REC-ERC-72-38

LABORATORY LOAD TESTS ON BURIED FLEXIBLE PIPE PROGRESS REPORT NO. 4

Reinforced Plastic Mortar (RPM) Pipe

Amster K. Howard
Engineering and Research Center
Bureau of Reclamation

November 1972

MS-230 (8-70)
Bureau of Reclamation

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. REC-ERC-72-38	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE Laboratory Load Tests on Buried Flexible Pipe—Progress Report No. 4—Reinforced Plastic Mortar (RPM) Pipe		5. REPORT DATE Nov 72 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Amster K. Howard		8. PERFORMING ORGANIZATION REPORT NO. REC-ERC-72-38
9. PERFORMING ORGANIZATION NAME AND ADDRESS Engineering and Research Center Bureau of Reclamation Denver, Colorado 80225		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. 13. TYPE OF REPORT AND PERIOD COVERED
12. SPONSORING AGENCY NAME AND ADDRESS Same		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Reinforced Plastic Mortar (RPM) pipe 18 and 24 inches in diameter with different wall thicknesses were buried in a large soil container and load tested. Surcharge loads were applied to the soil surface over the pipe with a large testing machine. For each test, pipe cross sectional deflections and shape, strain on the inner surface, soil movement around the pipe, and soil pressures on the container walls were measured during a 1-day period. Six RPM pipes were tested with the surrounding lean clay backfill placed at 90 percent Proctor maximum dry density and one at 100 percent. Behavior was compared with steel pipe tested under similar conditions. Conclusions are: (1) in high density clay backfill tests (100 percent Proctor), the RPM pipe was more resistant to elastic buckling than steel pipe of similar stiffness, deflecting about the same as steel pipe of much greater stiffness. (2) In low density clay backfill tests (90 percent Proctor), the RPM pipe deflected 2 to 3 times more than steel pipe of similar stiffnesses. (3) For RPM pipe manufactured with the same fiberglass-resin ratio, the pipe deflection varied inversely with the Ring Stiffness Factor. (4) RPM pipe without exterior sand coating deflected the same as RPM pipe of similar stiffness with the coating.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. *DESCRIPTORS*-- / pipelines/ backfills/ soil mechanics/ loading tests/ test procedures/ cohesive soils/ pressure cells/ *buried pipes/ strain gages/ *flexible pipes/ pressure measuring instruments/ *soil pressure/ lateral forces/ pressure sensors/ steel pipes/ strain/ *deflection/ deformation/ laboratory tests/ plastics/ *plastic pipes/ polymers/ stiffness/ resins

b. *IDENTIFIERS*-- / Iowa Formula/ soil-structure interaction/ *reinforced plastic mortar pipe/ glass reinforced plastics/ deflection measurement

c. *COSATI Field/Group* 13K

18. DISTRIBUTION STATEMENT *Available from the National Technical Information Service, Operations Division, Springfield, Virginia 22151.*	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 75
	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. PRICE

REC-ERC-72-38

LABORATORY LOAD TESTS ON BURIED FLEXIBLE PIPE PROGRESS REPORT NO. 4

Reinforced Plastic Mortar (RPM) Pipe

by
Amster K. Howard

November 1972

Earth Sciences Branch
Division of General Research
Engineering and Research Center
Denver, Colorado

UNITED STATES DEPARTMENT OF THE INTERIOR
Rogers C. B. Morton
Secretary

*

BUREAU OF RECLAMATION
Ellis L. Armstrong
Commissioner

ACKNOWLEDGMENT

This study was conducted by Amster K. Howard under the supervision of Chester W. Jones, Head, Special Investigations and Research Section. Harold J. Gibbs is Chief of the Earth Sciences Branch. The report was reviewed by C. W. Jones and C. E. Selander.

Reprint or republication of any of this material shall give appropriate credit to the Bureau of Reclamation, U.S. Department of the Interior.

CONTENTS

	Page
Introduction	1
Testing Program	2
Test Procedure	2
Three-edge Bearing Test	2
Preparation for Load Testing	5
Load Test	5
Test Equipment and Instrumentation	5
Soil Container	5
Pressure Cells	6
Soil Movement Indicators	6
Dial Gages	6
Strain Gages	6
Summary of Previous Tests on Steel Pipe	6
Iowa Formula	6
Steel Pipe in 90 Percent Backfill	7
Steel Pipe in 100 Percent Backfill	7
Results of Tests of RPM Pipe	7
RPM Pipe Deflection—90 Percent Backfill	7
RPM Pipe Deflection—100 Percent Backfill	14
Affect of Exterior Surface of RPM Pipe on Pipe Deflection	14
Conclusions	23
Applications	23
Personnel Performing Tests	26
References	26

LIST OF TABLES

Table		
1	Description of test conditions for RPM pipe	2
2	Physical properties of RPM pipe	3
3	Soil backfill properties	5
4	Comparison of test conditions for RPM and steel pipe—90 percent backfill	15
5	Comparison of test conditions for RPM and steel pipe—100 percent backfill	16
6	Physical properties of plain and sand-coated RPM pipe	24
7	Soil backfill properties for RPM Tests PA-18-A and PA-18-D	24

CONTENTS—Continued

LIST OF FIGURES

Figure		Page
1	Cross section of RPM pipe showing laminated or layered structure	1
2	Test procedure for soil container load tests of buried flexible pipe	4
3	Comparison of steel pipe with Iowa Formula, EI/r^3 = 0 psi	8
4	Comparison of steel pipe with Iowa Formula, EI/r^3 = 10 psi	9
5	Three-edge bearing deflection of pipe with EI/r^3 = 2.0 psi—Comparison of horizontal deflections of RPM and steel pipe	10
6	Deflection comparison of pipe with EI/r^3 = 2 psi—Horizontal deflections of RPM and steel pipe from soil container tests	11
7	Three-edge bearing deflections of pipe with EI/r^3 = 4.0 psi—Comparison of horizontal deflections of RPM and steel pipe	12
8	Deflection comparison of pipe with EI/r^3 = 4.0 psi—Horizontal deflections of RPM and steel pipe from soil container tests	13
9	Deflection comparison of pipe with EI/r^3 = 3 to 4 psi—Horizontal deflections of RPM and steel pipe from soil container tests	17
10	Deflection comparison of pipe with EI/r^3 = 16 to 20 psi—Horizontal deflections of RPM and steel pipe from soil container tests	18
11	Deflection comparison of RPM pipe from different manufacturers with steel pipe—Horizontal deflections of RPM and steel pipe from soil container tests	19
12	Horizontal deflections of RPM pipe in 90 percent backfill	20
13	Deflection comparison of pipe in 100 percent density backfill—Horizontal deflections of RPM and steel pipe from soil container tests	21
14	Comparison of RPM pipe in 90 and 100 percent backfill	22
15	Typical surface of standard RPM pipe	23
16	Exterior surface of RPM pipe with sand omitted	23

APPENDIX A

MODULUS OF ELASTICITY OF RPM PIPE

Introduction and Discussion 27

LIST OF TABLES

Table		
A–1	Empirical modulus of elasticity (E) values for RPM pipe	28

LIST OF FIGURES

Figure		
A–1	Strain gage readings around inside pipe circumference—PA-18-A Three-Edge Bearing Test	29

CONTENTS—Continued

Figure		Page
A–2	Strain gage readings around inside pipe circumference—PA-18-F Three-Edge Bearing Test	30
A–3	Strain gage readings around inside pipe circumference—PB-18 Three-Edge Bearing Test	31
A–4	Strain gage readings around inside pipe circumference—PA-24 Three-Edge Bearing Test	32

APPENDIX B

INDIVIDUAL TEST RESULTS OF RPM PIPE TESTS

Introduction . . . 33
Test Results . . . 33

Pipe Deflection . . . 33
Soil Pressures on Container Walls . . . 33
Strain Gage Readings . . . 33
Soil Movement Between Pipe and Soil Container Walls . . . 34
Shape of the Pipe Cross-Section Under Load . . . 34

LIST OF FIGURES

Figure		
B–1	Load deflection curves, PA-18-A	35
B–2	Load deflection curves, PA-18-B	36
B–3	Load deflection curves, PA-18-C	37
B–4	Load deflection curves, PA-18-D	38
B–5	Load deflection curves, PA-18-F	39
B–6	Load deflection curves, PA-24	40
B–7	Load deflection curves, PB-18	41
B–8	Soil pressures on container wall, PA-18-A	42
B–9	Soil pressures on container wall, PA-18-B	43
B–10	Soil pressures on container walls, PA-18-C	44
B–11	Soil pressures on container wall, PA-18-D	45
B–12	Soil pressures on container walls, PA-18-F	46
B–13	Soil pressures on container wall, PA-24	47
B–14	Soil pressures on container wall, PB-18	48
B–15	Strain gage readings around inside pipe circumference, PA-18-A	49
B–16	Strain gage readings around inside pipe circumference, PA-18-B	50
B–17	Strain gage readings around inside pipe circumference, PA-18-D	51
B–18	Strain gage readings around inside pipe circumference, PA-18-F	52
B–19	Strain gage readings around inside pipe circumference, PA-24	53
B–20	Strain gage readings around inside pipe circumference, PB-18	54
B–21	Soil movement between pipe and soil container wall, PA-18-A	55
B–22	Soil movement between pipe and soil container wall, PA-18-B	56
B–23	Soil movement between pipe and soil container wall, PA-18-C	57
B–24	Soil movement between pipe and soil container wall, PA-18-D	58
B–25	Soil movement between pipe and soil container wall, PA-18-F	59
B–26	Soil movement between pipe and soil container wall, PA-24	60

CONTENTS—Continued

Figure		Page
B–27	Soil movement between pipe and soil container wall, PB-18	61
B–28	Cross section of pipe under load, RPM pipe test, PA-18-A	62
B–29	Cross section of pipe under load, RPM pipe test, PA-18-B	63
B–30	Cross section of pipe under load, RPM pipe test, PA-18-C	64
B–31	Cross section of pipe under load, RPM pipe test, PA-18-D	65
B–32	Cross section of pipe under load, RPM pipe test, PA-18-F	66
B–33	Cross section of pipe under load, RPM pipe test, PA-24	67
B–34	Cross section of pipe under load, RPM pipe test, PB-18	68
B–35	Comparison of deformed shape of RPM pipe to deformed shape of steel pipe	69
B–36	Physical properties summary plot of test soil 24G-103	70

APPENDIX C

FAILURE CHARACTERISTICS OF RPM PIPE

Introduction 71
Individual Test Pipe Performance 71

PA-18-A 71
PA-18-B 72
PA-18-C 72
PA-18-D 73
PA-18-F 73
PA-24 74
PB-18 75

LIST OF FIGURES

Figure		
C–1	Typical crazing pattern on interior surface of RPM pipe	71
C–2	Separation of fiberglass strands on exterior of RPM pipe	71
C–3	Separation of laminations in wall of RPM pipe	71
C–4	Four-foot-long longitudinal exterior crack of Test Pipe PA-18-A	72
C–5	Circumferential location of exterior cracks on Test Pipe PA-18-A	72
C–6	Test Pipe PA-18-B with 27 percent vertical deflection	72
C–7	Three-foot longitudinal crack at south end of Test Pipe PA-18-B at 90°	72
C–8	Test Pipe PA-18-C showing reverse curvature at 0°	73
C–9	Exterior cracking of Test Pipe PA-18-C	73
C–10	Closeup of exterior cracking of Test Pipe PA-18-C	73
C–11	Test Pipe PA-18-D showing reverse curvature at 0°	73
C–12	Interior cracking of Test Pipe PA-18-D at 0°	74
C–13	Interior cracking pattern of Test Pipe PA-18-D at 0°	74
C–14	Exterior longitudinal cracking of Test Pipe PA-18-D at 270°	74
C–15	Test Pipe PA-18-F with 50 percent vertical deflection	74

CONTENTS—Continued

Figure		Page
C—16	Compressive crushing of interior wall of Test Pipe PA-18-F at 110°	74
C—17	Exterior cracking of Test Pipe PA-18-F at 110°	75
C—18	Closeup of exterior cracking of Test Pipe PA-18-F	75
C—19	Test Pipe PA-24 with 31 percent vertical deflection	75
C—20	Fiberglass strands pulled loose from an end of Test Pipe PA-24	75

INTRODUCTION

The Bureau of Reclamation (USBR) is primarily noted for the construction of large dams in the Western United States. In addition to providing these water collection systems the Bureau also furnishes the distribution systems for transporting the water to the irrigation districts, municipalities, and industries that have contracted for it. In the past, canals have been the primary means of distribution. The emphasis is now on closed conduit systems for reasons of safety, reduced water losses, reduced maintenance costs, and greater land use. In 1966 the Bureau began investigating reinforced plastic mortar (RPM) pipe as a potential economical alternative to pipe now being used.

As one part of the investigation, the Earth Sciences Branch of the USBR has been conducting laboratory load tests on buried pieces of RPM pipe. The pipe is buried in a large soil container and surcharge loads applied to the soil surface over the pipe with a universal testing machine. Pipe deflections and soil pressures are measured during a 1-day testing period.

RPM pipe is a new type of pipe that is a composite built primarily from polyester resin, silicate sand, and glass filament reinforcing. The resin used is a basic isophthalic polyester resin which gives the product excellent resistance to a wide variety of chemical solutions. The sand is a clean, well-graded, high-silica content sand. The reinforcing filament is a particular type of boro-silicate glass with a special surface treatment to enhance the adhesion of resin to glass. The layered structure of pipe with a sand-rich liner is shown in Figure 1. The pipe is built up in layers on a mandrel on a machine which is essentially a filament winding process modified to incorporate the sand into the process. It is flexible and lightweight yet provides high tensile hoop strength.

The USBR and the pipe manufacturers engaged in an extensive cooperative study of RPM pipe. The study is called the Government-Industry Cooperative Study (GICS) of RPM pipe. The ultimate goal was the preparation of Bureau specifications which could, with adequate assurance, result in obtaining a reliable pipe of good durability. These specifications were issued in early 1971.

The GICS laboratory studies were divided into several series to study the basic physical properties of RPM pipe, the scaling factors, the stiffness correlations and the behavior of the pipe buried in soil.

Two GICS progress reports have been published covering the developmental history, the testing program, and the accumulated data.[1 2*]

This report presents a detailed discussion of the results of the load tests on buried RPM pipe. After a background discussion of the results of a similar testing program of steel pipe, the RPM pipe behavior is

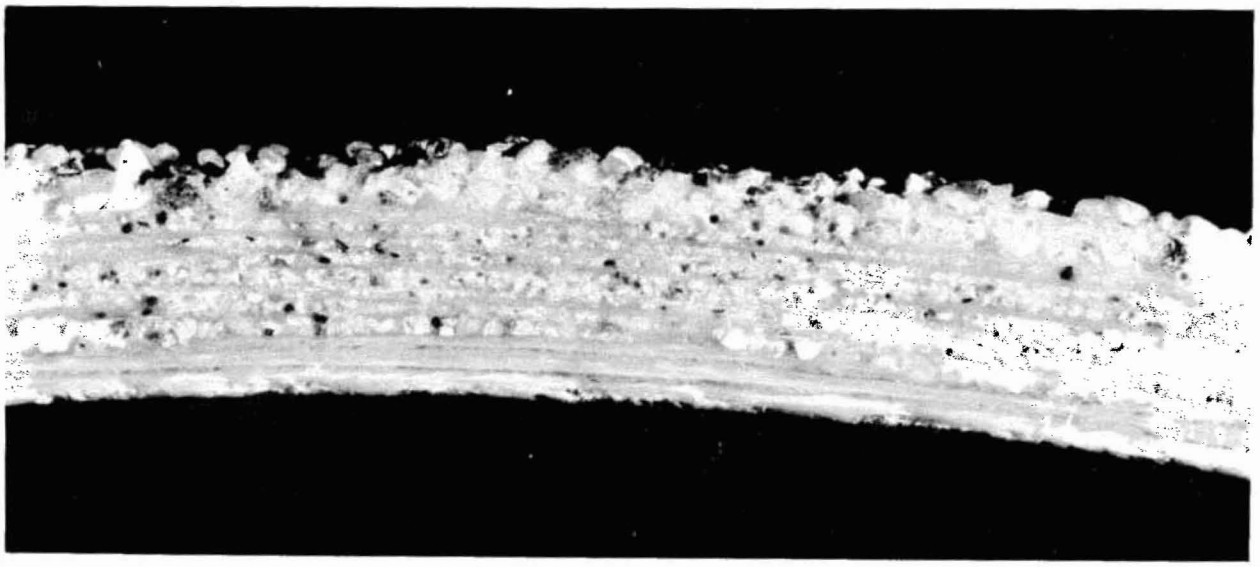


Figure 1. Cross section of RPM pipe showing laminated or layered structure. 4X magnification. Photo PX-D-65568

*Numbers designate references at end of text.

compared to that of the steel pipe. Evaluated in terms of the Ring Stiffness Factors of each pipe, the steel pipe results showed a good correlation with theory. The same type of evaluation is used for the RPM soil load tests.

TESTING PROGRAM

The load tests on RPM pipe used the same equipment and procedures developed for the Bureau's investigation of buried flexible steel pipe. The first three progress reports of this series describe the testing equipment, procedures, data, and conclusions of the tests on steel pipe.[3 4 5]

The testing program for RPM pipe included standard production pipe as well as specially manufactured pipe with Ring Stiffness Factors (EI/r^3) similar to some of the steel pipe tested. Seven pieces of RPM pipe have been tested.

The test conditions are listed in Table 1. Six of the tests had 90 percent backfill (90 percent of the Proctor maximum dry density) and one had 100 percent backfill. The percent Proctor was determined using Test Designations E-11 and E-24 of the Bureau's Earth Manual.[6]

Each individual test can be identified as in the following example:

Test PA-18-B

P refers to plastic-base pipe

The second letter, A (or B in other cases) refers to the soil condition around the pipe.

A is a homogeneous backfill compacted to 90 percent Proctor at optimum moisture.

B is a homogeneous backfill compacted to 100 percent Proctor at optimum moisture.

18 refers to the pipe diameter in inches.

B refers to the physical properties of the pipe (usually a specific Ring Stiffness Factor).

The physical properties of the pipe are shown in Table 2. Tests PA-18-A, PB-18, and PA-18-F were standard production pipe. The other test pipe were especially designed to give specific Ring Stiffness Factors, EI/r^3. Test PA-18-D was manufactured similar to Test PA-18-A except the sand coating was left off of the exterior. The sand was omitted to see if the rough exterior of the pipe affected the deflections.

TEST PROCEDURE

The testing procedures are basically the same as used for the steel pipe. Figure 2 illustrates the different phases of each test.

Three-edge Bearing Test

Before each pipe was buried in the soil container, a three-edge bearing test was run on the pipe. The test procedure is similar to the procedure in ASTM: D 2412, "External Loading Properties of Plastic Pipe by Parallel-Plate Loading," except that bearing blocks are used instead of parallel plates. The blocks are those used for three-edge bearing tests of concrete pipe, as described in ASTM: C 14 and ASTM: C 76. The purpose of these tests is to determine an empirical wall

Table 1

DESCRIPTION OF TEST CONDITIONS FOR RPM PIPE

Test No.	Pipe nominal inside diameter		Approximate thickness		Approximate wall stiffness (EI)		Approximate Ring Stiffness Factor (EI/r^3)		Backfill soil density	Design
	inches	cm	inches	mm	in.^{2} lb/in.	cm^2 kg/cm	psi	kg/cm^2	percent Proctor	
PA-18-A	18	46	1/4	6	2,200	36,000	3	0.21	90	Standard
PA-18-B	18	46	3/8	9	12,000	197,000	16	1.52	90	Special
PA-18-C	18	46	1/4	6	1,400	23,000	2	0.14	90	Special
PA-18-D	18	46	1/4	6	2,200	36,000	3	0.21	90	No sand coating on exterior
PA-18-F	18	46	5/16	8	4,500	74,000	6	0.44	90	Standard*
PA-24	24	61	5/16	8	7,000	115,000	4	0.28	90	Special
PB-18	18	46	1/4	6	2,200	36,000	3	0.21	100	Standard

*By a different manufacturer than for the others tested, designed for gravity flow.

Table 2

PHYSICAL PROPERTIES OF RPM PIPE

Test No.	Wall thickness (on sand)		Length[1]		EI/r^3 from[2] vertical deflections		EI/r^3 from[3] horizontal deflections		Pipe internal diameter[4]			
									North end		South end	
	inches	cm	inches	cm	psi	kg/cm^2	psi	kg/cm^2	inches	cm	inches	cm
PA-18-A	≃0.28	0.71	71	180.3	3.1 to 3.7	0.22 to 0.26	3.1 to 3.6	0.22 to 0.25	18.056	45.862	18.063	45.880
PA-18-B	0.41	1.04	70-13/16	179.9	15.0 to 17.2	1.05 to 1.21	15.2 to 17.5	1.07 to 1.23	18.053	47.909	18.074	45.908
PA-18-C	0.23	0.58	71	180.3	1.8 to 2.0	0.127 to 0.141	1.8 to 2.0	0.13 to 0.14	18.026	45.786	18.055	45.860
PA-18-D	0.24	0.61	71-5/16	181.1	3.8 to 4.5[5]	0.267 to 0.316	4.0 to 4.7[5]	0.28 to 0.33	18.071	45.900	18.095	45.961
PA-18-F	0.29 (north)	0.74	71	180.3	5.9 to 6.6	0.415 to 0.464	5.9 to 6.6	0.41 to 0.46	18.095	45.961	18.125	46.038
	0.35 (south)	0.89										
PA-24	0.35	0.89	70-7/8	180.0	3.5 to 3.9	0.246 to 0.274	3.7 to 4.0	0.26 to 0.28	24.173	61.399	24.137	61.308
PB-18	0.28	0.71	≃71	180.3	2.7 to 3.2	0.190 to 0.225	3.0 to 3.4	0.21 to 0.24	18.128	46.045	18.100	45.974

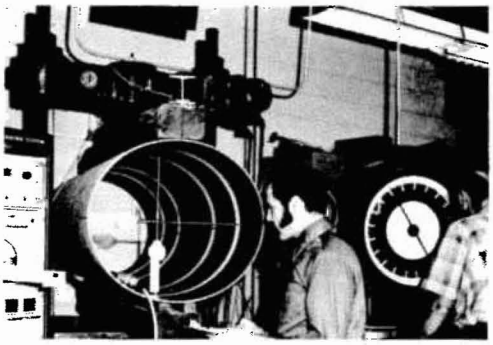
[1] Average of four measurements.

