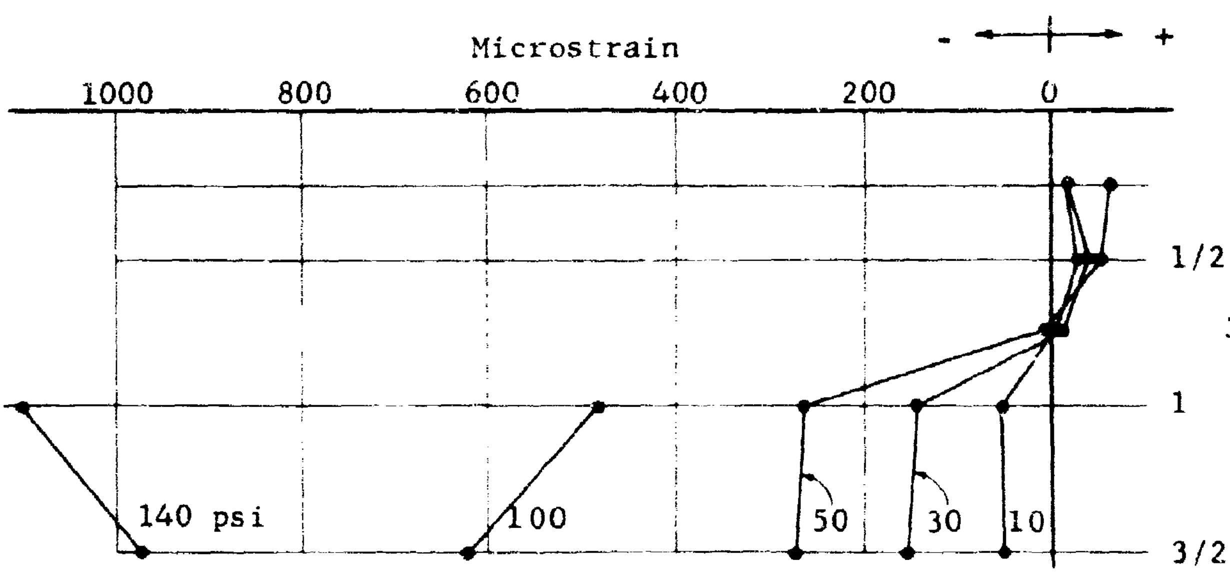


Figure 25. Direct and flexural strains at crown (d/t = 250)



(a) Strain gage 3





(b) Strain gage 4

Figure 26. Strains at springline (d/t = 250)