[2] $EI/r^3 = 0.149\ W/\Delta Y$ where W = load on pipe per linear inch.
ΔY = vertical deflection of pipe in inches.

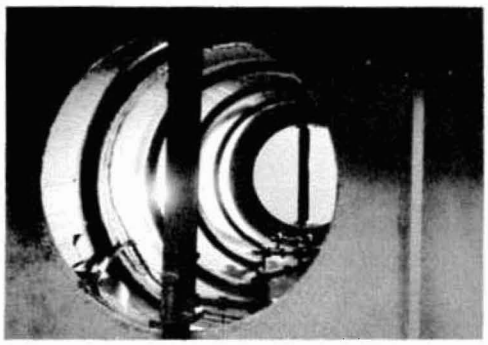
[3] $EI/r^3 = 0.136\ W/\Delta X$ where ΔX = horizontal deflection of pipe in inches.

[4] Average of at least eight measurements.

[5] Run on companion section, not actual pipe tested.

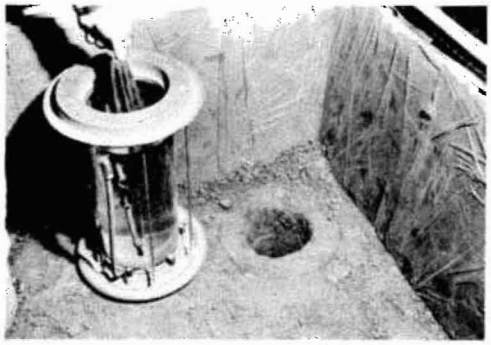


(a) The strength of the pipe is determined from the three-edge bearing test. Vertical and horizontal deflections and strain gage measurements are made. Photo PX-D-63173

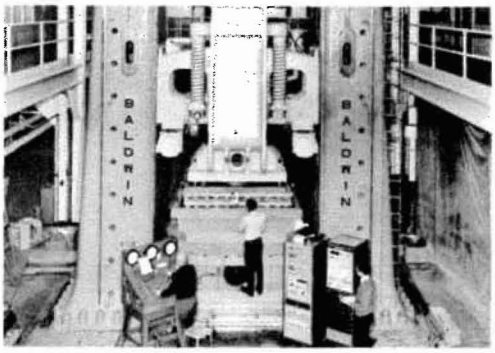


(b) Circular stiffeners are placed inside the pipe to prevent distortion of the pipe from the soil compaction. These and the braces holding the pipe in place are removed when the container is full. Photo PX-D-72334

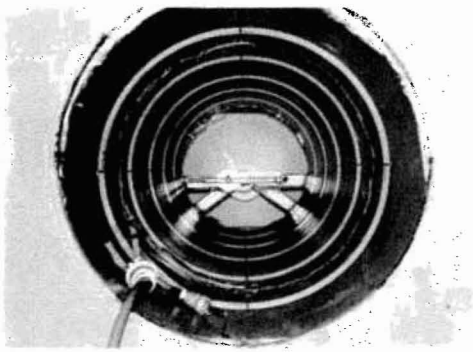
(c) Equal lifts of loose soil are placed in the container and compacted with a pneumatic hand tamper at a uniform rate. Photo PX-D-69559



(d) The soil density is measured for every vertical foot of soil placed in the container with a balloon densiometer. Photo PX-D-69554



(e) The container is placed under the universal testing machine. Load is applied in increments at 1-hour intervals to the soil surface over the pipe. Photo PX-D-69558



(f) Inside of the pipe showing the revolving dial gage and the circumferential ring of SR-4 type strain gages. Photo PX-D-72335

Figure 2. Test procedure for soil container load tests of buried flexible pipe.

stiffness, EI, of the pipe where E is the modulus of elasticity of the wall material and I is the moment of inertia of a section of the pipe wall. The wall stiffness, EI, expresses the strength of the pipe and is an important part of the pipe design. The approximate EI values are listed in Table 1.

Preparation for Load Testing

To reduce the friction between the soil and container walls, a coating of petrolatum is applied to the walls and covered with 2-mil polyethylene film. The soil is placed in loose lifts and compacted with a pneumatic hand tamper to the required density. After the soil is placed to the desired elevation of the bottom of the pipe, the pipe is placed on the soil surface. Circular stiffeners are placed in the pipe to prevent the relatively flexible pipe from becoming deformed during the soil compaction around the pipe. The pipe is also braced into place to prevent the pipe from rising during soil compaction under the sides of the pipe. The soil is then compacted beside the pipe and on up to the top of the container. A wooden load plate is placed on the soil surface to distribute the surcharge load from the testing machine.

As the backfill soil was placed in the soil container and around the pipe, density determinations were made for every foot depth of compacted soil. A summary of the densities for each pipe load test is presented in Table 3. The mean density for each separate pipe test ranged from 89.4 to 90.6 percent Proctor with an average mean for all the tests of 89.8 percent Proctor for the tests at 90 percent backfill density. The mean density for the PB test was 100.6 percent Proctor. The standard deviation for the densities in each test ranged from 0.9 to 2.0 percent (approximately). The means of the moisture content for each test ranged from 11.6 to 11.9 percent (12.0 percent is the optimum moisture for the soil) with the standard deviations ranging from 0.3 to 0.5 percent (approximately). The values are close enough that the soil will be considered as having a uniform density and moisture content for all the tests.

A summary of the physical properties of the soil is presented in Appendix B of this report.

Load Test

The stiffeners and braces are removed. All instrumentation is connected and initial readings are taken. Each load increment is applied at 1-hour intervals with a uniform loading rate of 2 pounds per square inch (psi) (0.14 kilogram per square centimeter (kg/sq cm)) per minute. Most of the instruments are read at 1 and 60 minutes after each load is applied. Readings between these times vary with the instruments. The load increment for the RPM tests was either 5 psi (0.3 kg/sq cm) or 10 psi (0.7 kg/sq cm).

TEST EQUIPMENT AND INSTRUMENTATION

Soil Container

The pipe is buried in a 6-foot (1.8-meter) wide by 7-foot (2.1-meter) long by 7-foot (2.1-meter) deep steel soil container and placed with the longitudinal axis of the pipe 4 feet (1.2 meters) below the soil surface. Details of the container are given in Appendix B of Progress Report No. 3.

Table 3

SOIL BACKFILL PROPERTIES

Test No.	No. of tests	Soil density[1] —Percent of Proctor			Moisture content[2] —Percent		
		Range	Mean	Standard deviation	Range	Mean	Standard deviation
PA-18-A	9	87.6 to 93.0	89.7	1.89	11.0 to 12.1	11.6	0.29
PA-18-B	14	87.7 to 92.8	90.6	1.37	11.3 to 12.4	11.7	.32
PA-18-C	14	88.2 to 91.1	89.9	0.94	11.1 to 13.0	11.9	.50
PA-18-D	16	85.1 to 92.0	89.4	1.95	11.4 to 12.4	11.8	.25
PA-18-F	10	87.7 to 92.9	90.0	1.72	10.9 to 12.6	11.9	.52
PA-24	12	86.3 to 91.4	89.6	1.48	11.4 to 12.3	11.8	.27
PB-18	14	99.4 to 102.6	100.6	1.02	11.3 to 12.5	11.8	.31

[1] Proctor Maximum Dry Density = 120.0 pounds per cubic foot (pcf) (1.92 gram/cu cm).
[2] Optimum Moisture Content = 12.0 percent.

Pressure Cells

Pressure cells are mounted in the walls of the soil container to measure the horizontal soil pressures. The pressure cell is one developed by the Earth Sciences Branch (details in Appendix B of Progress Report No. 3). The cell contains a fluid-filled chamber covered by a sensitive outer diaphragm. Pressures created within this fluid chamber by soil acting on the outer diaphragm are measured by applying air pressure to a small sensitive inner diaphragm. The balance of the known air pressure against the unknown fluid pressure in the cell is determined by the making and breaking of an electrical contact on the small sensitive inner diaphragm. The cells were filled with de-aired water and calibrated by applying a pneumatic load to the outer diaphragm of the pressure cell.

Soil Movement Indicators

Telescoping tubes with small plates on the ends are buried in the soil in line with the horizontal diameter of the pipe. The ends of the tubes extend through the soil container walls so that horizontal soil movements during the loading can be measured.

Dial Gages

Dial gages calibrated to 0.001 inch (0.025 millimeter (mm)) are used to measure the soil surface settlement and the deflection and settlement of the pipe. A dial gage mounted to a revolving shaft along the longitudinal axis of the pipe is used at intervals to measure the changing shape of the pipe during loading.

Strain Gages

Circumferential rings of SR-4 type strain gages are applied on the inside of the pipe to measure the strain in the pipe wall.

SUMMARY OF PREVIOUS TESTS ON STEEL PIPE

The soil load on a flexible pipe causes a decrease in the vertical diameter (ΔY) and an increase in the horizontal diameter (ΔX). The horizontal movement into the soil develops a passive resistance that acts to help support the pipe. This soil resistance is defined as e', the "modulus of passive resistance" in the Iowa Formula for predicting pipe deflection. Professor M. G. Spangler developed this formula at Iowa State University from an extensive field testing program.[7 8] Generally, a constant e' value of 700 psi (49 kg/sq cm) is suggested for all pipe loads for all soils for backfill placed at 90 percent of their maximum dry density. Professor Spangler now recommends that e' values be selected based on experience and judgment.[9]

A steel pipe test is identified as FA-18-10, where F refers to flexible steel pipe, A is the backfill conditions (A is 90 percent Proctor, B is 100 percent Proctor), 18 is the pipe diameter in inches, and 10 is the gage of the pipe wall.

Iowa Formula

The present version[8] of the Iowa Formula is given as:

$$\Delta X = D_1 \frac{KW r^3}{EI + 0.061\, e' r^3}$$

where

- ΔX = horizontal deflection of the pipe, inches (centimeters)
- D_1 = deflection lag factor to compensate for the time-consolidation rate of the soil, dimensionless
- K = bedding constant which varies with the angle of the bedding, dimensionless
- W = load on the pipe per unit length, pounds per linear inch (kilograms per centimeter)
- r = pipe radius, inches (centimeters)
- EI = pipe wall stiffness per unit length, in square inch-pounds per inch (square centimeter-kilogram per cm)
- e' = modulus of passive resistance of soil, pounds per square inch (kilograms per square centimeter)

Several assumptions were made to apply the Iowa Formula to the USBR laboratory load tests. A bedding coefficient, K, of 0.1 was selected assuming that the support of the bedding was somewhere between a line load and full 90° support. The load on the pipe was assumed to be equal to the surcharge load (p) acting on a projection of the pipe diameter (2r) or W = p(2r). The weight of the backfill soil was ignored since it is small compared to the surcharge loads. In addition, the pipe was stiffened and restrained during backfilling so that whatever backfill load was imposed did not deflect the pipe. The pressure cell readings at a no-load condition, which are due to the backfill load, were subtracted from the pressure cell readings made during the load test. The result is that the pipe deflections, soil pressures, circumferential strain, and soil settlement were all considered to be zero with the pipe in the buried condition without any surcharge load applied.

Although the incremental surcharge loads were held constant for an hour, the 1-minute readings were used for analysis. The later readings are due to the time-consolidation rate of the soil and are a function of the density and type of soil. These data will be correlated later with long-term field tests to develop deflection lag factors. Meanwhile, a deflection lag factor, D_1 of 1.0 was used for the 1-minute readings.

Incorporating these assumptions and expressing the deflection as a percentage, the equation becomes:

$$\Delta X/D = \frac{0.1p}{EI/r^3 + 0.061\,e'}\,(100)$$

The physical properties of the pipe are now in one expression, EI/r^3, referred to as the Ring Stiffness Factor. Since the Ring Stiffness Factor is a constant for the pipe and e' is assumed to be constant, the equation then is a linear relationship between the percent deflection and the surcharge load. The slope of the linear curve for percent horizontal deflection versus surcharge would be dependent on the Ring Stiffness Factor of the pipe.

The Ring Stiffness Factor, EI/r^3, was obtained directly from three-edge bearing tests on each pipe.

Steel Pipe in 90 Percent Backfill

The nine steel pipe tests were divided into four groups according to their Ring Stiffness Factors. Within each group of pipe with similar stiffnesses, the load-horizontal deflection curves for individual tests were very similar. Comparison of the four groups showed that the horizontal deflection of the pipe is inversely proportional to the Ring Stiffness Factor as predicted by the Iowa Formula.

Each group of load-horizontal deflection curves were compared with a theoretical curve based on the Iowa Formula assuming an e' of 500 psi (35 kg/sq cm). Two of these comparisons are shown in Figures 3 and 4. With one minor adjustment, the empirical and theoretical curves compare closely. The theoretical curve was shifted over 10 psi (0.7 kg/sq cm) on the surcharge scale to allow for a "delay" in the empirical data. The same type of delay or seating load could be seen in the data for the settlement of the soil surface over the pipe. The 10 psi "seating load" appeared to be necessary to overcome the frictional resistance between the soil and the container walls.

Steel Pipe in 100 Percent Backfill

Five steel pipes were tested with the backfill compacted to 100 percent of Proctor maximum dry density. The two stiffest pipes, 18-inch 7-gage and 18-inch 10-gage, deflected without forming plastic hinges. The other three pipes failed by elastic buckling at vertical deflections less than 10 percent. The load-horizontal deflection curves for the two stiffest pipes compare well with the Iowa Formula. As in the case of the 90 percent backfill, their horizontal deflections are dependent on their Ring Stiffness Factors, EI/r^3. The Iowa Formula curves were based on a seating load of 20 psi (1.4 kg/cm) and an e' of 920 psi (64 kg/sq cm).

RESULTS OF TESTS OF RPM PIPE

RPM Pipe Deflection—90 Percent Backfill

Six RPM pipes of various stiffnesses were load tested with the backfill soil compacted to 90 percent Proctor; five were 18-inch (45.7-cm) diameter pipe and one was a 24-inch (61.0-cm) diameter pipe.

Since the tests on steel pipe had shown that pipe with similar stiffnesses would deflect similarly, the load-horizontal deflection curves for each RPM pipe were compared to those of steel pipe of similar stiffness. The comparison was made on the basis of the Ring Stiffness Factor, EI/r^3, determined from the three-edge bearing tests. As an example, the three-edge bearing test load-deflection curves for RPM pipe test, PA-18-C, and steel pipe test, FA-18-14, are shown in Figure 5. The two curves are almost identical and the EI/r^3 calculated from the horizontal deflections were the same for each pipe, 2 psi (0.14 kg/sq cm).

According to the results from the steel pipe tests, the two pipes should deflect similarly in the soil container load test. The load-horizontal deflection curves for the two are shown in Figure 6. The RPM pipe deflected from 2 to 3 times more than the steel pipe. The actual ratio of the RPM pipe deflection to the steel pipe deflection is shown on the graph at various load increments.

The 24-inch (61.0-cm) RPM pipe, PA-24, had almost identical three-edge bearing test results as one of the 24-inch steel pipes tested, FA-24-10. Their load-horizontal deflection curves are shown in Figure 7 and the EI/r^3 was 4.0 psi (0.3 kg/sq cm) for both. The load-horizontal deflection curves from the soil container load test on the two pipes are shown in Figure 8. The RPM pipe deflected about twice as much.

For the other RPM pipes tested, there were no steel pipes with stiffnesses as close as in the first two cases.

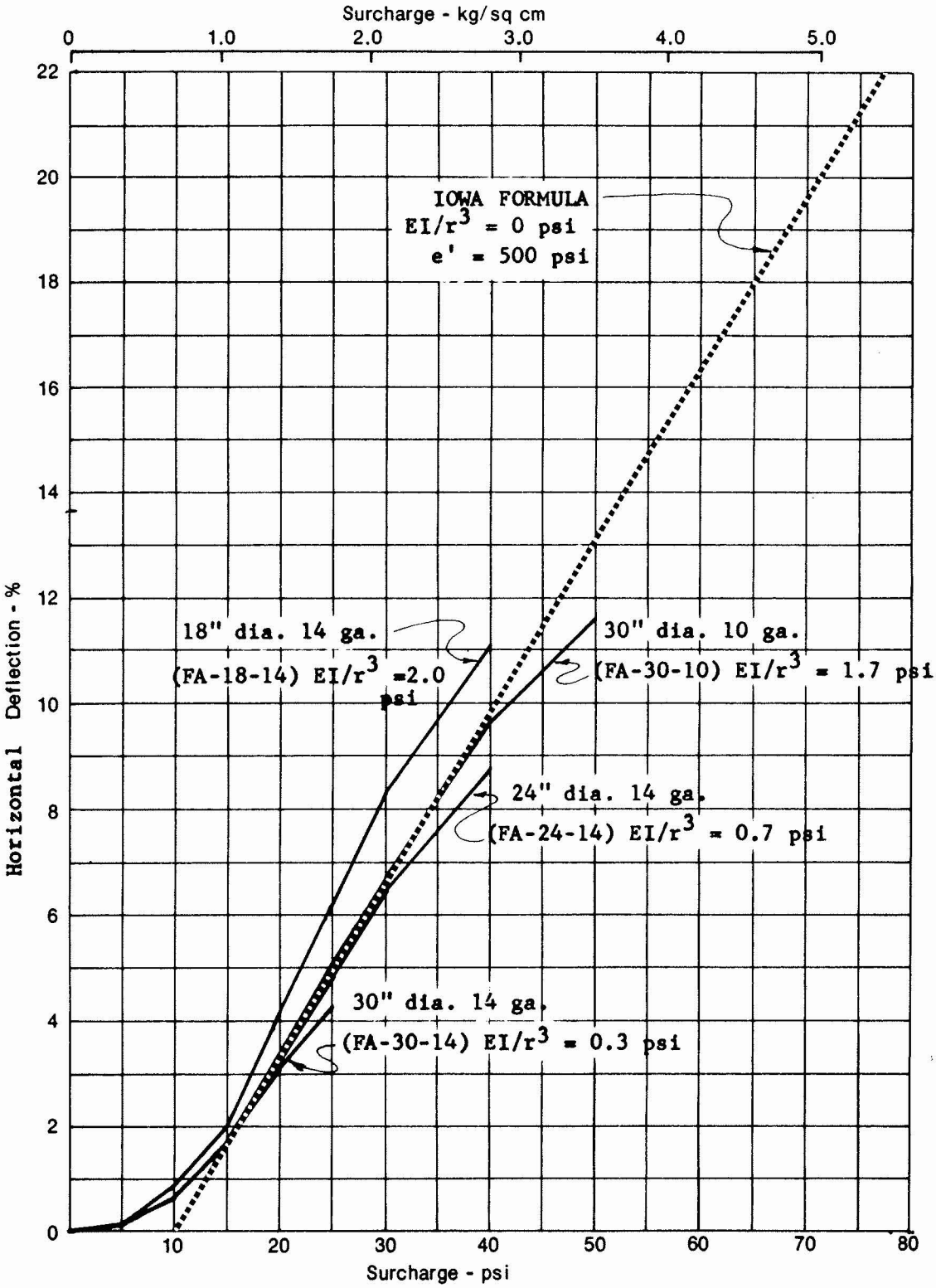


Figure 3. Comparison of steel pipe with Iowa Formula, $EI/r^3 = 0$ psi.