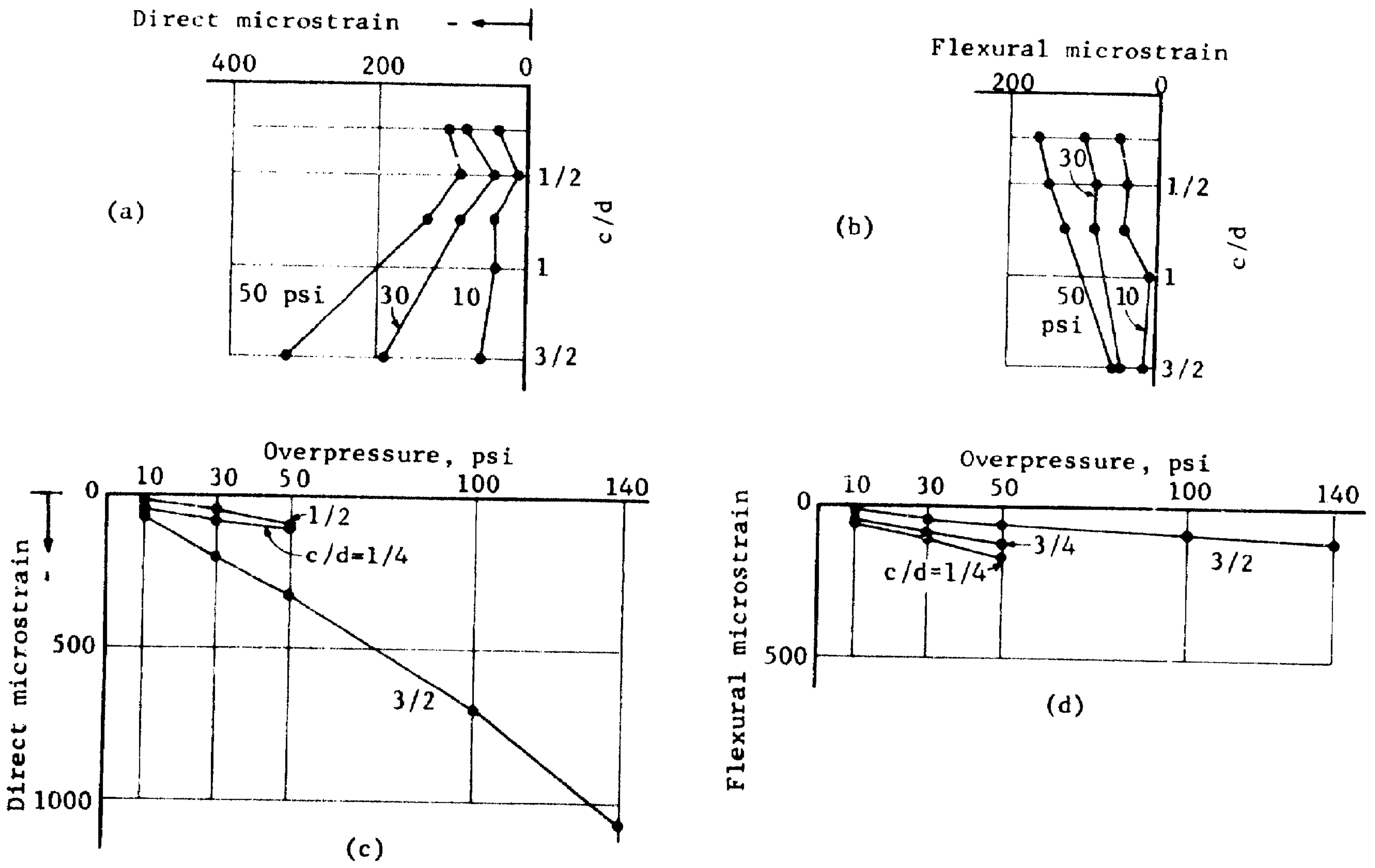
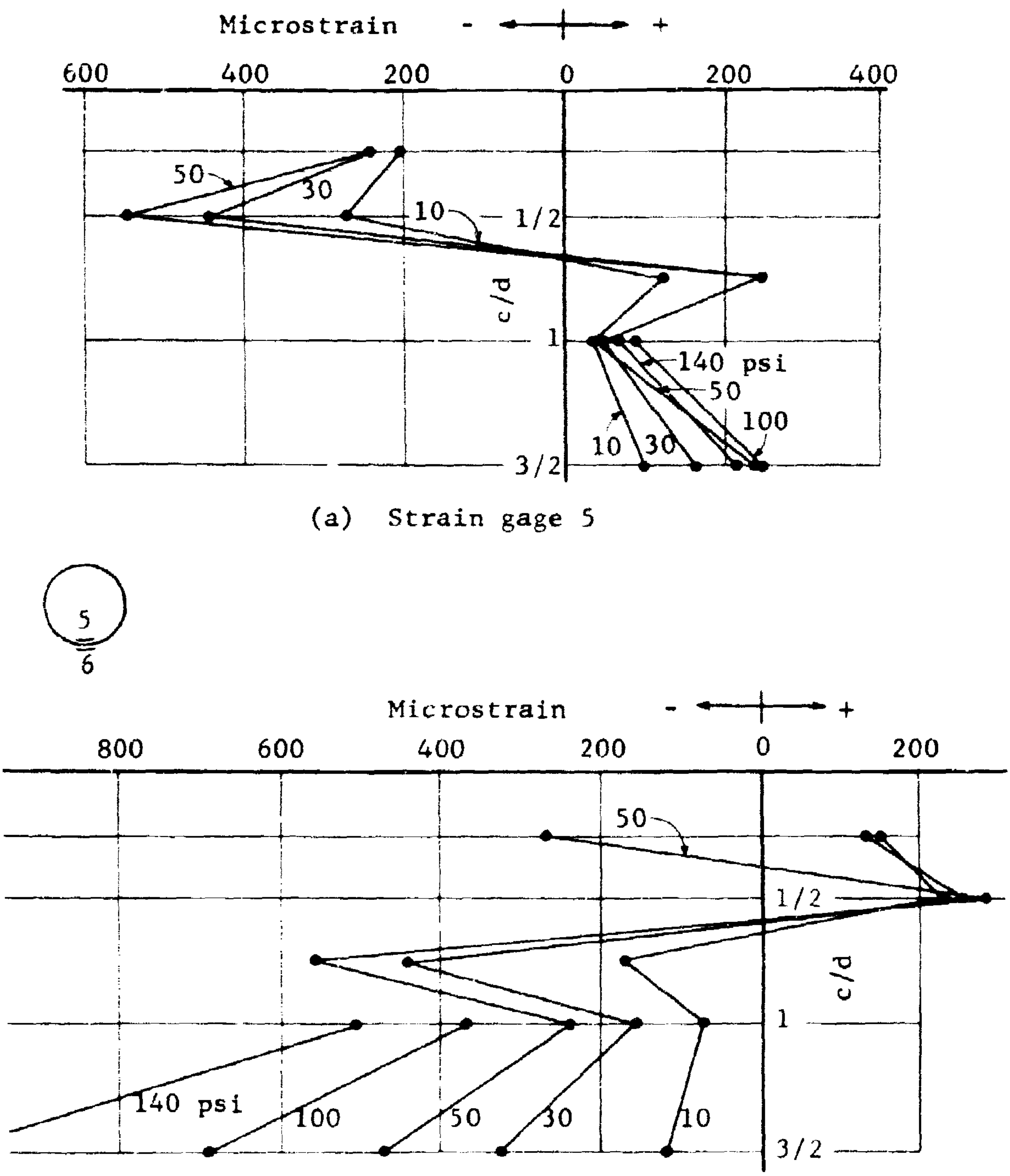


Figure 27. Direct and flexural strains at springline (d/t = 250)



(a) Strain gage 5

(b) Strain gage 6

Figure 28. Strains at invert (d/t = 250)