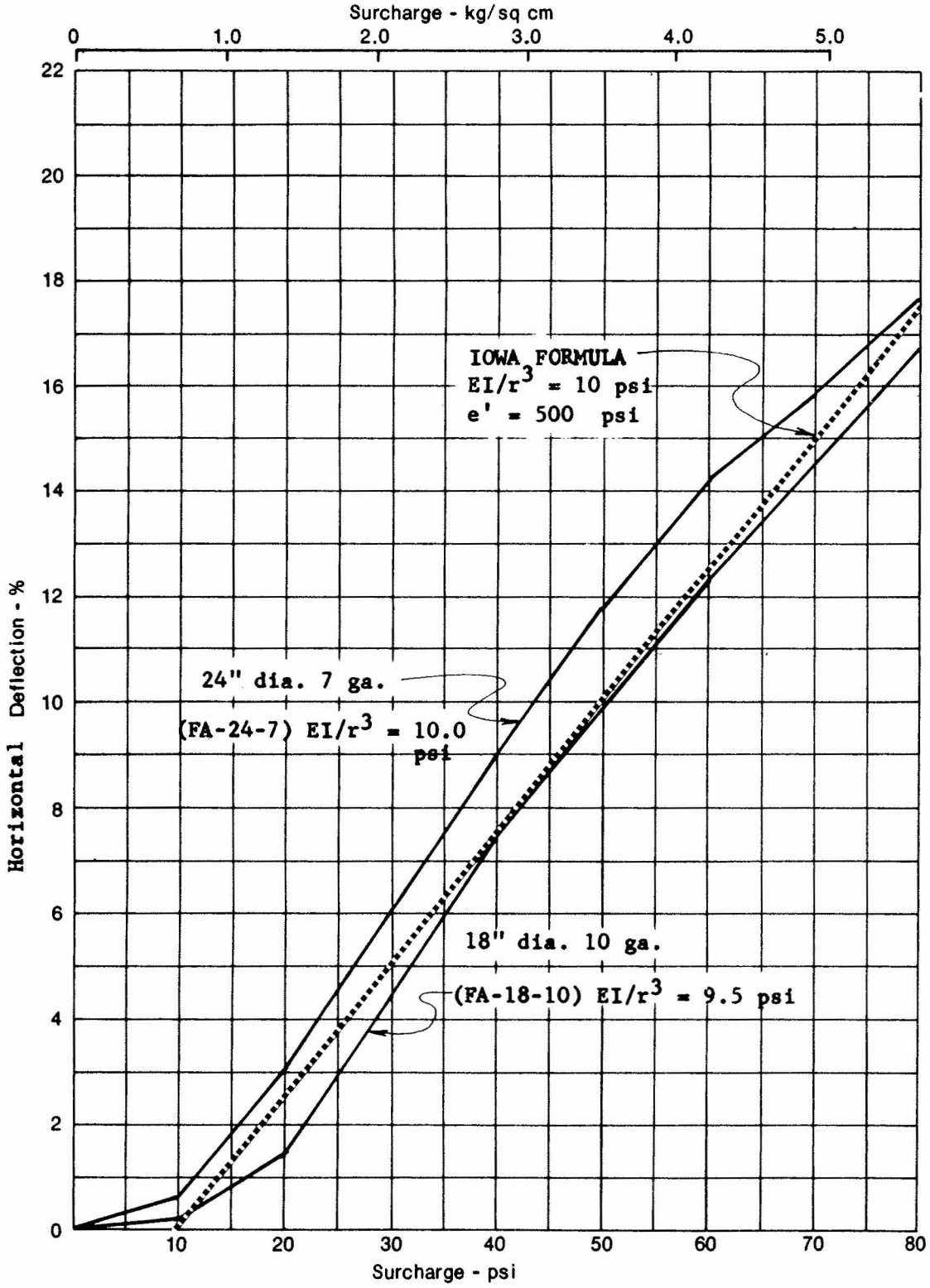


Figure 4. Comparison of steel pipe with Iowa Formula, EI/r^3 = 10 psi.

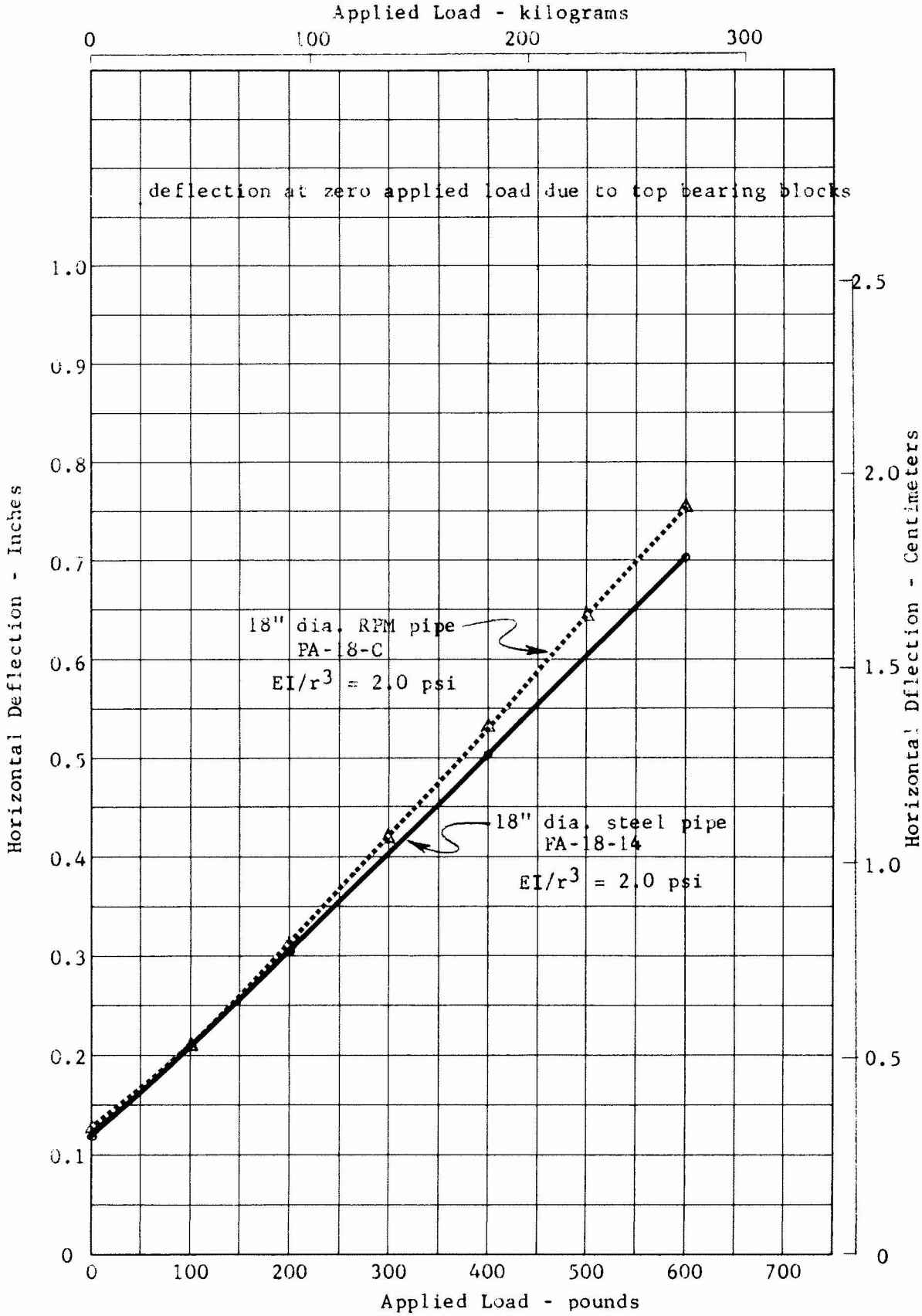


Figure 5. Three-edge bearing deflection of pipe with EI/r^3 = 2.0 psi—Comparison of horizontal deflections of RPM and steel pipe.

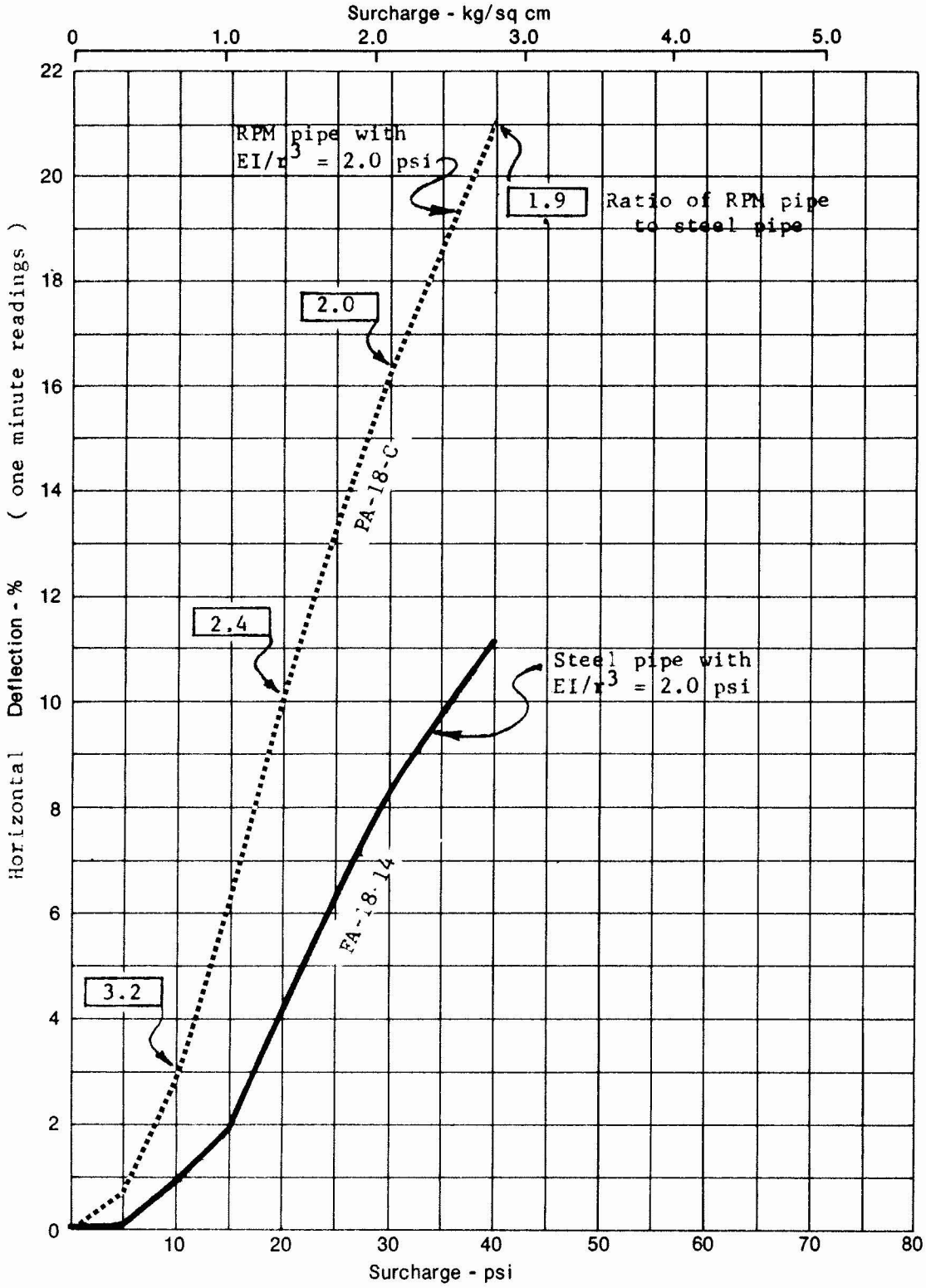


Figure 6. Deflection comparison of pipe with EI/r^3 = 2 psi—Horizontal deflections of RPM and steel pipe from soil container tests.

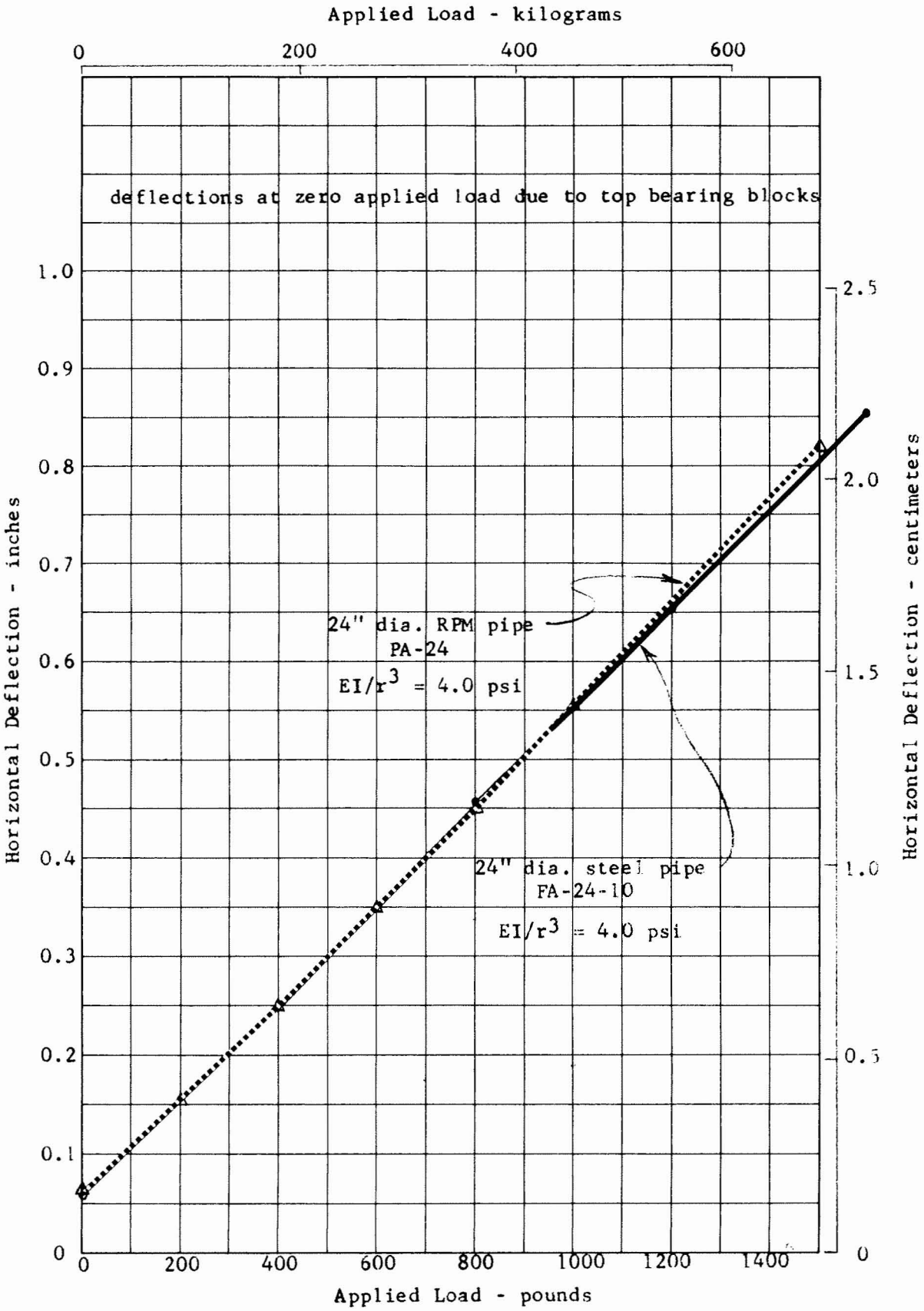


Figure 7. Three-edge bearing deflections of pipe with EI/r^3 = 4.0 psi—Comparison of horizontal deflections of RPM and steel pipe.

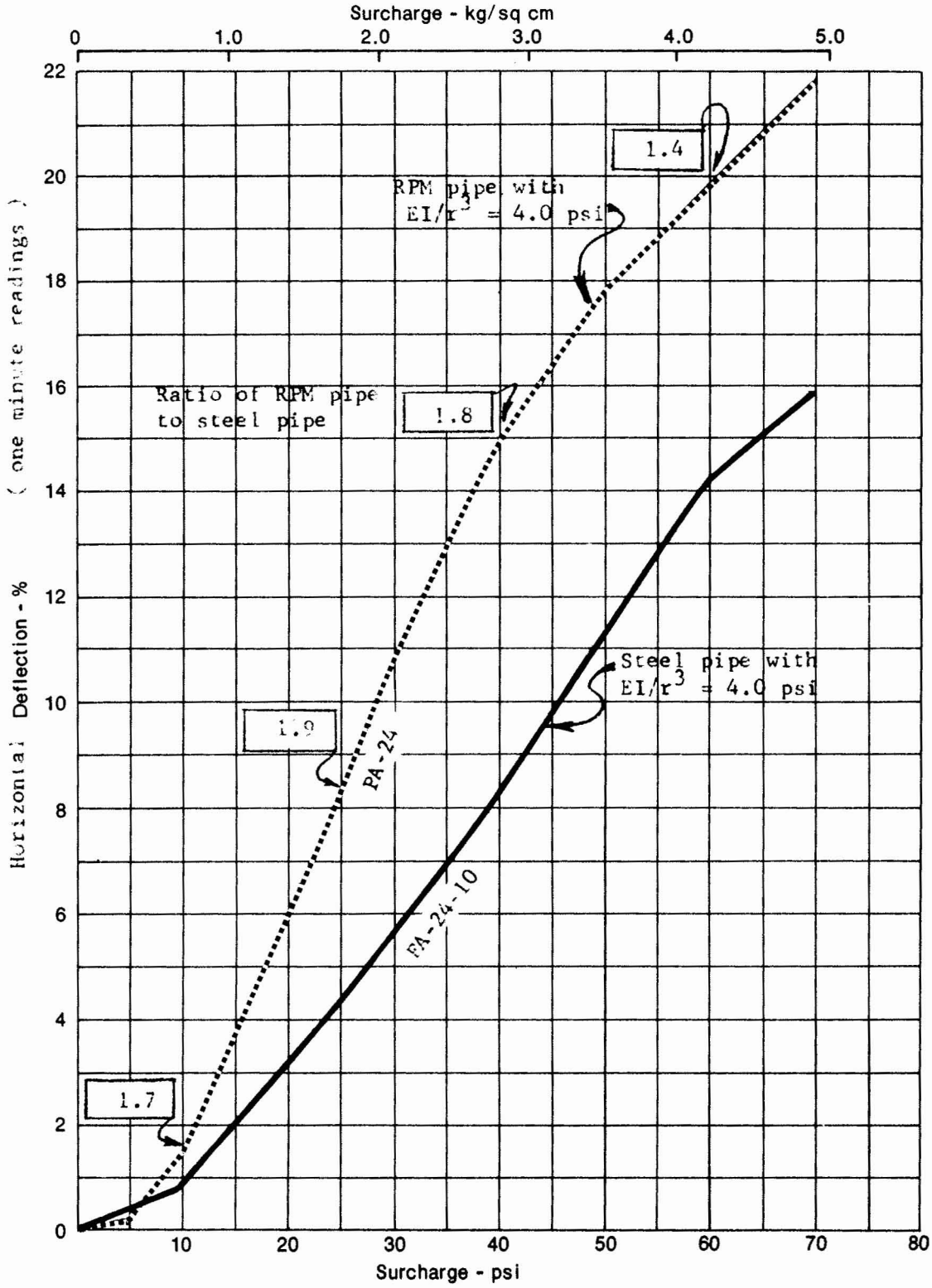


Figure 8. Deflection comparison of pipe with EI/r^3 = 4.0 psi—Horizontal deflections of RPM and steel pipe from soil container tests.

However, they can be compared to steel pipe that had similar stiffnesses and were grouped accordingly. These comparison groups, the EI/r^3 values, and the soil densities and moisture contents are summarized in Table 4.

Figure 9 compares RPM test PA-18-A (EI/r^3 = 3.5 psi (0.3 kg/sq cm)) and PA-18-D (EI/r^3 = 4 psi (0.3 kg/sq cm)) to steel pipe test FA-30-7 (EI/r^3 = 4.3 psi (0.3 kg/sq cm)). At the initial surcharge loads, the RPM pipe deflections are about 3 times greater than the steel pipe and at the higher surcharges, the RPM to steel pipe deflection ratio is about 2. Figure 10 compares the stiffest RPM pipe tested, PA-18-B (EI/r^3 = 16 psi (1.1 kg/sq cm)), to the stiffest steel pipe tested, FA-18-7 (EI/r^3 = 20 psi (1.4 kg/sq cm)). As in the other comparisons, the RPM to steel pipe deflection ratio is about 3 at low surcharges and 2 at higher surcharges.

Test pipe PA-18-F, EI/r^3 = 6 psi (0.4 kg/sq cm), came from a different manufacturer than did the other RPM pipe. No steel pipe was tested with a EI/r^3 between 4.3 and 10 psi so a comparison was not made on a similar stiffness basis. However, a deflection curve comparison with a steel pipe test, FA-18-14 (EI/r^3 = 2 psi) is made in Figure 11 and shows almost twice as much deflection. In addition, the deflection curve for PA-18-A (EI/r^3 = 3.5 psi) is shown. Test Pipe PA-18-F, EI/r^3 = 6 psi, deflected twice as much as a steel pipe one-third as stiff and the same as another RPM pipe one-half as stiff.

Figure 12 shows all the horizontal deflection curves for the RPM pipe with the pipe by one manufacturer in solid lines and the one pipe by a different manufacturer in dashed lines. The solid line curves show that the horizontal deflection of the pipe is inversely proportional to the Ring Stiffness Factors of the pipe. But PA-18-F, shown by the dashed line, did not follow that relationship.

PA-18-F was a standard production pipe designed for gravity flow. The other RPM pipe were pressure pipe designed for about twice the internal pressure of the gravity flow pipe. The fiberglass to resin ratio was less for the PA-18-F test pipe and may account for its variant behavior in the soil container tests.

RPM Pipe Deflection—100 Percent Backfill

Five steel pipe and one RPM pipe were tested with the backfill compacted to 100 percent of Proctor maximum dry density. The pipe Ring Stiffness Factors, EI/r^3, and the densities and moistures of the soil are compared in Table 5. The steel pipe behaved in one of two ways.[4] The pipe that had Ring Stiffness Factors of 4 psi (0.3 kg/sq cm) or less, deformed rectangularly and buckled elastically at low deflections. The pipe with Ring Stiffness Factors of 9 psi (0.6 kg/sq cm) or more deformed elliptically and deflected vertically up to 15 percent without failing.

RPM test PB-18 had a Ring Stiffness of about 3 psi (0.2 kg/sq cm) and should be compared with steel pipe of similar stiffness. However, all of the similar steel pipe buckled elastically at low deflections where as the RPM pipe did not buckle. Although the stiffness of the RPM pipe was the same as the steel pipe that buckled, it was more resistant to buckling. RPM test PB-18 deflected similarly to steel pipe tests FB-18-7 and FB-18-10 and is compared with the two steel pipes in Figure 13.

The deflections of PB-18 and PA-18-A, two RPM pipe with similar Ring Stiffness Factors and manufactured at the same time are compared in Figure 14. The higher density reduced the pipe deflections about 80 percent.

According to the Iowa Formula, the higher the soil modulus, e', the less influence the Ring Stiffness Factor has on the deflection. This is demonstrated by these tests at 100 percent Proctor backfill. Three pipe with Ring Stiffness Factors from 3 to 20 psi (0.21 to 1.41 kg/sq cm) deflected similarly, with only slight variations in deflection due to the Ring Stiffness of each pipe.

Apparently the higher the soil modulus of passive resistance, e', for a backfill soil the less difference in deflection values would occur for pipes with different stiffnesses. The differences exhibited in the deflection behavior of RPM pipe and steel pipe in the low modulus soil used in the 90 percent backfill tests would become insignificant in backfill soils with high modulus values.

Affect of Exterior Surface of RPM Pipe on Pipe Deflection

RPM pipe is manufactured with a sand coating on the exterior surface of the pipe. In addition to providing a more aesthetic appearance, the sand serves to protect the pipe during transport and handling. Surface scratches and exposure of the fiberglass roving used in the manufacture must be avoided because of the possible detrimental affect of water on fiberglass.

Since the RPM pipe deflected more than anticipated, it was felt that the rough exterior coating of the RPM

Table 4

COMPARISON OF TEST CONDITIONS FOR RPM AND STEEL PIPE
90 Percent Backfill

Test No.[1]	EI/r^3 from vertical deflections		EI/r^3 from horizontal deflections		Density—Percent Proctor		Moisture—Percent		Average diameter	
	psi	kg/cm^2	psi	kg/cm^2	Mean	Standard deviation	Mean	Standard deviation	inches	cm
PA-18-C	1.8 to 2.0	0.13 to 0.14	1.8 to 2.0	0.13 to 0.14	89.9	0.92	11.9	0.50	18.055	45.860
FA-18-14	1.8 to 2.0	0.13 to 0.14	1.8 to 2.0	0.13 to 0.14	90.1	1.78	11.7	.37	17.990	45.695
PA-24	3.5 to 3.9	0.25 to 0.27	3.7 to 4.0	0.26 to 0.28	89.6	1.48	11.8	.27	24.137	61.308
FA-24-10	3.7 to 3.9	0.26 to 0.27	3.9 to 4.0	0.27 to 0.28	89.5	1.47	11.7	.32	23.998	60.955
PA-18-A	3.1 to 3.7	0.22 to 0.26	3.1 to 3.6	0.22 to 0.25	89.7	1.89	11.6	.29	18.058	45.867
PA-18-D	3.8 to 4.5[2]	0.27 to 0.32	4.0 to 4.7[2]	0.28 to 0.33	89.4	1.95	11.8	.25	18.095	45.961
FA-30-7	3.8 to 4.0	0.27 to 0.28	4.2 to 4.3	0.30	90.2	2.61	11.3	.22	30.015	76.238
PA-18-F	5.9 to 6.6	0.41 to 0.46	5.9 to 6.6	0.41 to 0.46	90.0	1.72	11.9	.52	18.125	46.038
PA-18-B	15.0 to 17.2	1.05 to 1.21	15.2 to 17.5	1.07 to 1.23	90.6	1.37	11.7	.32	18.074	45.908
FA-18-7	20.6 to 22.6	1.45 to 1.59	21.4 to 21.7	1.05 to 1.53	90.2	2.51	11.6	.53	18.013	45.753

[1] PA = RPM pipe test.
FA = steel pipe test.
[2] Run on companion section, not actual pipe tested.

Table 5

COMPARISON OF TEST CONDITIONS FOR RPM AND STEEL PIPE
100 Percent Backfill

Test No.[1]	EI/r^3 from vertical deflections		EI/r^3 from horizontal deflections		Density—Percent Proctor		Moisture—Percent		Average diameter	
	psi	kg/cm^2	psi	kg/cm^2	Mean	Standard deviation	Mean	Standard deviation	inches	cm
RPM pipe										
PB-18	2.7 to 3.2	0.19 to 0.22	3.0 to 3.4	0.21 to 0.24	100.6	1.02	11.8	0.31	18.100	45.974
Steel pipe	$EI/r^3 \leq 4$ psi	(0.28 kg/cm^2)								
FB-18-14	1.8 to 1.9	0.13	1.9 to 2.0	0.13 to 0.14	100.0	0.84	11.8	.27	17.994	45.705
FB-24-10	3.9 to 4.1	0.27 to 0.29	4.0 to 4.1	0.28 to 0.29	100.3	1.52	11.5	.28	24.006	60.975
FB-30-10	1.7 to 1.8	0.12 to 0.13	1.8 to 1.9	0.13	100.5	0.97	11.9	.45	30.002	76.205
Steel pipe	$EI/r^3 \geq 9$ psi	(0.63 kg/cm^2)								
FB-18-10	8.6 to 8.8	0.60 to 0.62	9.0 to 9.1	0.63 to 0.64	100.1	1.04	11.8	.24	17.948	45.588
FB-18-7	19.3 to 19.5	1.36 to 1.37	19.7 to 20.4	1.39 to 1.43	100.7	0.93	11.9	.42	18.021	45.773

[1] PB = RPM pipe test
FB = steel pipe test

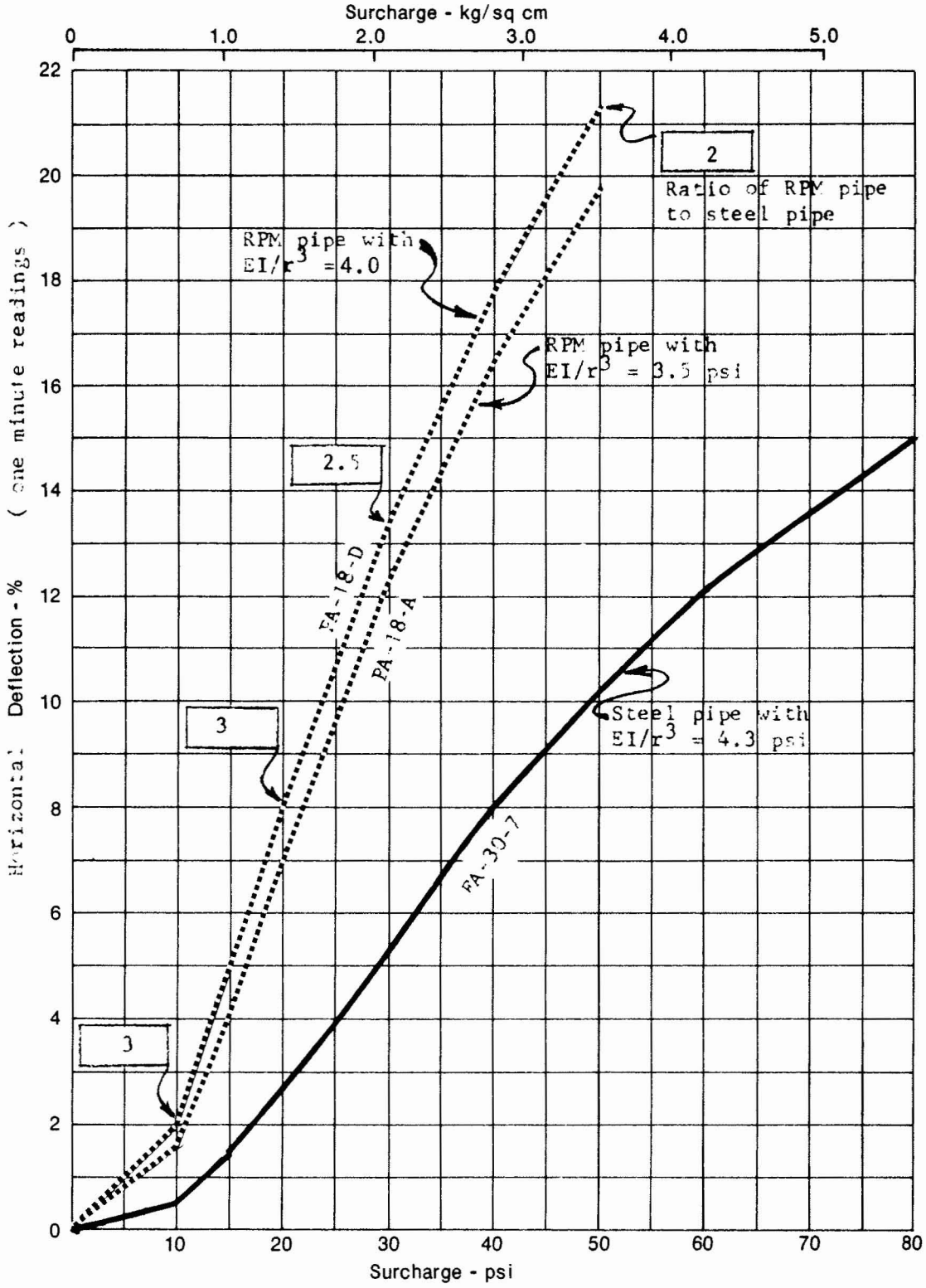


Figure 9. Deflection comparison of pipe with EI/r^3 = 3 to 4 psi—Horizontal deflections of RPM and steel pipe from soil container tests.

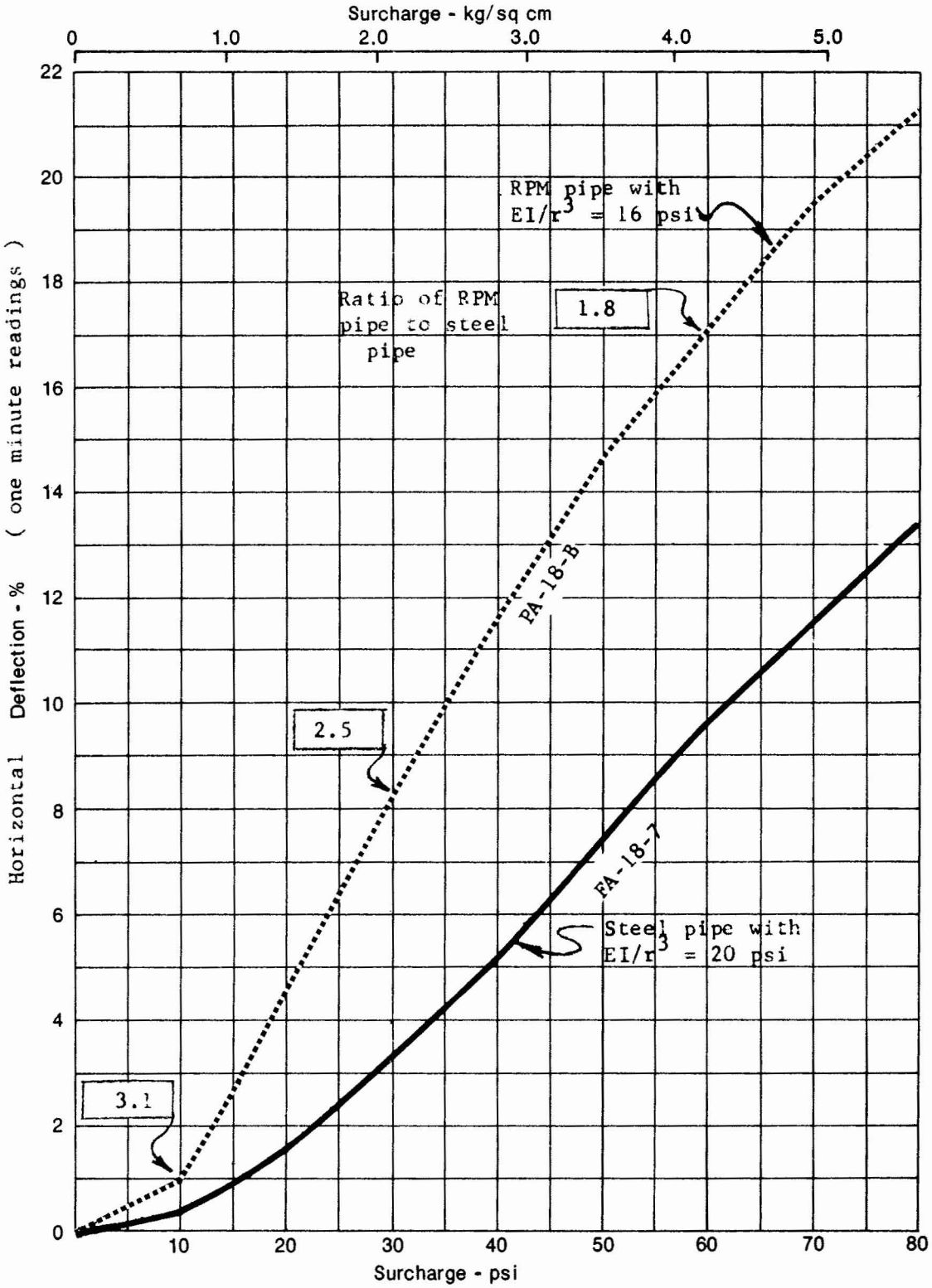


Figure 10. Deflection comparison of pipe with EI/r^3 = 16 to 20 psi—Horizontal deflections of RPM and steel pipe from soil container tests.

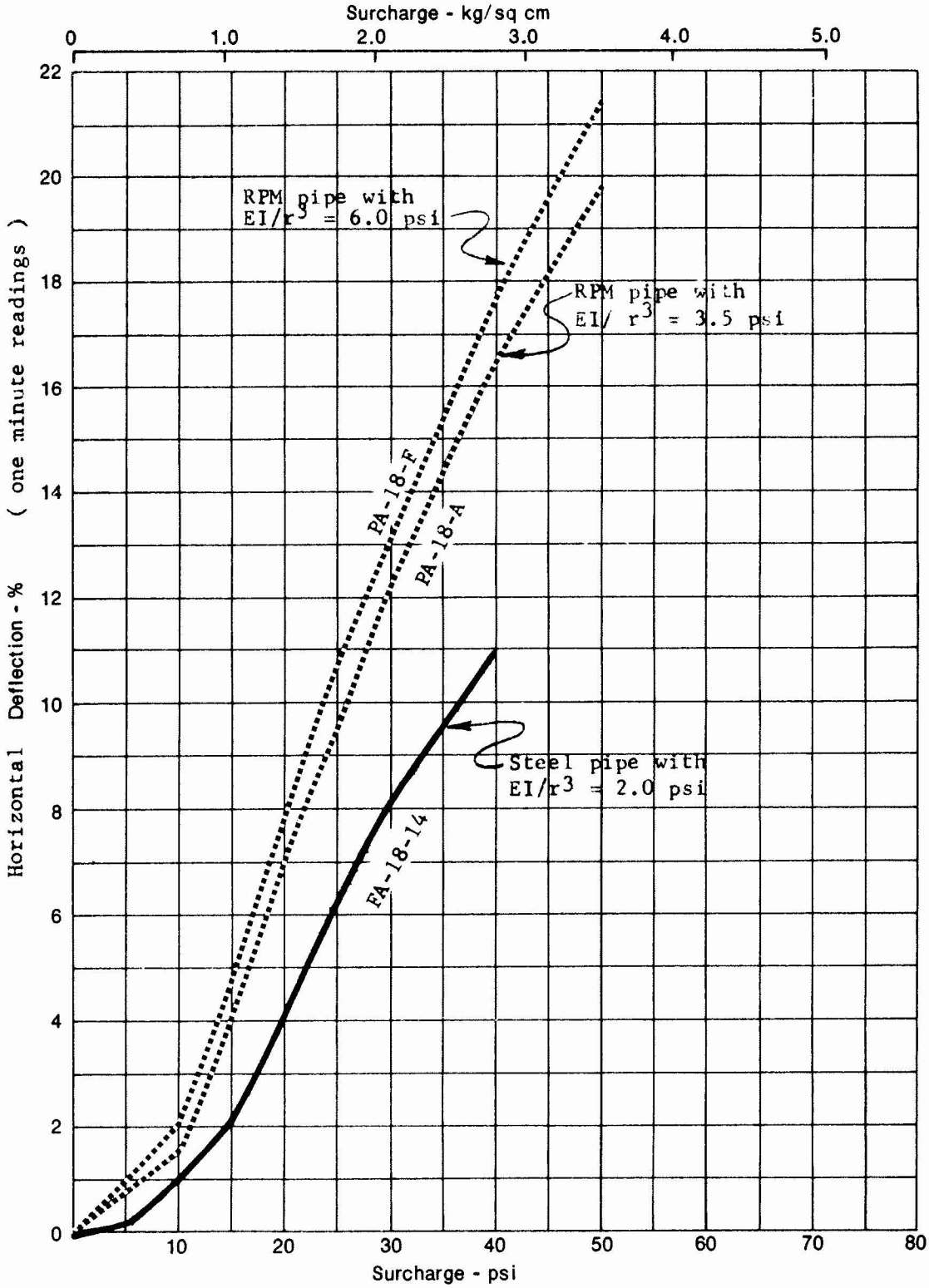


Figure 11. Deflection comparison of RPM pipe from different manufacturers with steel pipe—Horizontal deflections of RPM and steel pipe from soil container tests.

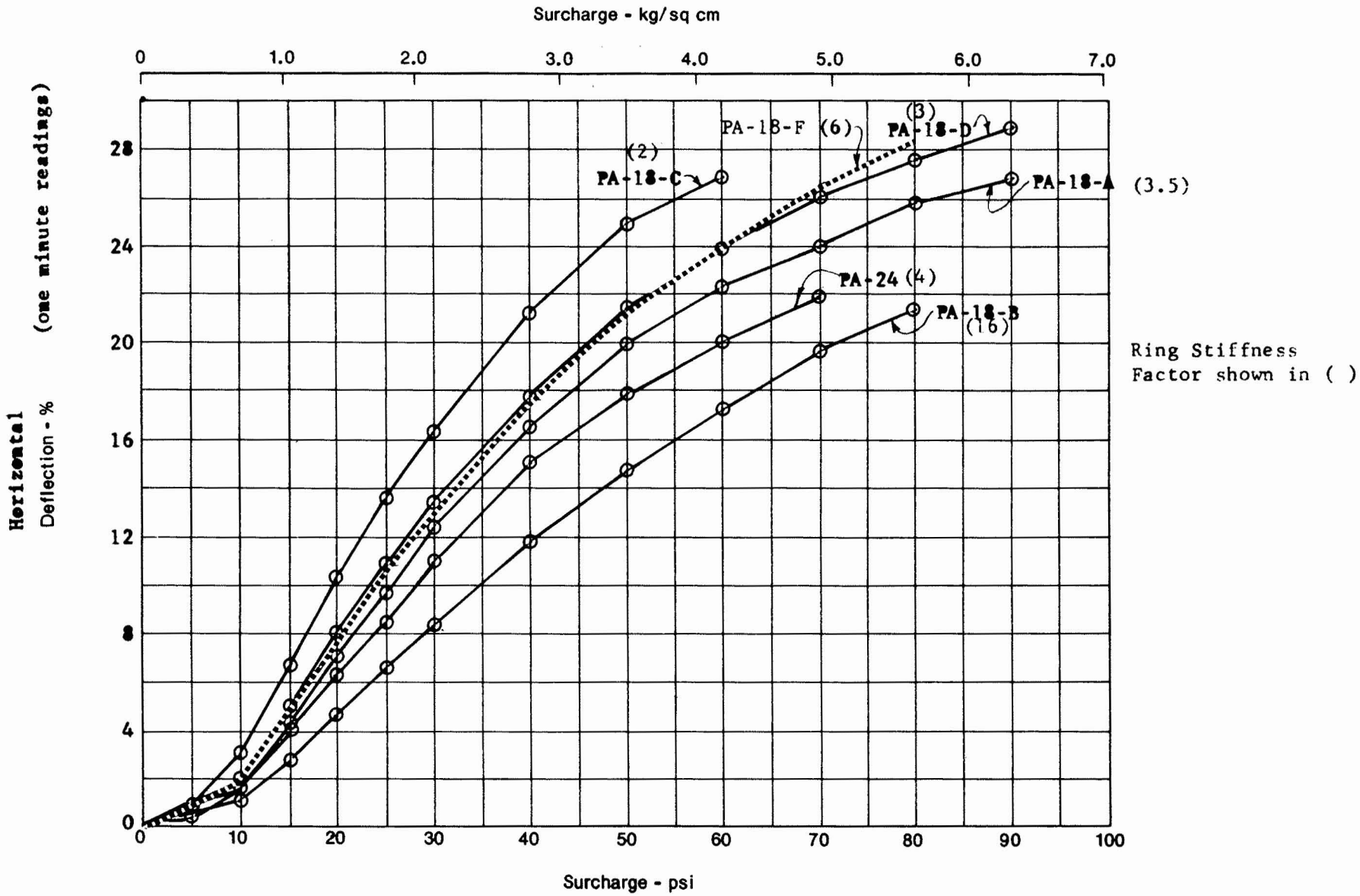


Figure 12. Horizontal deflections of RPM pipe in 90 percent backfill.