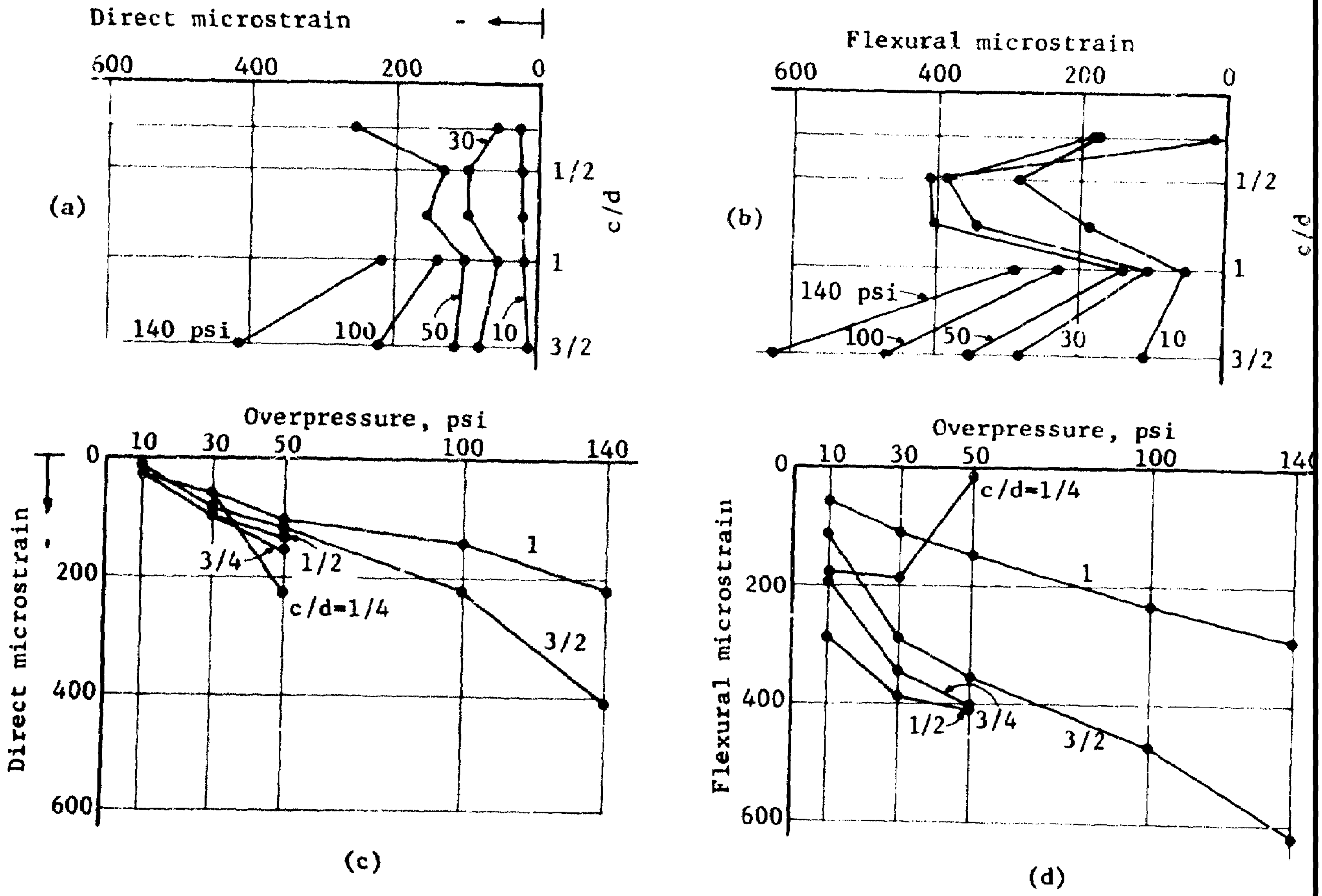
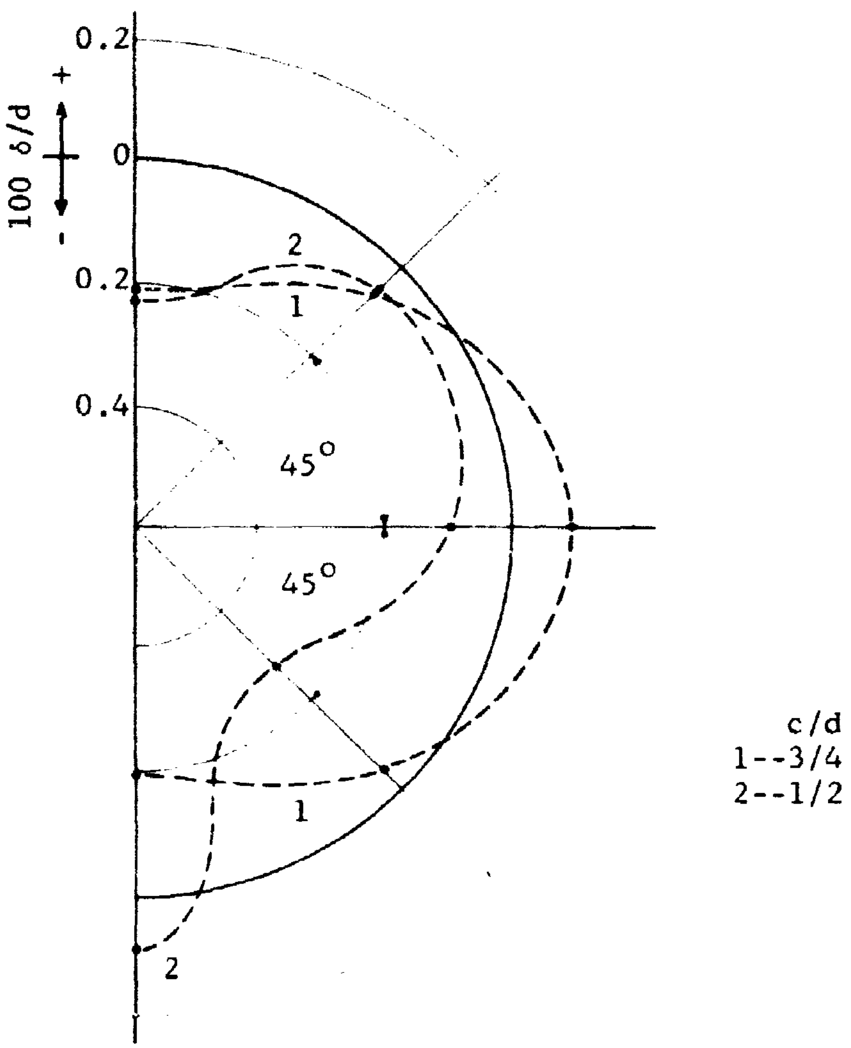
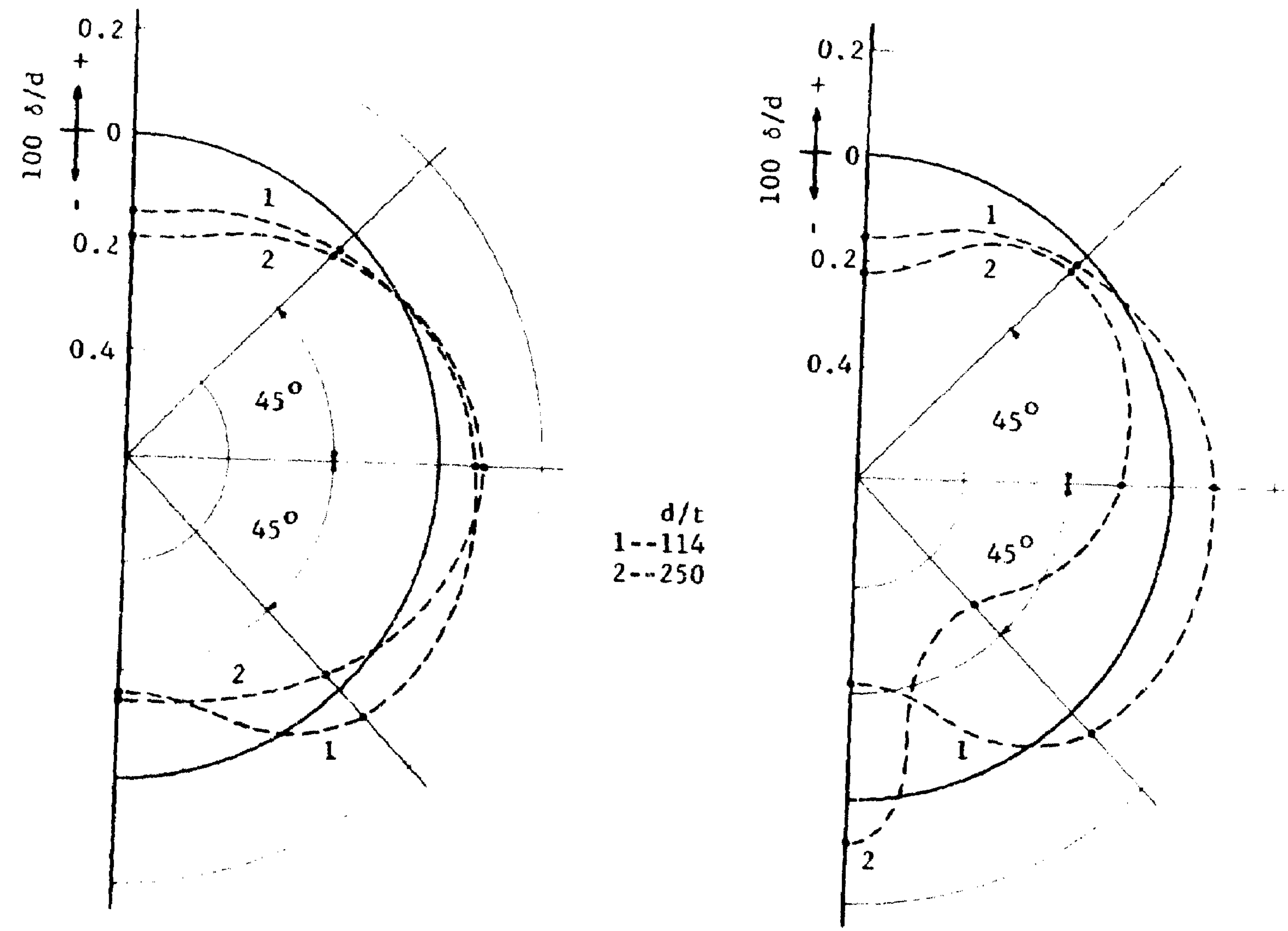