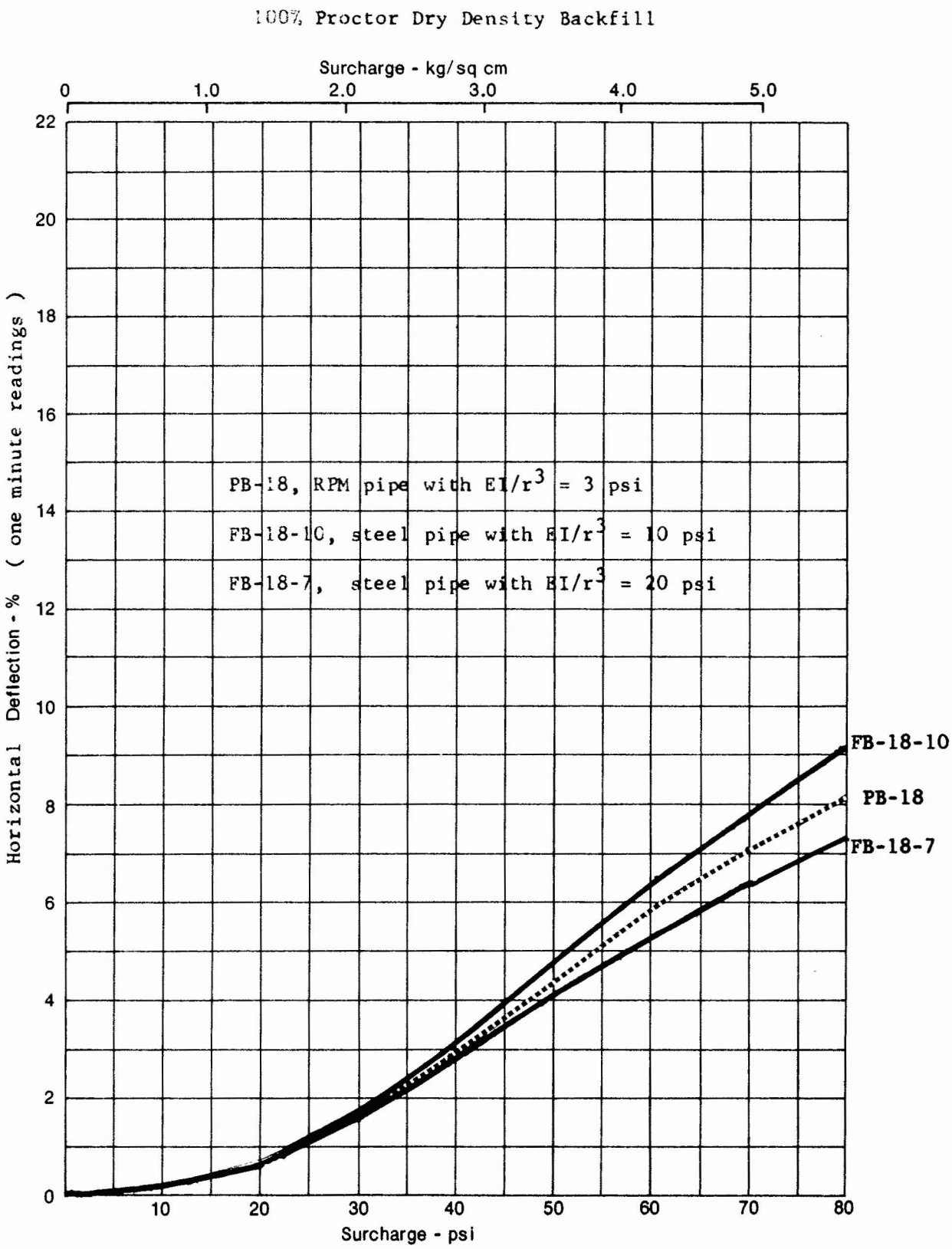


Figure 13. Deflection comparison of pipe in 100 percent density backfill—Horizontal deflections of RPM and steel pipe from soil container tests.

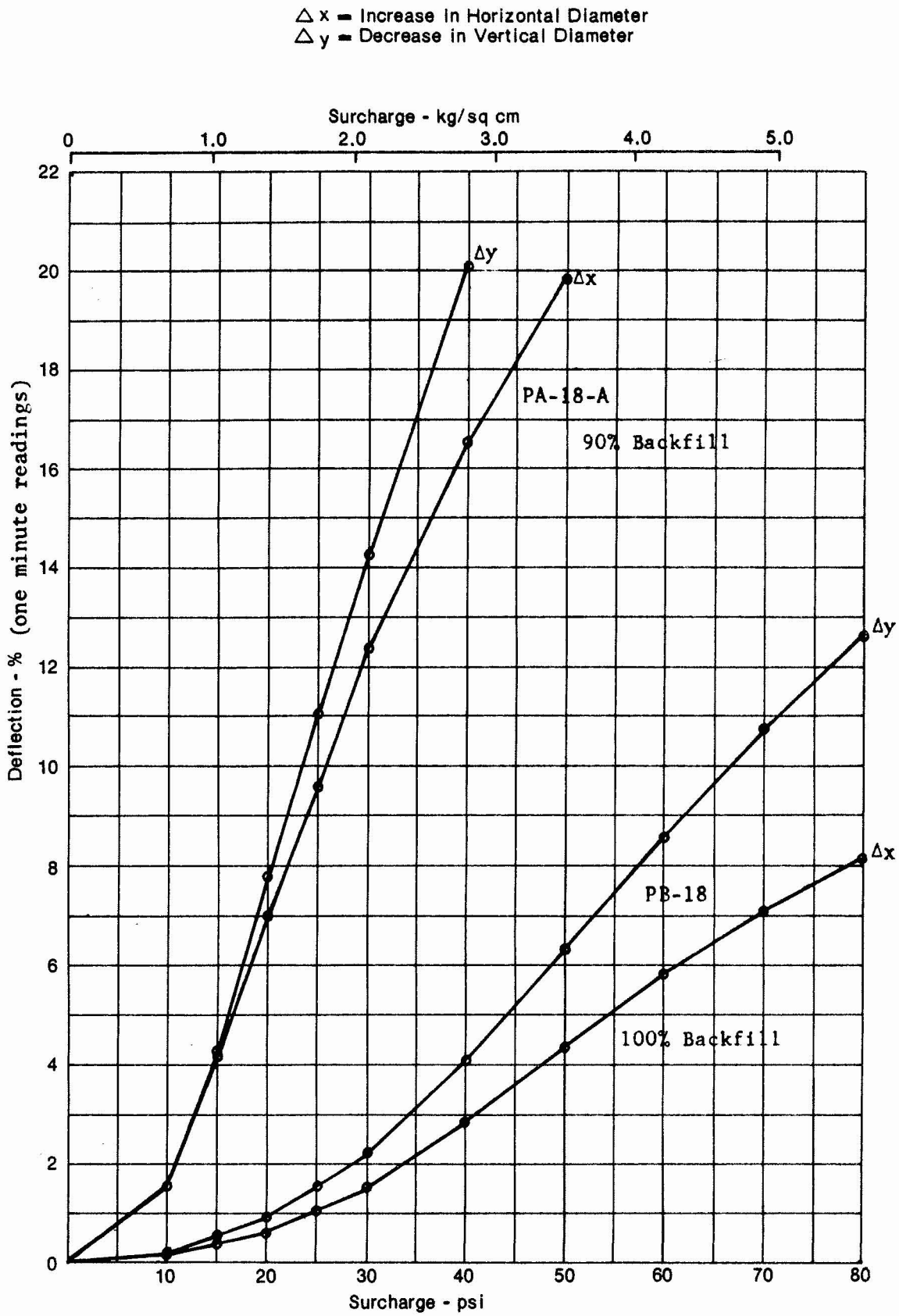


Figure 14. Comparison of RPM pipe in 90 and 100 percent backfill.

pipe may have created higher frictional forces between the pipe and the soil than existed between the steel pipe and the soil. The frictional forces would tend to cause higher loads on the RPM pipe resulting in higher deflections.

A special section of RPM pipe was manufactured omitting the sand coating. Figures 15 and 16 show the surface of a standard RPM pipe and the special section without the sand. A soil container load test was run on the bare Pipe PA-18-D using the same procedures as the other RPM pipe tests in 90 percent backfill except that the smooth pipe was wrapped with 2-mil polyethylene film to exaggerate the smooth surface. Table 6 shows the comparison of the physical features of the smooth pipe with a standard pipe of similar ring stiffness. Table 7 lists the soil properties of the two load tests.

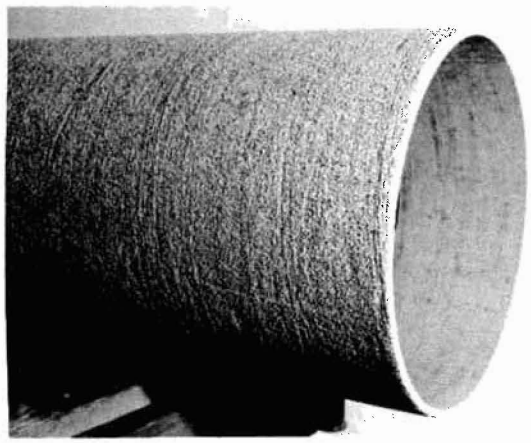


Figure 15. Typical surface of standard RPM pipe. Photo PX-D-72332

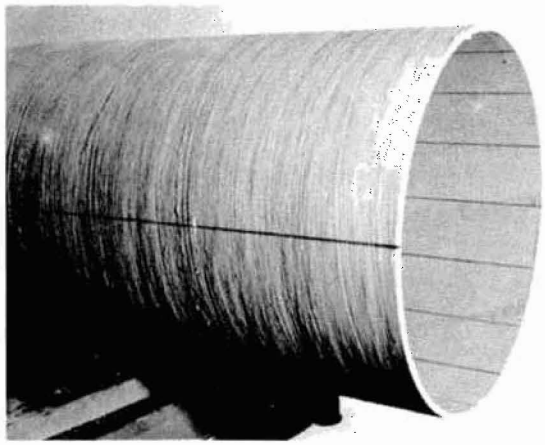


Figure 16. Exterior surface of RPM pipe with sand omitted. Photo PX-D-72333

Figure 17 compares the deflections of the pipe for the two soil container load tests. The deflections are similar enough to conclude that the sand coating does not adversely affect the pipe deflection. All other data, such as soil pressures and soil movement, were also very similar.

CONCLUSIONS

Reinforced Plastic Mortar (RPM) pipe of various diameters and wall thicknesses were buried in a large soil container and increasing surcharge loads were applied to the soil surface over the pipe. Six RPM pipe were tested with the surrounding lean clay backfill placed at 90 percent of Proctor maximum dry density and one RPM pipe was tested with the backfill at 100 percent Proctor. The behavior of RPM pipe is compared with steel pipe tested under similar circumstances. The comparison is made on the basis of the Ring Stiffness Factor, EI/r^3, of each pipe. The following conclusions resulted from these tests:

1. In the high density clay backfill tests (100 percent Proctor), the RPM pipe was more resistant to elastic buckling than steel pipe of similar stiffness and deflected about the same as steel pipe of much greater stiffness.

2. In the low density clay backfill tests (90 percent Proctor), the RPM pipe deflected about two to three times more than steel pipe of similar stiffnesses.

3. The fiberglass-resin ratio apparently influences the buried deflection behavior of RPM pipe. For RPM pipe manufactured with the same fiberglass-resin ratio, the pipe deflection varied inversely with the Ring Stiffness Factor, EI/r^3 of the pipe.

4. An RPM pipe without the exterior sand coating deflected the same as a RPM pipe of similar stiffness with the exterior sand coating.

APPLICATIONS

RPM pipe may provide an economical alternative for pipelines for water distribution systems. The test results illustrate the importance of having well compacted backfill around flexible pipe and accordingly, emphasize the necessity of good inspection and control in pipeline construction. The load-deflection data provided by this study were essential for the preparation of final specifications for

Table 6

PHYSICAL PROPERTIES OF PLAIN AND SAND-COATED RPM PIPE

Test No.	Description	Wall thickness		Pipe inside diameter				EI/r^3			
				North end		South end		Vertical deflections		Horizontal deflections	
		inches	cm	inches	cm	inches	cm	psi	kg/cm^2	psi	kg/cm^2
PA-18-A	Standard sand exterior	≃0.28	0.71	18.056	45.862	18.063	45.880	3.1 to 3.7	0.22 to 0.26	3.1 to 3.6	0.22 to 0.25
PA-18-D	Plain exterior	0.24	0.61	18.071	45.900	18.095	45.961	3.8 to 4.5	0.27 to 0.32	4.0 to 4.7	0.28 to 0.33

Table 7

SOIL BACKFILL PROPERTIES FOR RPM TESTS PA-18-A AND PA-18-D

Test No.	No. of tests	Soil density—Percent of Proctor			Moisture content—Percent		
		Range	Mean	Standard deviation	Range	Mean	Standard deviation
PA-18-A	9	87.6 to 93.0	89.7	1.89	11.0 to 12.1	11.6	0.29
PA-18-D	16	85.1 to 92.0	89.4	1.95	11.4 to 12.4	11.8	.25

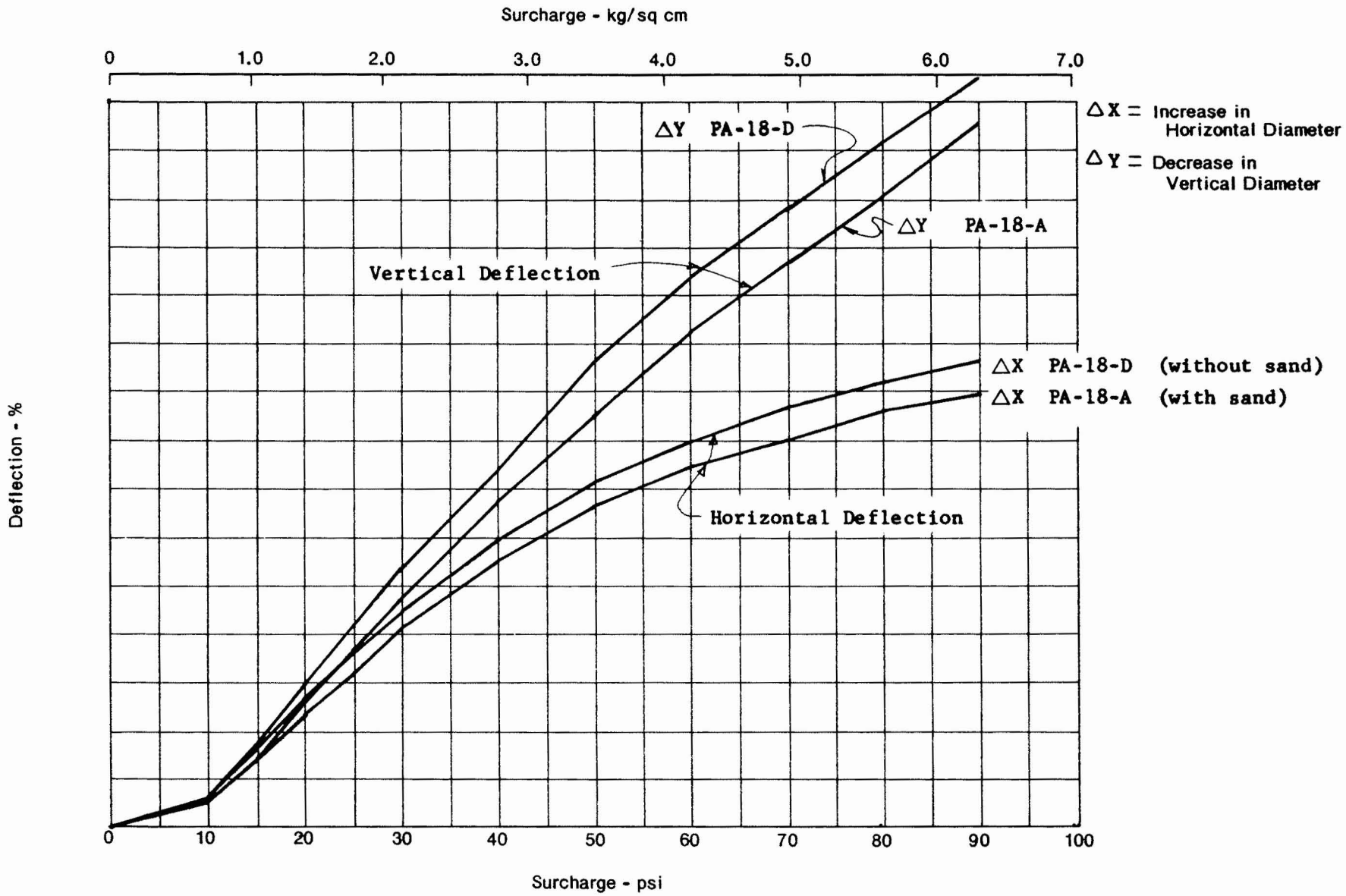


Figure 17. Deflection comparison of RPM pipe with and without sand exterior.

RPM pipe. The conclusions and procedures from this study are presently being used in evaluating other types of plastic base pipe such as Fiberglass Reinforced Plastic (FRP), polyvinyl chloride (PVC), and polyethylene.

PERSONNEL PERFORMING TESTS

The assistance of the following people in conducting the tests is greatly appreciated:

J. H. Aikele	D. L. Elkins
A. A. Benavidez	J. M. Horner
E. M. Bowers	R. I. Kingery
B. A. Callow	F. B. Larcom
C. T. Coffey	D. G. Miedema
L. J. Cox	R. D. Richmond

Photography by Wilbourn M. Batts

REFERENCES

1. Selander, C. E., Causey, F. E., Howard, A. K., and Hickey, K. B. "First Progress Report on Evaluation of Reinforced Plastic Mortar Pipe. A Governmental-Industry Cooperative Study," Report No. REC-OCE-70-34, Bureau of Reclamation, Denver, Colorado, August 1970

2. Selander, C. E., Hickey, M. B. Causey, F. E., and Howard, A. K., "Report on Evaluation of Reinforced Plastic Mortar Pipe, A Governmental-Industry Cooperative Study," Report No. REC-ERC-72-26, Bureau of Reclamation, Denver, Colorado, June 1972

3. Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe—Progress Report No. 1," Report No. EM-763, Bureau of Reclamation, Denver, Colorado, June 1968

4. Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe—Progress Report No. 2," Report No. REC-OCE-70-24, Bureau of Reclamation, Denver, Colorado, June 1970

5. Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe—Progress Report No. 3, Steel Pipe in High Density Cohesive Soil," Report No. REC-ERC-71-35, Bureau of Reclamation, Denver, Colorado, June 1971

6. U.S. Bureau of Reclamation, *Earth Manual* First Edition, Revised 1963, Denver, Colorado

7. Spangler, M. G., "The Structural Design of Flexible Pipe Culverts," Iowa Engineering Experiment Station Bulletin No. 153, 1941

8. Watkins, R. K. and Spangler, M. G., "Some Characteristics of the Modulus of Passive Resistance of Soil: A Study in Similtude," Highway Research Board Proceedings, Vol. 37, 1958

9. Spangler, M. G., "Factors of Safety in the Design of Buried Pipelines," Paper at Annual Meeting of Highway Research Board, National Research Council, January 1969

APPENDIX A

MODULUS OF ELASTICITY OF RPM PIPE

INTRODUCTION AND DISCUSSION

In the three-edge bearing test, the pipe section was treated as an elastic ring under a two-point loading. The Modulus of Elasticity, E, of the pipe wall material can be found from either of two measurements made on the pipe during the two-point loading.

1. E can be calculated using either the measured change in the vertical diameter, ΔY, or the change in the horizontal diameter, ΔX. The following equations are used:

$$E = 0.136\, Pr^3/(I\Delta X) \text{ or}$$

$$E = 0.149\, Pr^3/(I\Delta Y)$$

where P is the load per linear unit, r is the pipe radius and I is the moment of inertia of a unit length of pipe.

2. The Modulus of Elasticity can also be calculated from the strain gage measurements by:

$$E = \frac{3\,Pr}{\epsilon\, t^2\ (2/\pi - \sin\theta)}$$

where ϵ is the circumferential strain in microunits per unit, t is the pipe wall thickness and θ is the angle of the gage location with the vertical diameter of the pipe. Sixteen equally spaced strain gages were mounted on the inner surface of the pipe in the circumferential direction about at the longitudinal one-fourth point. Of the seven RPM pipe tested, only four had strain measurements made during the three-edge bearing test.

The comparison of the E value from the deflection data and the strain gage data is shown in Table A–1. Theoretically, the E values for the ΔX data and the ΔY data should be the same and E should not change as the load changes. The ΔX and ΔY E values are within 10 percent and E shows a consistent decrease with increasing loads for all the tests. This is similar to results from three-edge bearing tests on steel pipe. The E values from strain readings also show a decrease with increasing load.

For each test pipe, the E values from strain readings and the E values from deflection data compare very well. The biggest difference is between the different test pipes. Pipes PA-18-A and PB-18 were manufactured at the same time and probably were cut from the same length of pipe, and yet the E value for the former is 30 to 40 percent higher. There appears to be a large variability in the strength of the wall material even in the same section of pipe.

Although the average E for the 16 gages compared well within the deflection E values, the individual strain gage E values varied greatly. Because some of the readings were at locations where only 5 or 10 microinches/inch difference would make a large change in the E value, the average E value was used to plot a theoretical strain-curve to compare to the actual strain readings. Figures A–1 to A–4 show the theoretical strain as solid lines for different loads for each pipe. The actual strain readings are shown as triangles. Except at the 180° location, the empirical data compares well. Since the theoretical strain is based on a two-point loading, the lower support for the pipe is actually two closely spaced line loads, the strain pattern is altered somewhat at the bottom of the pipe.

The plots also show no variation between the areas of the pipe in tension and in compression; so the RPM pipe behaves as though the modulus of elasticity is the same in tension or compression. The behavior of the RPM pipe in the three-edge bearing test is similar to the behavior of steel pipe.