Figure 29. Direct and flexural strains at invert (d/t = 250)



ıre 30. Normalized radial displacement at 50-psi overpressure
(d/t = 250)



(a) c/d = 3/2

(b) c/d = 1/2

Figure 31. Normalized radial displacement at 50-psi overpressure (d/t = 114 and 250)

5. ANALYSIS OF DATA.

a. Stiff, instrumented cylinder (d/t = 114).

(1) Displacements.

The displacements at the crown showed an essentially constant inward movement of the cylinder with depth, except for a sharp increase at small c/d values (fig. 5a). The c/d value at which this change in behavior took place increased with the overpressure. At the lowest value of 10 psi, no change in behavior with c/d is exhibited; and at the highest value of 140 psi, the change takes place at a c/d value of about 1/2. Figure 5b emphasizes in a different manner the increase in the deflection of the crown as the c/d values were reduced. It is also seen that, in the range of overpressure considered, the response of this gage with overpressure is for all practical purposes linear.

Displacement gage 2, inclined at 45° above the horizontal, registered an inward displacement which remained constant with depth for each overpressure level when c/d was equal to or exceeded 1/2 (fig. 6a). The behavior at a c/d value of 2 was erratic, but no significance is attached to this. At smaller c/d values, the output of the gage decreased and actually reversed sign at the higher overpressure levels. Two points are worthy of mention regarding this change in behavior. First, the c/d value at which the change took place appears to be independent of overpressure, at least in the range of overpressure considered. Second, both the inward displacement, when c/d was equal to or greater than 1/2, and the outward displacement, when c/d was less than about 5/16, increased in magnitude with overpressure. Figure 6b shows the relationship between both the inward and the outward deflections with overpressure.

Displacement gage 3 monitored the movement at the springline. The response curves indicate an outward displacement at all times (fig. 7). At the lower overpressure levels, the output of the gage proved insensitive to c/d. However, at the maximum overpressure level of 140 psi, the outward movement increased somewhat as c/d was reduced from 2 to 1/4. No tests were conducted at lower c/d values for this overpressure. The relationships between overpressure and the outward displacements were linear for all c/d values (fig. 7b).

Figure 8 shows plots of the data from displacement gage 4 which was inclined 45° below the horizontal. For all practical purposes it can be said that the radial displacements were outward and constant with depth for each overpressure level when c/d exceeded a certain value. This value increased with the overpressure. At low c/d values the output of the gage decreased. At c/d equal to zero and for an overpressure of 50 psi, the displacement reversed sign. There are indications that still greater inward displacements would have occurred at higher overpressure levels.

The deflections at the invert were inward and increased in a linear manner for all overpressure levels as c/d was reduced to 1/8 (fig. 9). At smaller c/d values, a sharp reduction in output of the gage took place which resulted in an unusual pattern of the curves in figure 9b. This behavior is documented by two tests at c/d equal to 1/16 and three tests at c/d equal to zero.

(2) Strains.

The strain-gage data from the crown are presented in figures 10 and 11. The curves in figures 10a and 10b show the variations in strain on the interior and exterior surfaces with respect to c/d for five overpressure levels. Three facts can be noted from these plots. First, relatively high strains were recorded at low c/d values. These strains were tensile on the interior surface and compressive on the exterior surface. Second, the response of both gages was essentially independent of the cover when c/d exceeded a value of about 1/2. In this range of c/d, the strains on the interior surface were tensile at low overpressures but compressive at the higher levels. Third, the c/d value at which the change in behavior took place increased with the overpressure and may be as large as 5/8 for the strain on the exterior surface at 140-psi overpressure. Figures 10c and 10d show the same data plotted versus overpressure. Except for low values of c/d, it can be seen that the response of the gages increased more or less linearly with overpressure in the range of overpressure considered.

Figure 11 shows the direct and flexural components of strain at the crown plotted against both c/d and overpressure. The comments about the total strains can be applied equally well to the components of strain. The flexural strains increased significantly as c/d was reduced to low values.

Figures 12 and 13 show plots of the strain-gage data at the springline. The data are somewhat erratic, but some trends are evident. As was the case with the displacements along a horizontal radius (fig. 7), neither the total strains nor the components of strain proved sensitive to c/d. This is significant in that the direct strain at the springline is indicative of the vertical load on the cylinder. The direct compressive strains in figure 13a indicate that somewhat less than 50 percent of the applied overpressure was carried by the cylinder. All curves of the total strain and the components of strain versus overpressure fall in a narrow band and are linear in the range of overpressure considered. The flexural strains are of the order of one-half the direct strains for all c/d and overpressure values. However, figure 13b indicates that at higher overpressures and low c/d values the flexural strain might increase significantly.

The strains at the invert were monitored by strain gages 5 and 6, and the data were plotted in figures 14 and 15. No significance should be attached to the fact that the curves of strain versus c/d are tortuous. The origin of this effect probably lies in variations in the seating of the cylinder. Little or no tendency toward a sudden increase in total strain or components of strain at low c/d values is exhibited by the curves. The flexural strains exceeded the direct strains by a factor of about two. Figures 15c and 15d indicate that the direct strains increased linearly with overpressure while the flexural strains exhibited a tendency to flatten off somewhat.

(3) General behavior.

In assessing the overall behavior of the cylinder, it was found helpful to bear in mind the mode of failure in the destructive tests. Collapse in these tests was found to be initiated by snap-through at the crown. This fact is stated explicitly for two reasons. First, the very flexible cylinders tested by Bulson[9] first showed distress in the vicinity of the invert. Second, in dynamic tests at the Shock Tube Facility, in which identical buried cylinders were subjected to plane wave loading, collapse was found to take place at the invert. It is readily seen that symmetry about a horizontal diameter cannot be assumed.

There is no doubt that more information on the displacements and strains in the quasi-static test cylinders would help tremendously in establishing their overall behavior. However, some significant observations can still be made.

Figure 16 shows the normalized displacement, direct strain, and flexural strain for a deeply buried cylinder (c/d = 3/4). The displacements at the crown and invert were inward. The deflections at the springline were outward and smaller in magnitude than those at the crown. On the radii, inclined 45° above and below the horizontal, the deflections were inward and outward, respectively. The magnitude of the displacement at each of the five gage locations increased with the overpressure.

The direct strain varied little at the three gage locations and, bearing in mind the inherent spread in data of this type, could be considered constant. A tendency toward a somewhat greater direct strain at the springline than at either of the other two stations can be seen, especially at the higher overpressure levels.

The flexural strains were least at the springline, larger by a factor of about two at the crown, and larger still at the invert. The flexural strains at the invert exceeded those at the crown by a factor of about four and at the springline by a factor of seven or eight. Even though the deflections at the crown and invert were of the same order of magnitude, the curvature was greater at the invert, thus accounting for the larger flexural strains.

Similar data for a case of shallow burial (c/d = 1/16) are presented in figure 17.

The displacements at the crown were larger than for the deeply buried cylinder (fig. 5). The displacements at the springline remained essentially unchanged (fig. 7). The displacements, on a radius inclined 45° above the horizontal, were zero for the lower overpressures and outward for the 100-psi overpressure level. The outward movement is indicative of the formation of a mode of relatively high order in the vicinity of the crown. Figure 6 indicates that the outward displacements would be even greater at 140-psi overpressure, provided, of course, collapse did not occur.

The deflections on an inclination 45° below the horizontal were outward but smaller in magnitude than the corresponding values for a deeply buried cylinder (fig. 16). Furthermore, as the overpressure was increased, the magnitude of the movement increased when the cylinder was deeply buried, but decreased when it was buried at shallow depth.

Figure 8 indicates that an inward movement would have taken place at this cover (c/d = 1/16) if higher overpressures had been used. Again, this would be dependent upon the cylinder remaining intact. At the invert the displacements were inward and also of smaller magnitude than when the cylinder was deeply buried.

Two observations are worthy of note from figures 17b and 17c. First, the magnitudes of the direct strains and flexural strains at the springline and invert were essentially the same for shallow as for deep burial. Second, a large increase in the flexural component and a somewhat smaller though significant increase in the direct component of strain took place at the crown. The flexural strain increased by a factor of two at 10-psi overpressure and by a factor of four at 100-psi overpressure. An increase of 75 percent in the direct strain at 100-psi overpressure was recorded.