Table A–1

EMPIRICAL MODULUS OF ELASTICITY (E) VALUES FOR RPM PIPE

Test No.	Load on pipe P		Percent vertical deflection	E from[1] deflection data				E from strain[1] gage reading	
				E (ΔY)		E (ΔY)		E (strain)	
	lbs/lin in.	kg/cm		psi	kg/cm^2	psi	kg/cm^2	psi	kg/cm^2
PA-18-A	1.70	0.304	0.4	3.49	0.245	3.34	0.235	3.28	0.231
	4.52	0.807	1.0	3.18	.224	3.13	.220	3.13	.220
	7.34	1.311	1.7	3.17	.223	3.10	.218	2.98	.210
	10.15	1.813	2.4	3.08	.217	3.04	.214	3.03	.213
	12.97	2.316	3.1	2.98	.210	2.94	.207	2.99	.210
	15.79	2.820	4.0	2.86	.201	2.85	.200	2.89	.203
	18.61	3.323	4.9	2.72	.191	2.73	.192	2.96	.208
	22.83	4.077	6.3	2.61	.184	2.66	.187	2.86	.201
PB-18	1.70	0.304	0.4	2.51	.176	2.64	.186	2.64	.186
	8.75	1.563	2.3	2.36	.166	2.50	.176		
	15.79	2.820	4.4	2.22	.156	2.34	.165		
	22.83	4.077	6.7	2.10	.148	2.24	.157		
	29.87	5.334	9.3	1.97	.139	2.15	.151	2.13	.150
PA-18-F	1.70	0.304	0.2	1.76	.124	1.65	.116	2.16	.152
	5.93	1.050	0.8	1.72	.121	1.69	.119	2.01	.141
	10.15	1.813	1.3	1.79	.126	1.78	.125	2.10	.148
	14.38	2.568	2.0	1.64	.115	1.65	.116	1.98	.139
	18.61	3.323	2.6	1.58	.111	1.60	.112	1.90	.134
PA-24	1.70	0.304	0.3	2.89	.203	3.03	.213	3.55	.250
	4.52	0.807	0.7	3.08	.217	3.23	.227	3.08	.217
	7.34	1.311	1.2	3.09	.217	3.20	.225	2.95	.207
	10.15	1.813	1.6	3.07	.216	3.16	.222	2.91	.205
	12.97	2.316	2.1	3.03	.213	3.12	.219	2.88	.202
	15.79	2.820	2.6	3.0	.211	3.08	.217	2.85	.200
	22.83	4.077	3.9	2.92	.205	3.01	.212	2.82	.198
	29.87	5.334	5.3	2.81	.198	2.93	.206	2.77	.195

[1] x 10^6

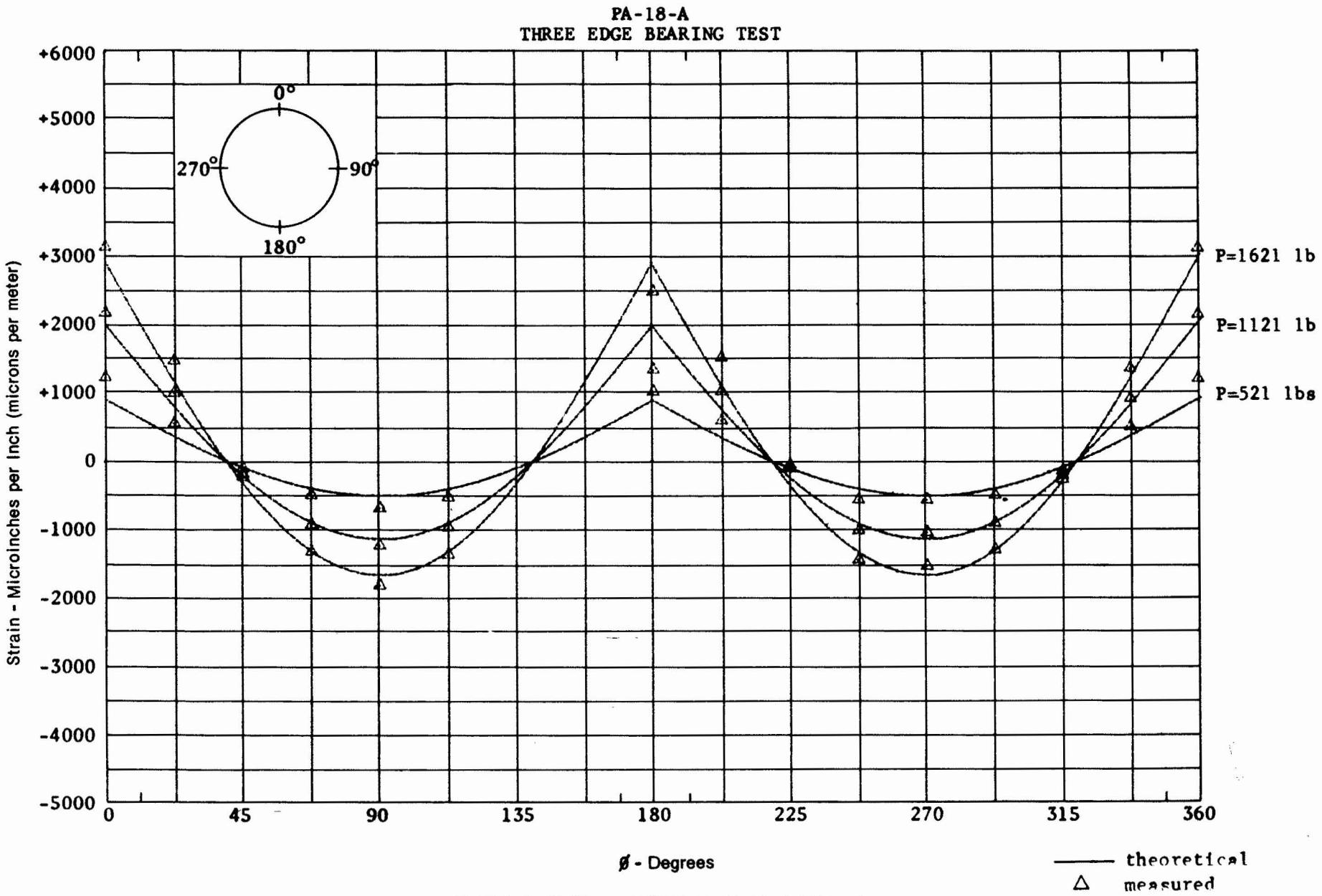


Figure A–1. Strain gage readings around inside pipe circumference.

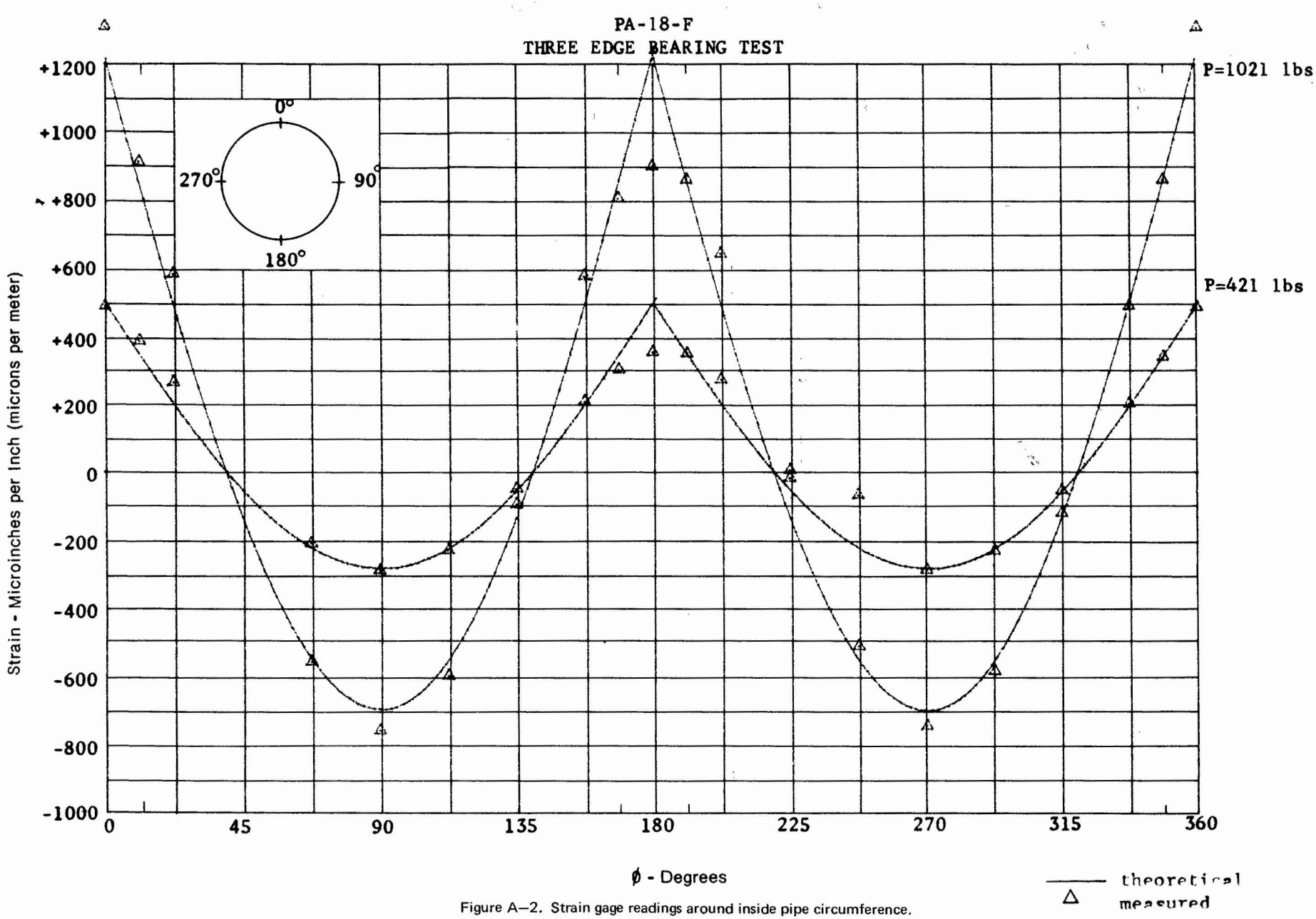


Figure A–2. Strain gage readings around inside pipe circumference.

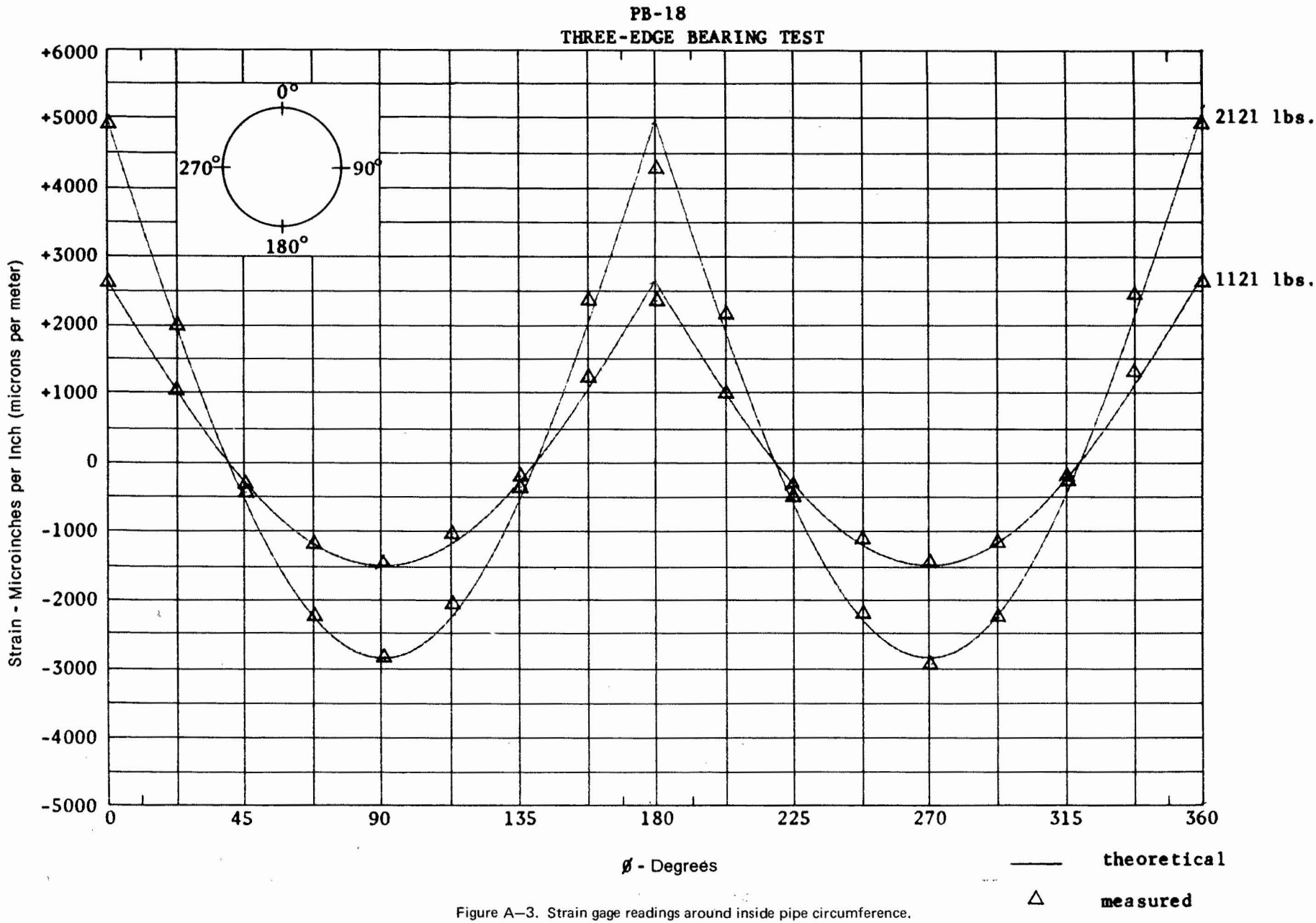


Figure A–3. Strain gage readings around inside pipe circumference.

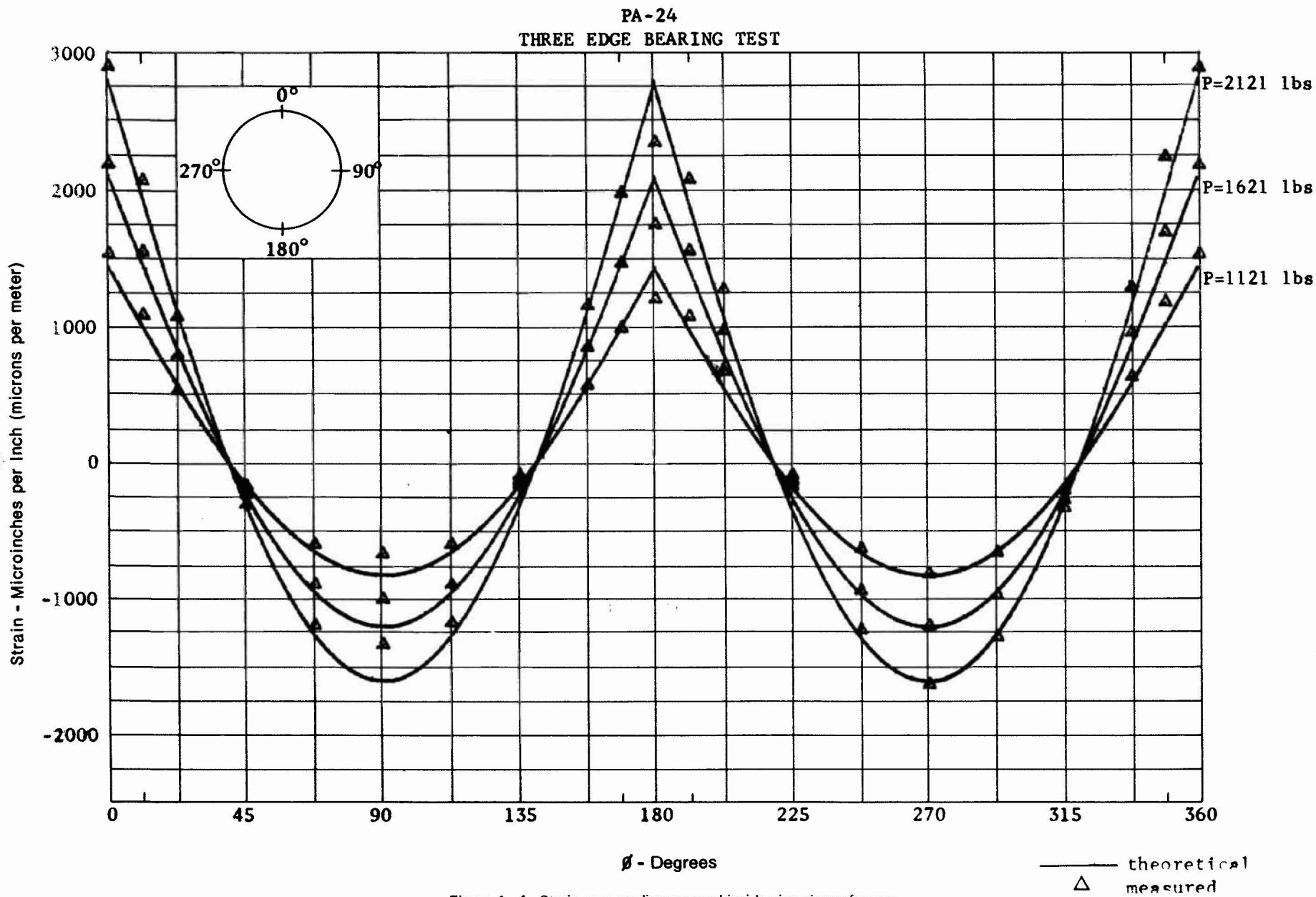


Figure A—4. Strain gage readings around inside pipe circumference.

APPENDIX B

INDIVIDUAL TEST RESULTS OF RPM PIPE TESTS

INTRODUCTION

The results of individual RPM pipe tests are shown graphically in Figures B–1 through B–34 in the following order:

Load-deflection curves	B–1 through B–7
Soil pressures on container walls	B–8 through B–14
Strain gage readings around pipe circumference	B–15 through B–20
Soil movement between pipe and soil container wall	B–21 through B–27
Cross-sections of pipe under load	B–28 through B–34

Unless otherwise noted, the data shown are the 1-minute readings.

Figure B–35 shows the shape of an RPM and a steel pipe, both with a deflection of about 5 percent.

The physical properties of the backfill soil are shown in Figure B–36.

TEST RESULTS

Pipe Deflection

The 1-minute vertical and horizontal pipe deflections are shown as Figures B–1 through B–7. The ratio of $\Delta X/\Delta Y$ is shown on each graph for each load increment. Flexible pipes are assumed to deform elliptically with the horizontal deflection (ΔX) equal to the vertical deflection (ΔY). The pipes all deformed somewhere between an elliptical shape and a rectangular shape. The actual shape ranges between these extremes depending on the relationship of the pipe stiffness to the soil stiffness. The deformation pattern affected the ratio of the horizontal to vertical deflections $\Delta X/\Delta Y$.

Soil Pressures on Container Walls

Pressure cells mounted in the soil container walls measured the horizontal soil pressures on the wall. Two cells (one on each sidewall) were mounted 4 feet (1.2 meters) from the top of the container opposite the horizontal diameter of the pipe. These cells should measure pressures due to the deflecting pipe in addition to the lateral pressures. The other two cells were 2 feet (0.6 meter) from the top of the container (one on each wall) and measured the lateral pressures without any significant interference from the pipe. Because of the small differences in elevation and the large surcharge applied, the lateral pressures are assumed to be the same at each location.

In the steel pipe tests, the pressure cells opposite the pipe measured higher pressures than the other cells above the pipe for the 24-inch (61-cm) diameter and 30-inch (76-cm) diameter pipe tests (except for the pipe that buckled elasticity at low deflections). The pressures on the walls for the 18-inch (46-cm) diameter pipe tests were about the same at all locations. The cells above the pipe measured horizontal pressures about 50 and 75 percent of the vertical applied surcharges pressures for Test Series FA and FB, respectively.

The soil pressures on the container walls for the RPM pipe tests are shown as Figures B–8 through B–14. In Tests PA-24 and PB-18, the cells opposite the pipe showed higher pressures than those cells above the pipe. For the other RPM pipe tests, the pressures on the walls were all about the same. There appears to be more variation in the pressure cell readings for the RPM pipe tests than for the steel pipe tests. The pressures on the container walls for the RPM tests ranged from about 50 to 75 percent of the vertical applied surcharge pressures.

Strain Gage Readings

The 1-minute strain gage readings for six of the tests are shown in Figures B–15 through B–20. Strain gages were not used in Test PA-18-C. Test PB-18, 100 percent backfill, definitely deflected rectangularly. PA-24 was more rectangular than elliptical. PA-18-B and PA-18-A deformed elliptically while the other tests were somewhere in between elliptical and rectangular. An elliptically deformed pipe is one where high compressive strains occur in the inner surface of the pipe at the horizontal diameter (at 90° and 270° where 0° is the top of the pipe). The rectangularly deformed pipe has high compressive strains at four locations, about 45°, 135°, 225°, and 315°.

Soil Movement Between Pipe and Soil Container Walls

The soil movement as measured by the telescoping tubes is shown for each test in Figures B–21 through B–27. For two of the tests, PA-18-F and PA-24, the tubes extended all the way to the pipe wall. In test PA-18-F about 50 percent of the soil movement occurred in the 9 inches (23 cm) of soil adjacent to the pipe. In test PA-24, 40 to 60 percent of the soil movement occurred in the 6 inches (15 cm) of soil adjacent to the pipe. This is similar to results from the steel pipe tests. Test PB-18 had a linear soil movement pattern from the pipe wall to 6 inches from the soil container wall showing a high amount of influence of the container wall on the pipe deflection.

The other tests showed about 50 to 60 percent of the soil movement occurring in the 9 inches (23 cm) of soil adjacent to the pipe if half of the horizontal deflection is used as the soil movement at the pipe.

From a point 6 to 9 inches (15 to 23 cm) from the pipe to the container wall, the soil movement curves are linear if the soil movement is considered to be zero at the container wall. The walls have a definite influence on the soil movement in this area of the soil.

Shape of the Pipe Cross Section Under Load

For measuring the shape of the pipe cross section, a dial gage is attached perpendicularly to a shaft mounted to the soil container extending into the pipe. The shaft is located parallel to the longitudinal axis of the pipe and is turned from outside the soil container. The axis of the shaft is offset from the longitudinal axis of the pipe so that at 0° (top of the pipe) the dial gage is almost fully extended and at 180° the dial gage is almost fully retracted. This allows nearly the full range of the dial gage, 4 inches (10 cm), available to measure the settlement of the top of the pipe. Measurements inside the pipe are made at 15° intervals. The only comparable points between the dial gage angles and the angle markings on the pipe are at 0° and 180°.