Figure 18 affords a comparison at an overpressure level of 100 psi between the displacements and components of strain in a deeply buried cylinder (c/d = 3/4) and in a cylinder at shallow depth (c/d = 1/16). The deflection diagram in figure 18a shows the increase in the order of the deflection mode in the neighborhood of the crown, as c/d was reduced. Curiously, the reverse took place at the invert. Since collapse in this series of quasi-static tests has been found to be precipitated by snap-through at the crown, the deflections of the lower portion of the cylinder probably had little influence on the collapse overpressure.

Figure 18b indicates that the direct strain at the crown increased about 75 percent while that at the springline and invert remained unchanged when c/d was reduced from 3/4 to 1/16.

The flexural [illegible] cant increase at the invert, a 50-percent increase at the spring-line, and a 200-percent increase at the crown. It can be seen in figure 11b that the flexural strain at the crown increased twofold at 100-psi overpressure when c/d was reduced [illegible]. Thus, at this overpressure, the flexural strain at the crown varied by a factor of at least eight over the range in c/d. The indications from figure 11b are that this factor would be even larger at greater overpressures.

b. Flexible, instrumented cylinder (d/t = 250).

(1) Displacements.

The displacement data at the crown were plotted in figure 19. The relationship between the normalized deflection at the crown and c/d is shown in figure 19a for five overpressure levels. In the range of c/d tested, the output of the gage increased linearly as the cover was reduced. No tendency toward a sharp increase in deflection was detected in the range of overpressure tested. Figure 19b shows plots of the normalized deflection versus overpressure for five c/d values. For the overpressure range considered, the relationships are essentially linear.

The displacements, along a radius inclined 45° above the horizontal, were plotted in figure 20. All movement was inward. A reduction in the magnitude of this movement, similar to the behavior of the stiffer cylinder (fig. 9a), took place when c/d was less than one.

In figure 21 the displacements at the springline were plotted. Figure 21a shows the relationship between the normalized radial displacements and c/d for five overpressure levels. The outward movement at the springline increased linearly as c/d was reduced from 2 to 3/4. At the latter value, a sudden reduction in output of the gage took place. When c/d equaled about 5/8, zero displacement was recorded for all three overpressure levels tested. At still smaller c/d values, the gage recorded inward movement of the cylinder. At a c/d value of 1/2, the magnitude of the inward movement was almost as great as that of the outward movement at a c/d value of 3/4. Still greater inward deflections of the cylinder were recorded when c/d equaled 1/4. No tests were conducted on cylinders of this stiffness (d/t = 250) at shallower cover. It can be seen from figure 21a that, regardless of sign, the magnitude of the movement increased with the overpressure. These inward displacements at the springline are considered to be of great significance and will be discussed later.

Figure 21b shows the same displacement data plotted versus overpressure for six c/d values. The slopes of the curves, indicating outward movement, decreased as the overpressure increased. This contrasts somewhat with the curve indicating inward movement when c/d equaled 1/4. In this case, the movement at the springline was inward. In the range of overpressure considered at this c/d value, the curve exhibits a slight tendency toward an increase rather than a decrease in slope with overpressure.

The displacements along a radius inclined 45° below the horizontal were plotted in figure 22. The data are indeed erratic and do not follow any pattern.

The displacement data from the invert were plotted versus c/d in figure 23a. The displacements were inward and increased for all overpressure levels when c/d was reduced from 3/2 to 3/4. At c/d values less than 3/4, a sudden reversal in sign took place; and outward movements were recorded. The significance of this behavior is not understood. It will be recalled that, for the same gage location in the more rigid cylinder, a sudden reduction in inward displacement but no reversal in sign took place at small c/d values (fig. 9a).

(2) Strains.

The strain-gage data are presented in figures 24-29. These data are very erratic. The explanation advanced for this is that local buckling developed in a random manner in the very flexible cylindrical shell and resulted in spurious strains. The data are not conducive to detailed discussion, but some pertinent remarks may be made.

The interior strain gage at the crown recorded tensile strains when c/d was less than about 1 (fig. 24a). This was caused by inexplicably low, direct compressive strains and by relatively large flexural strains (figs. 25a and 25b).

The output of the interior strain gage at the springline (fig. 26a) proved very similar to that of the corresponding gage on the stiffer cylinder (fig. 12a). The tensile strains, recorded by the exterior strain gage at the springline when c/d was less than 3/4 (fig. 26b), are not consistent with the inward movement at the springline shown in figure 21. Assuming both sets of data are correct, this can only be accounted for by postulating the occurrence of local buckling.

The capricious nature of the strains at the invert is not entirely unexpected. Bulson[9] found that for very flexible cylinders it was the invert which first showed distress under load. Furthermore, irregularities in the density of the sand may have occurred in the neighborhood of the invert.

(3) General behavior.

To emphasize the significance of the inward movement at the springline at small c/d values (fig. 21), two deflected shapes were drawn in figure 30. Both correspond to an overpressure of 50 psi, but one is for deep burial (c/d = 3/4), and the other is for shallow burial (c/d = 1/2). The distinction is made on the basis of the change in behavior at the springline.

The deeply buried cylinder deflected in a low-order mode. The displacements were inward and of about equal magnitude at the crown and invert. At the springline, the displacements were outward and equal in magnitude to about one-half of those at the crown. The movements along radii inclined 45° above and below the horizontal were both inward and equal in magnitude to about one-quarter of those at the crown.