The shapes of the pipe after 1 minute of each load increment are shown in Figures B–28 through B–34. The readings start at 0° and the 0° reading is repeated at the end. The difference in the 0° readings for each load on the graphs illustrates the amount of deflection that occurs during the 4 to 5 minutes to make a round of readings.

Because of the combination of pipe settlement and pipe deflection, the most soil displacement does not occur right at the horizontal diameter of the pipe but under the haunches of the pipe. This indicates the importance of good soil compaction under the haunches of a pipe.

Because of the higher deflections of RPM pipe, the shape of the pipe was compared to the shape of the steel pipe under load. Figure B–35 shows the shape of an RPM pipe, PA-18-B, EI/r^3 = 16 psi (1.12 kg/sq cm) and a steel pipe, FA-18-7, EI/r^3 = 20 psi (1.41 kg/sq cm) both with a deflection of about 5 percent. The two shapes are nearly identical. The only difference is that the RPM pipe had half as much load, 20 psi (1.41 kg/sq cm), as the steel pipe, 40 psi (2.81 kg/sq cm). The pipe deformation shapes are apparently quite similar.

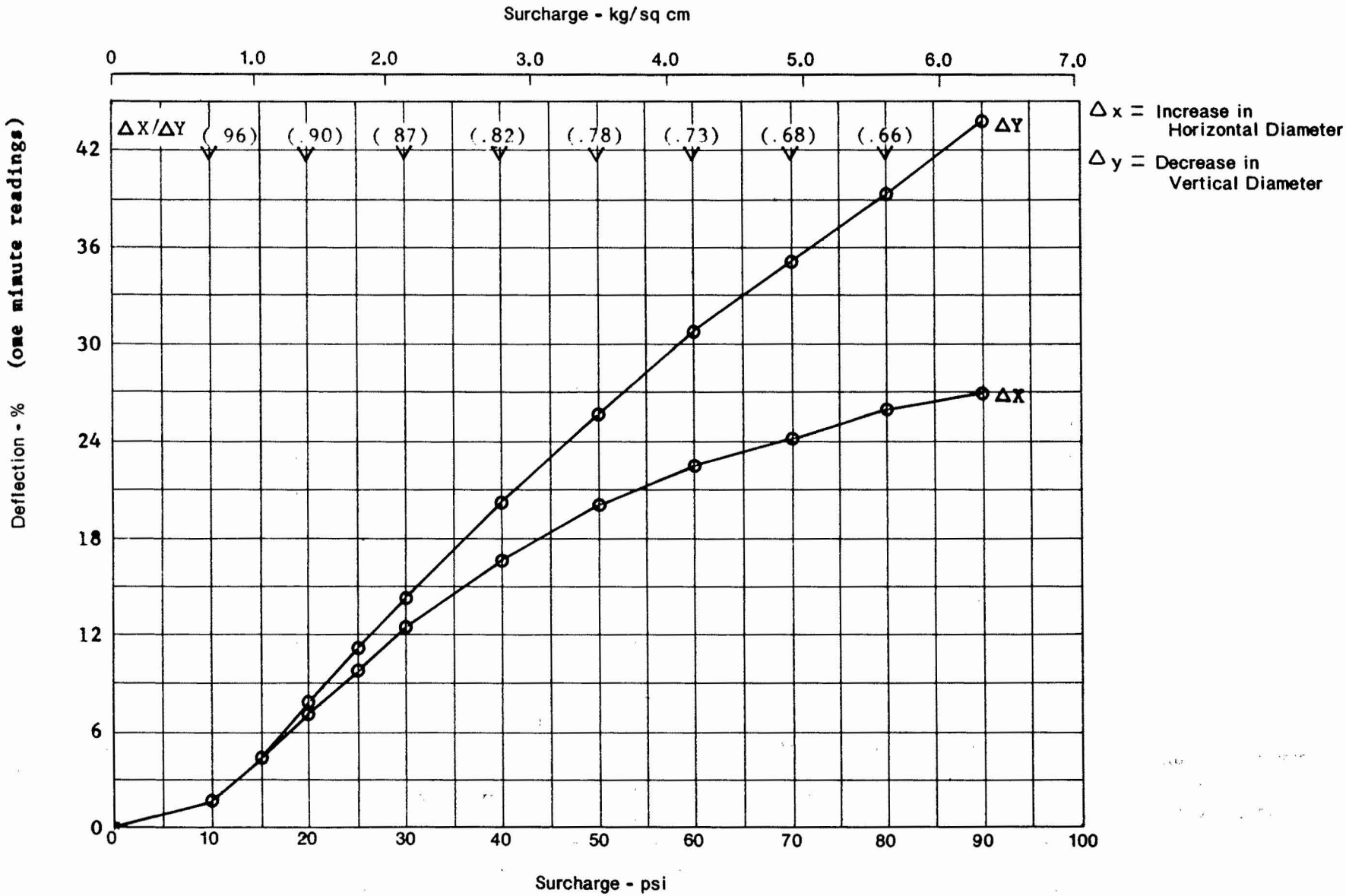


Figure B–1. Load deflection curves, PA-18-A.

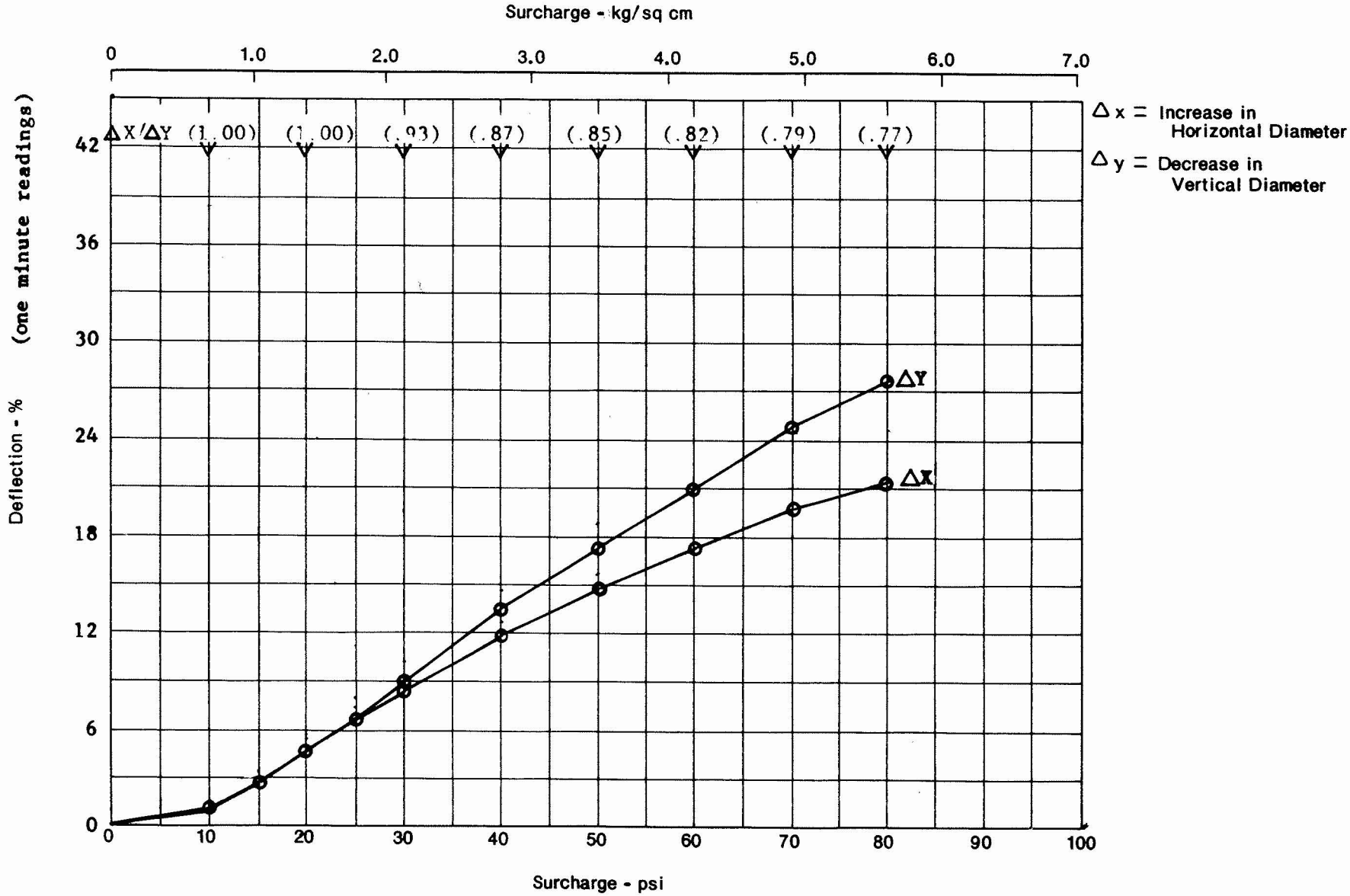


Figure B–2. Load deflection curves, PA-18-B.

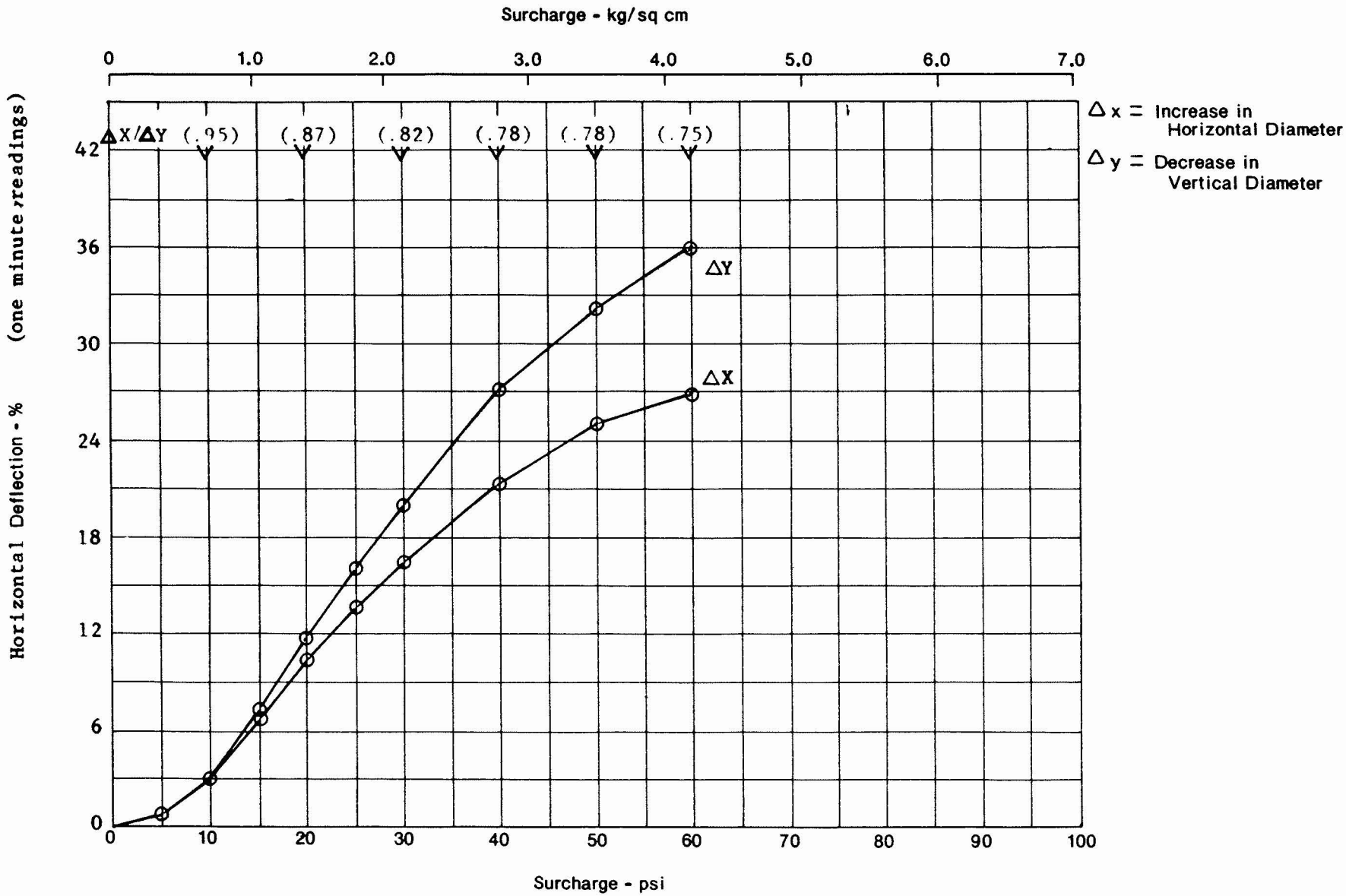


Figure B—3. Load deflection curves, PA-18-C.

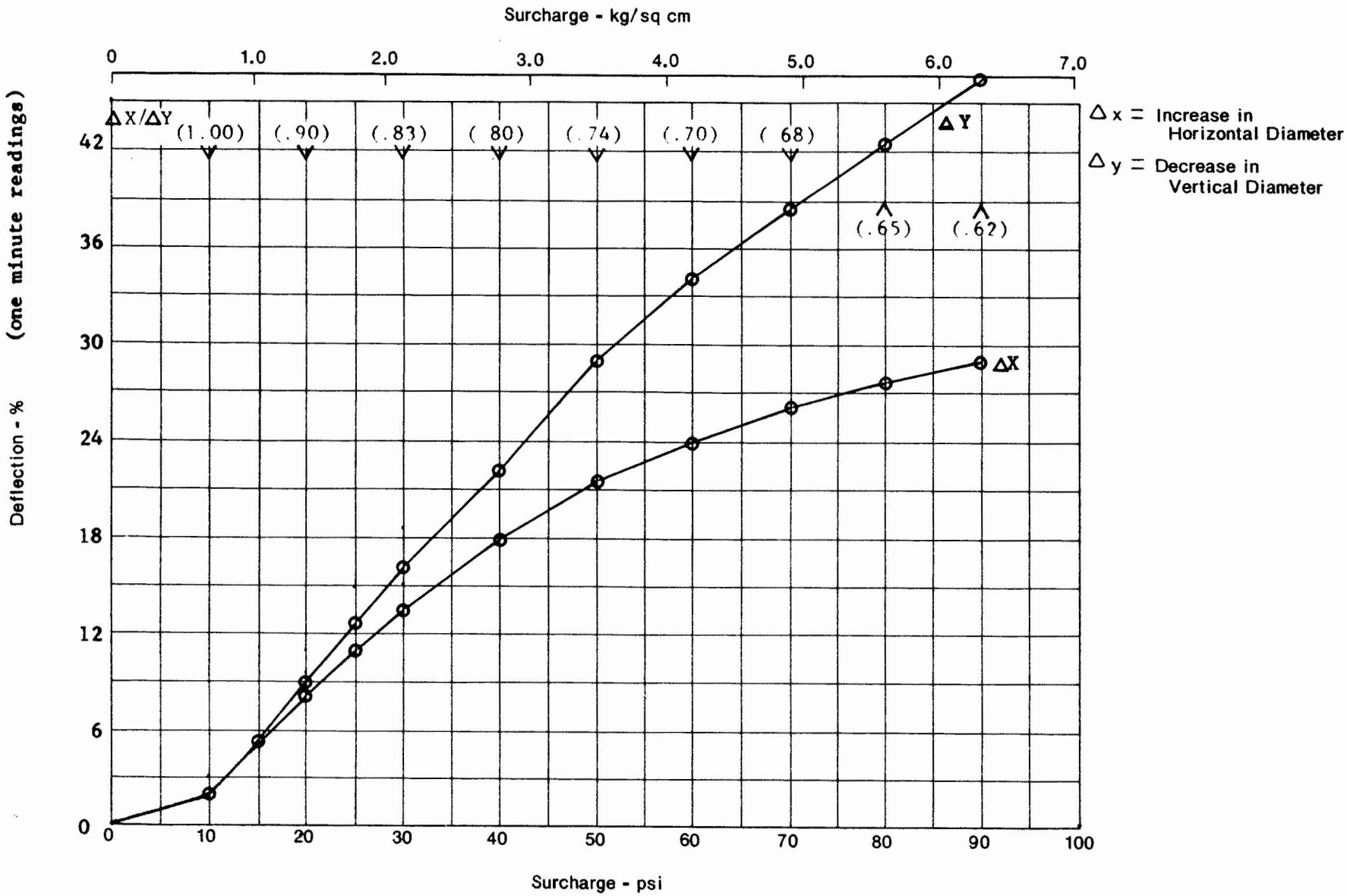


Figure B—4. Load deflection curves, PA-18-D.

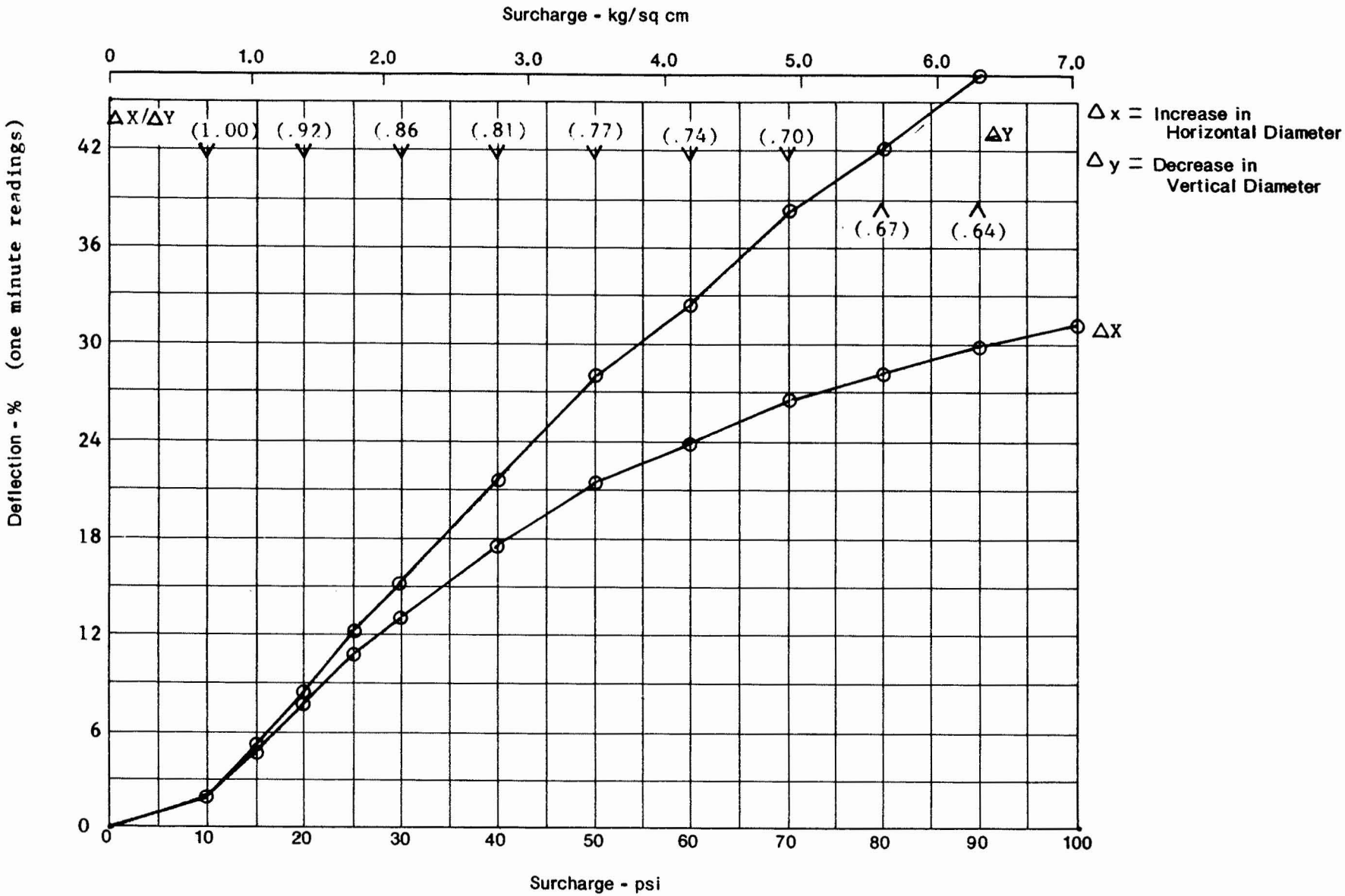


Figure B–5. Load deflection curves, PA-18-F.