The cylinder at the shallower cover assumed a high-order mode, at least in the vicinity of the crown. This is manifested by the fact that the inward movement at the crown was greater, while the inward movement along a radius inclined 45° above the horizontal was less, than the corresponding deflections in the deeply buried cylinder. At the springline, the inward displacement at shallow burial was about equal in magnitude to the outward displacement at deep burial. Furthermore, this inward displacement increased still more when c/d was reduced from 1/2 to 1/4 (fig. 21). On a radius inclined 45° below the horizontal, the inward displacement was very large, exceeding the corresponding value at deep burial by a factor of more than six. The displacement was, curiously, outward at the invert. The reason for this is not understood, but the phenomenon may be related to the inward movement of the cylinder at the springline. With the exception of this outward reading at the invert, all other displacement gages recorded an inward movement of the cylinder at shallow burial.

c. Comparison of stiff and flexible, instrumented cylinders.

In spite of a lack of experimental data for the more flexible cylinder at small c/d values, a comparison between cylinders of both stiffnesses shows many similarities and some differences. (Tests were not conducted lest collapse of the cylinder and damage to the displacement gages occur.)

The deflected shapes of [illegible] for different conditions of burial are shown on the same diagrams in figures 31a and 31b. The data in both figures correspond to the same overpressure of 50 psi.

Figure 31a shows the displacements at a c/d value of 3/2. Both cylinders deflected outward about an equal amount at the springline. However, it is seen that the more flexible cylinder assumed a "flatter" shape near the crown indicating a higher level of distress.

When c/d was reduced to 1/2 (fig. 31b), the stiffer cylinder showed little change. But the level of distress in the more flexible cylinder became much greater. The inward deflection at the crown increased; the outward deflection at the springline (c/d = 3/2) gave way to an inward deflection of about the same magnitude; and a very large inward deflection took place on a radius inclined 45° below the horizontal. Allusion has already been made to the outward movement of this cylinder (c/d = 1/2) at the invert. It probably would have little effect on the resistance of the upper portion of the cylinder to snap-through.

The deflected shapes in figure 31b portray the different kinds of behavior at the springline for the two cylinders at the same overpressure and depth of burial.

A comparison between the behavior of the two cylinders at nearly the same multiple of their respective theoretical in-air primary buckling pressures can be made by comparing the response of the stiffer cylinder (d/t = 114) at 140-psi overpressure (9.4 p_{cr}) to the response of the more flexible one (d/t = 250) at 10-psi overpressure (7.1 p_{cr}). From figures 5 and 19 it can be seen that the inward movement at the crown in the stiffer cylinder is several times greater than the corresponding movement in the more flexible one. The same is true of the inward movement on a radius inclined 45° above the horizontal (figs. 6 and 20) and the outward movement at the springline (figs. 7 and 21).

The relationships between the inward deflection at the crown and overpressure are shown in figure 5b for the stiffer cylinder (d/t = 114) and in figure 19b for the more flexible cylinder (d/t = 250). The slopes of these curves are a measure of the stiffnesses of the soil-structure systems at various depths of burial of the cylinders. For any convenient condition of deep burial (say, c/d = 3/2), the curves for the two cylinders are remarkably similar, in spite of the fact that their theoretical in-air primary buckling pressures differ by a factor of more than ten.

For the more rigid cylinder (d/t = 114), the first indication of a significant change in behavior as the cover was reduced was provided by displacement gage 2 (fig. 6). This gage was inclined 45° above the horizontal. The change in behavior took place when c/d equaled 1/2 for all overpressure levels.

The displacement and strain gages at the crown also exhibited a change in output as the cover was reduced (figs. 5a, 10a, 10b, 11a, and 11b). The c/d values at which these changes occurred were not always well defined; however, the greater the overpressure, the greater this c/d value. These c/d values separate zones of shallow and deep burial. The phenomenon is best illustrated by the displacements (fig. 5a), the strains on the exterior surface (fig. 10b), and the flexural component of strain (fig. 11b). A c/d value of 1/2 is again associated with the minimum value for deep burial at 140-psi overpressure. Whether this value increases at higher overpressure levels is, considering the available data, subject to conjecture. No curve separating deep from shallow burial is evident from the strains on the interior surface (fig. 10a). This is probably due to the fact that these strains represent the superposition of two components of unlike sign.

It is not possible from the data available to delineate zones of deep and shallow burial for the more flexible cylinder ($d/t = 250$). However, this cylinder exhibited changes in behavior at depths greater than the c/d value of 1/2 associated with the more rigid cylinder. The curves of displacements at the springline and invert break sharply at a c/d value of 3/4 (figs. 2[illegible] and 23).

d. <u>Destructive tests, noninstrumented cylinders.</u>

Table 1 presents the results of the destructive tests on noninstrumented cylinders. It shows the six convenient d/t values selected for testing, the theoretical in-air primary buckling pressure (p_{cr}) of each, and the experimental collapse overpressure at three c/d values. The experimental values are also stated in multiples of p_{cr}. Within the maximum available overpressure (160 psi), only four cylinders could be collapsed even at zero cover, and not even the most flexible could be collapsed when c/d exceeded 1/8. The maximum overpressure was 470 times the theoretical in-air primary buckling pressure of the most flexible cylinder.

As would be expected, the overpressure required to cause collapse at a particular c/d value increased with depth of burial. However, it was the large increase in the experimental collapse overpressure for any one cylinder, when c/d was increased from zero to 1/16, that proved most interesting.

The more flexible the cylinder, the greater was the ratio between the experimental collapse overpressure and the theoretical in-air primary buckling pressure. A cylinder with a d/t value of 400 collapsed at an overpressure of 265 p_{cr} when c/d was 1/8. At the same depth of burial, a cylinder whose d/t was 250 collapsed at 97 p_{cr}.

It is not possible to determine from the small amount of data available if zones of shallow burial and deep burial for cylinders of various stiffnesses can be established from destructive tests.

It is also worthy of ,te that in the stiffer, instrumented cylinder (d/t = 114), very large strains were recorded at the crown at 100-psi overpressure and zero cover (fig. 10b). Yet collapse could not be induced at 160-psi overpressure and the same condition of burial.

6. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS.

a. Summary.

The problem of analyzing a buried cylinder subjected to a surface-applied quasi-static air pressure should not be confused with the well-known culvert problem.

For culverts buried relatively deep, the primary consideration is one of arching of the dead load of the overlying material around or onto the culvert. The effects of live loads are usually insignificant for deeply buried culverts.

For culverts buried at relatively shallow depths, the effects of live loads become important, and the role of arching decreases.

Neither of these problems is akin to the one at hand. The shear strength of the overlying material permits development of arching around relatively deeply buried culverts. This is not true in this test problem since the surcharge (air under pressure) cannot mobilize shear stresses. Again, customary live loads are of limited areal extent and result in more distress in a culvert at relatively shallow depth than when the applied load is uniformly distributed.

The possibility of obtaining a theoretical solution to the problem of the buried cylinder, based on realistic assumptions, is extremely remote. A theoretical analysis of the arching around a movable, rigid trapdoor has been made, assuming constant-volume plastic flow.[16] An analysis of the arching in a dilatant sand around a flexible cylinder with an incompatibility of strain at the sand-cylinder interface would be much more complex and has not been attempted.

The most promising approach to the problem is by means of an experimental program. In this investigation small aluminum cylinders were buried with their axes horizontal in dense, dry, 20-30 Ottawa sand and subjected to quasi-static surcharges in the form of air pressure on a rubber membrane. The cylinders were 4 inches in diameter and 16 inches long.

The first part of the program was concerned with the testing of instrumented cylinders of two wall thicknesses (t = 0.035 inch, d/t = 114; and t = 0.016 inch, d/t = 250). The instrumentation consisted of radial displacement gages and tangential strain gages. The maximum applied overpressure was 140 psi. The depth of burial varied from zero to two cylinder diameters. Data corresponding to five overpressure levels and as many as eleven depths of burial are presented.

The objective of the second part of the program was to determine the overpressure required to cause collapse of non-instrumented cylinders of various stiffnesses over as great a range in depth of burial as the maximum overpressure would allow. The maximum applied overpressure was 160 psi. This was equal to 470 times the theoretical in-air primary buckling pressure of the most flexible cylinder.

b. Conclusions.

The following conclusions are drawn from the results of this experimental investigation:

(1) The increase in the resistance to collapse of cylinders by burial in dense sand was demonstrated. The existence of very large strains does not imply the imminence of collapse.

(2) The overpressure required to cause collapse, as measured in destructive tests over a very small range in depth of burial, increased with the depth of burial. Collapse occurred by snap-through at the crown.

(3) The ratio of the overpressure required to cause collapse at any depth to the theoretical in-air primary buckling pressure varied inversely with stiffness.

(4) Two zones of burial were defined by the variations in the magnitudes of the displacements and strains at the crown of the stiffer, instrumented cylinder. In the first zone (shallow burial), the displacements and strains were highly sensitive to small changes in depth of burial. In the second zone (deep burial), the displacements and strains were insensitive to changes in depth of burial. The minimum depth required for deep burial increased with the overpressure.

(5) The deflected shape assumed by a buried cylinder depends on its stiffness and zone of burial. Deeply buried, instrumented cylinders of both stiffnesses deformed into low-order modes. At shallow burial, the more rigid, instrumented cylinder assumed a high-order mode in the vicinity of the crown. Again at shallow burial, the more flexible, instrumented cylinder experienced inward radial displacements at the springline.

(6) The direct compressive strains were uniform around the more rigid, instrumented cylinder at deep burial.

(7) For the more rigid cylinder, the effect of arching, as reflected by the direct compressive strains at the springline, did not vary significantly with depth in the range of overpressure employed.

(8) Local buckling of the more flexible cylinder resulted in spurious strain data.

c. Recommendations for further research.

Guided by the experience gained in this experimental investigation and bearing in mind the goal of establishing criteria for the design of protective structures, the writer recommends that more tests be conducted on stiffer cylinders. The overpressure should be sufficiently large (perhaps 1,000 psi) to induce collapse of very stiff cylinders, even at deep burial. When valid assumptions are established, a theoretical plastic analysis can be undertaken.

The displacement fields in the surrounding medium should be determined. These would be of assistance in the choice of a suitable test bin and later in a study of arching phenomena. Pilot studies of this problem are being conducted, using X-ray equipment, at the Shock Tube Facility.

It is recommended that the deformations of test cylinders be determined photo-optically. The possibility of determining the displacements of several hundred points on the inner surface of a buried cylinder, to a precision of one-thousandth inch, is being studied at the Shock Tube Facility.

It is recommended that the strains be calculated from the displacement data. The use of a computer would be all but mandatory.

The soil should be placed to give uniform density at all points before application of overpressure. This could be accomplished by placing the soil with the axis of the cylinder vertical and by use of a mandrel.

In the future, it may prove desirable to use soil other than dense, dry Ottawa sand.

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An experimental investigation was conducted into the response of small buried aluminum cylinders to quasi-static overpressures. The cylinders were buried with their axes horizontal in dense, dry, 20-30 Ottawa sand.

Cylinders of two stiffnesses were tested at depths ranging from zero to two cylinder diameters. Their behavior was evaluated quantitatively by radial displacement gages and tangential strain gages. Data at five overpressure levels up to 140 psi are presented. This maximum value exceeded the theoretical in-air primary buckling pressure of the cylinders by factors of [illegible] and [illegible].

Destructive tests were conducted on noninstrumented cylinders of six stiffnesses. This maximum applied overpressure was [illegible] psi, [illegible] times the theoretical in-air primary buckling pressure of the most flexible cylinder. The overpressure required to cause collapse of the various cylinders was determined for as many depths of burial as the maximum overpressure would allow.

The destructive tests demonstrate the great resistance to collapse imparted to a cylinder by burial. The nondestructive tests afford a comparison between the behavior of stiff and flexible cylinders as the depth of burial and the overpressure are changed. Two zones of burial, deep and shallow, are defined. These zones depend on the rigidity of the cylinder and the magnitude of the overpressure.

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