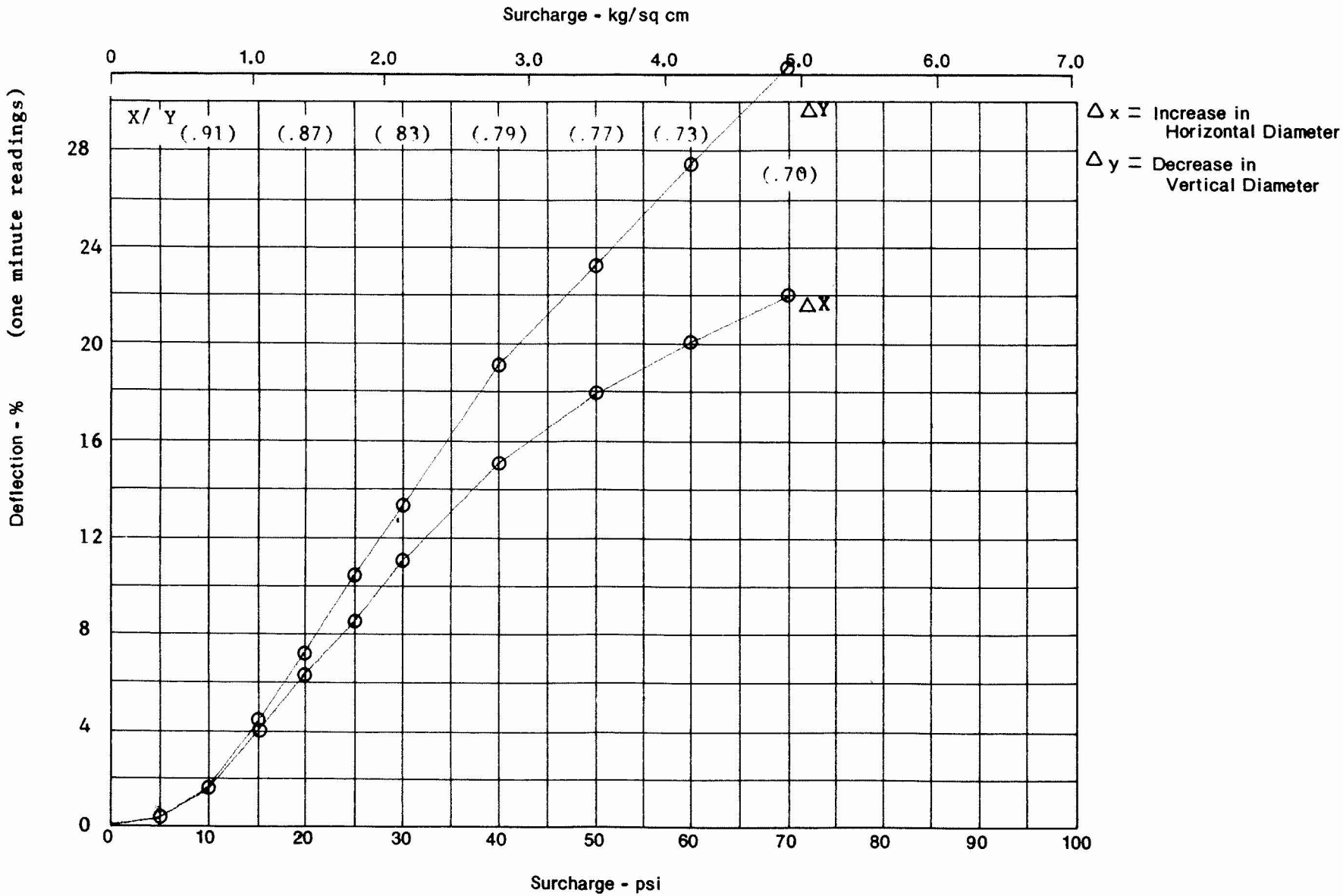


Figure B–6. Load deflection curves, PA-24.

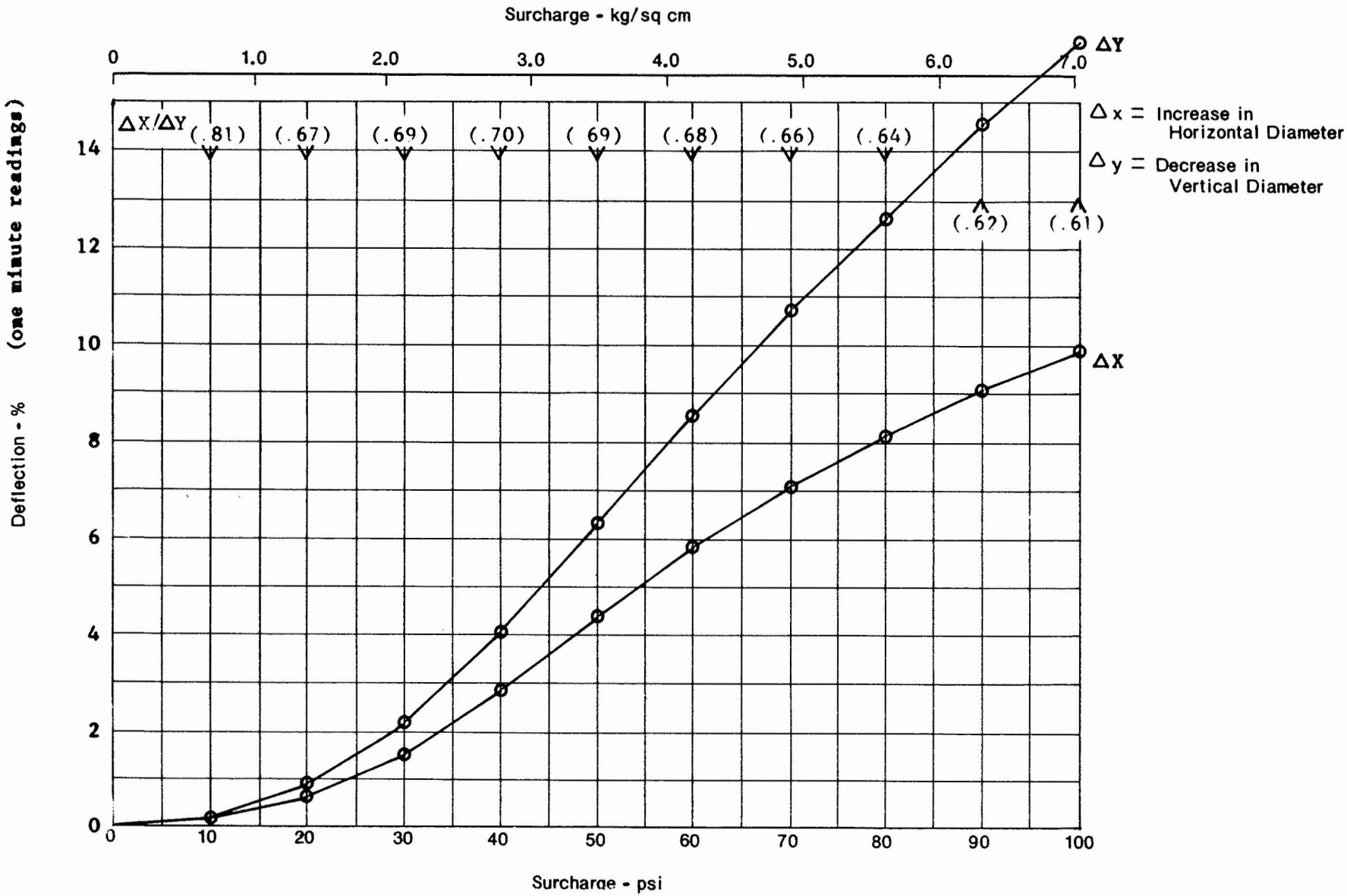


Figure B–7. Load deflection curves, PB-18.

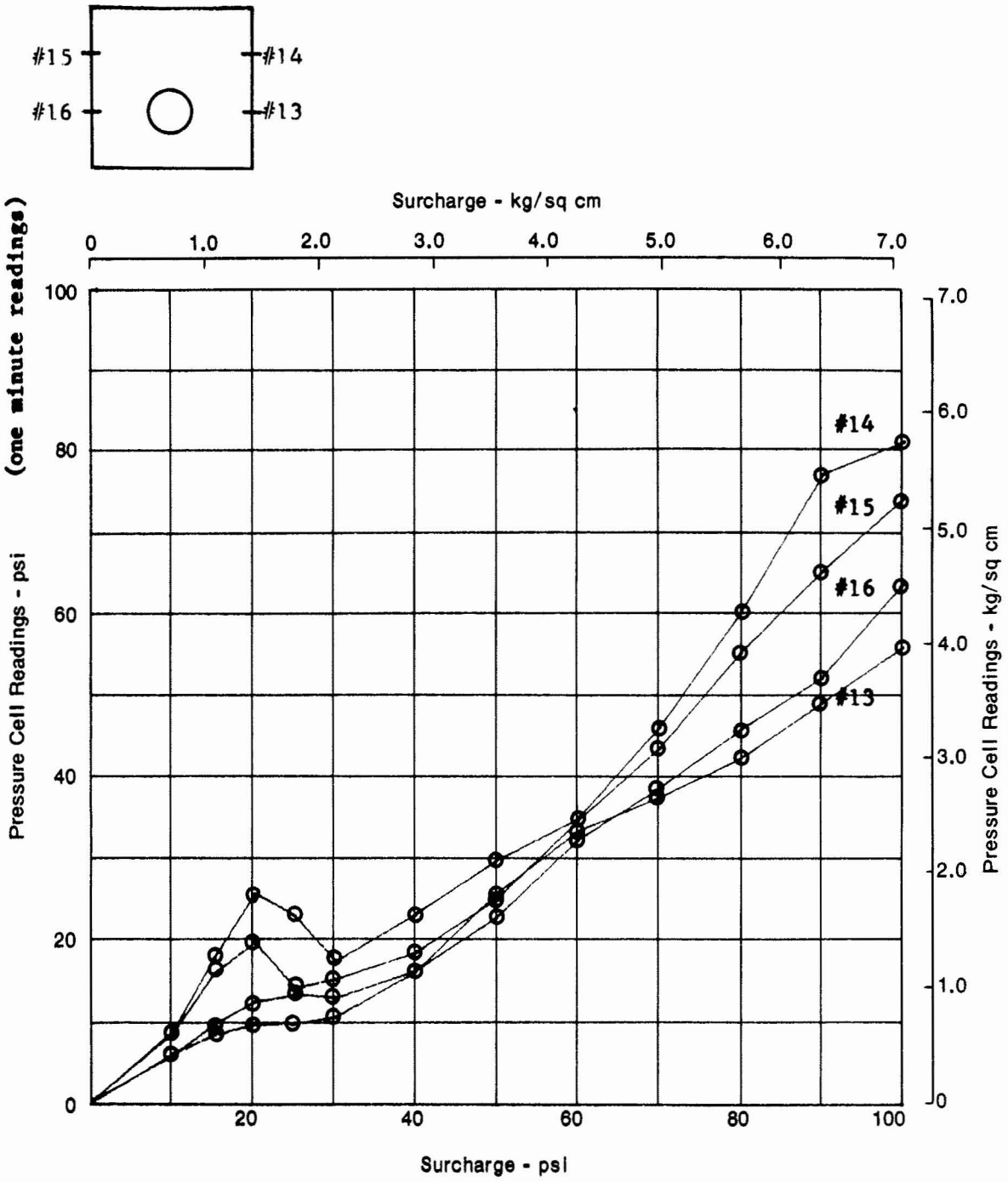


Figure B–8. Soil pressures on container wall, PA-18-A.

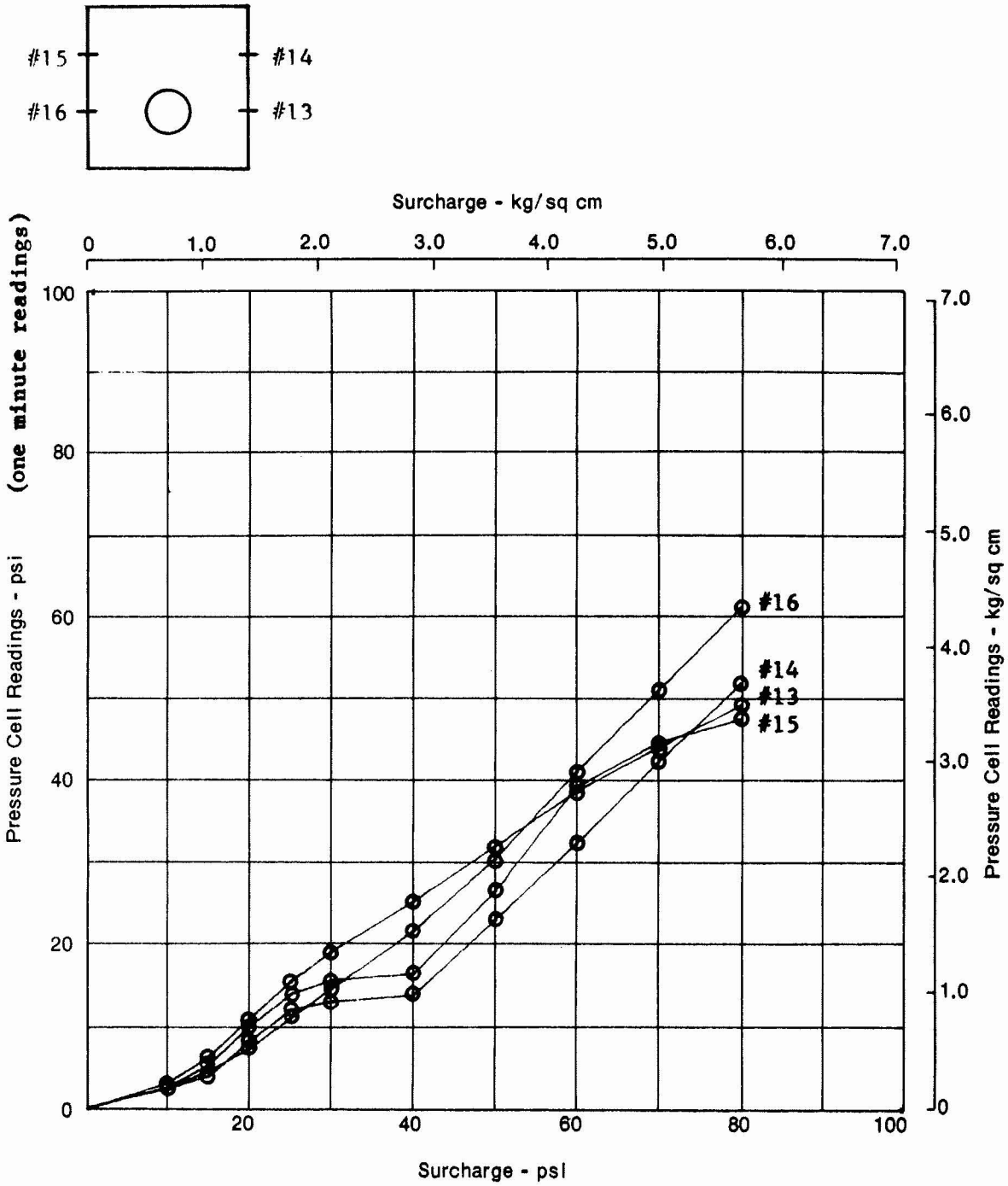


Figure B–9. Soil pressures on container wall, PA-18-B.

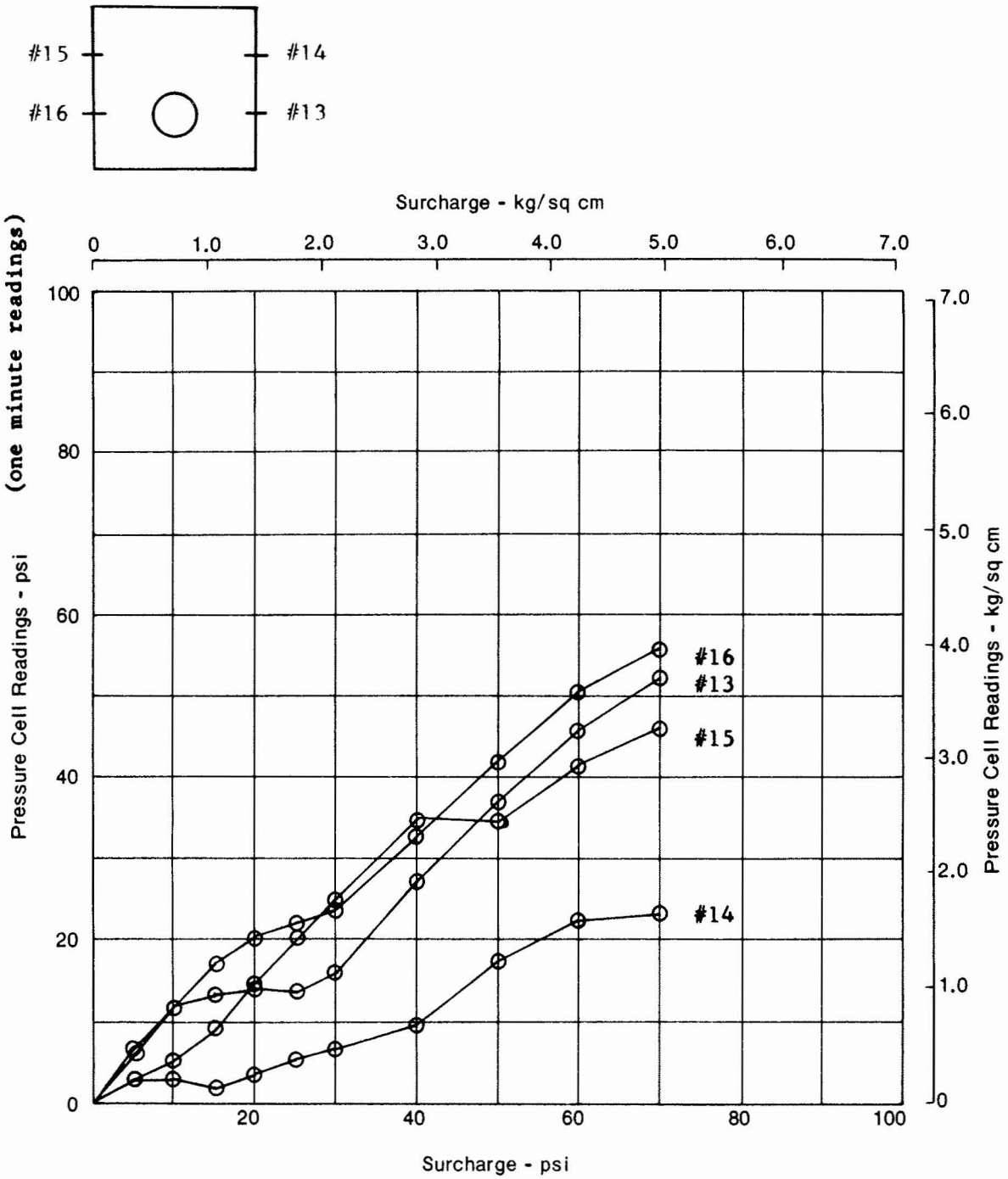


Figure B–10. Soil pressures on container walls, PA-18-C.

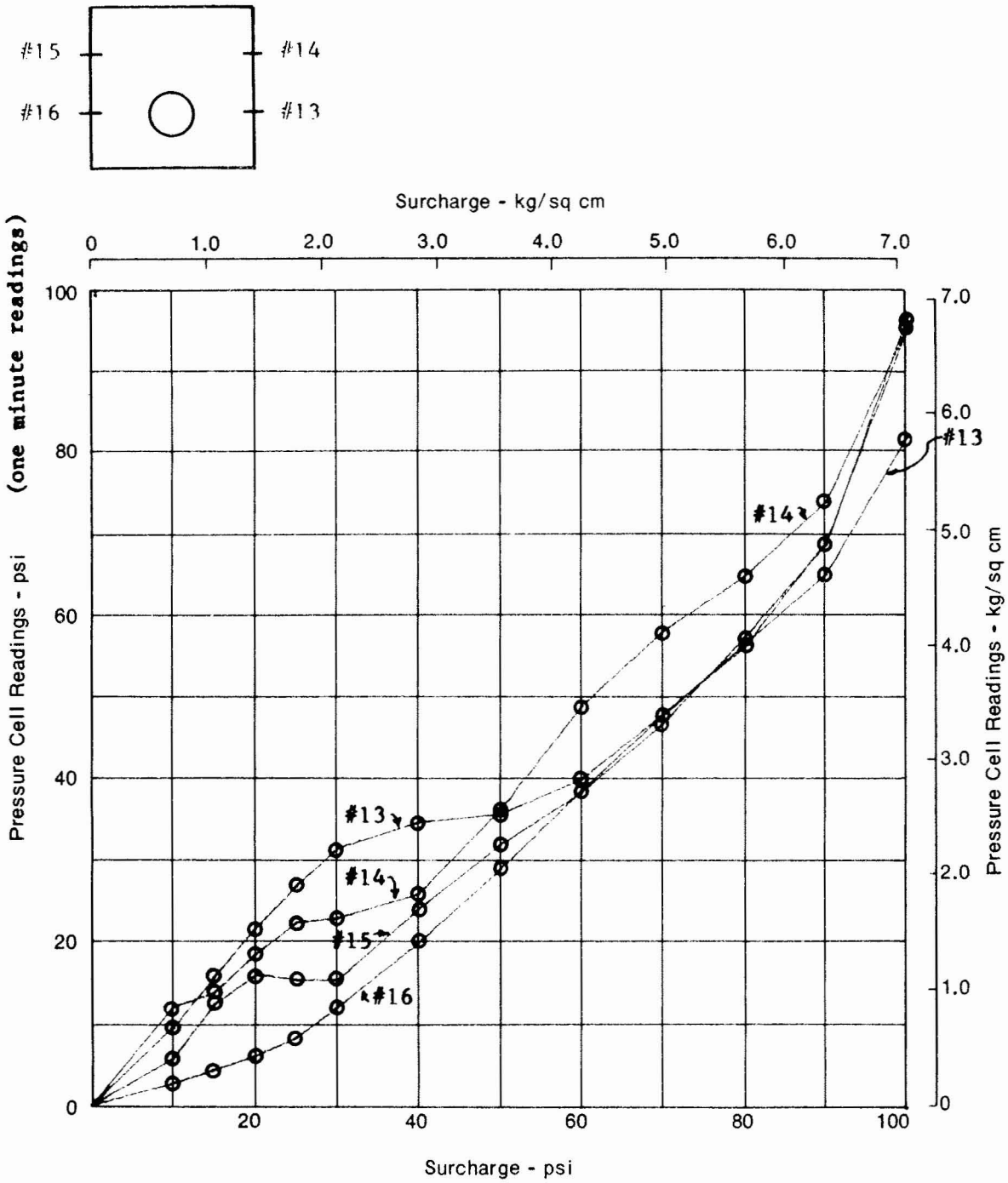


Figure B–11. Soil pressures on container wall, PA-18-D.

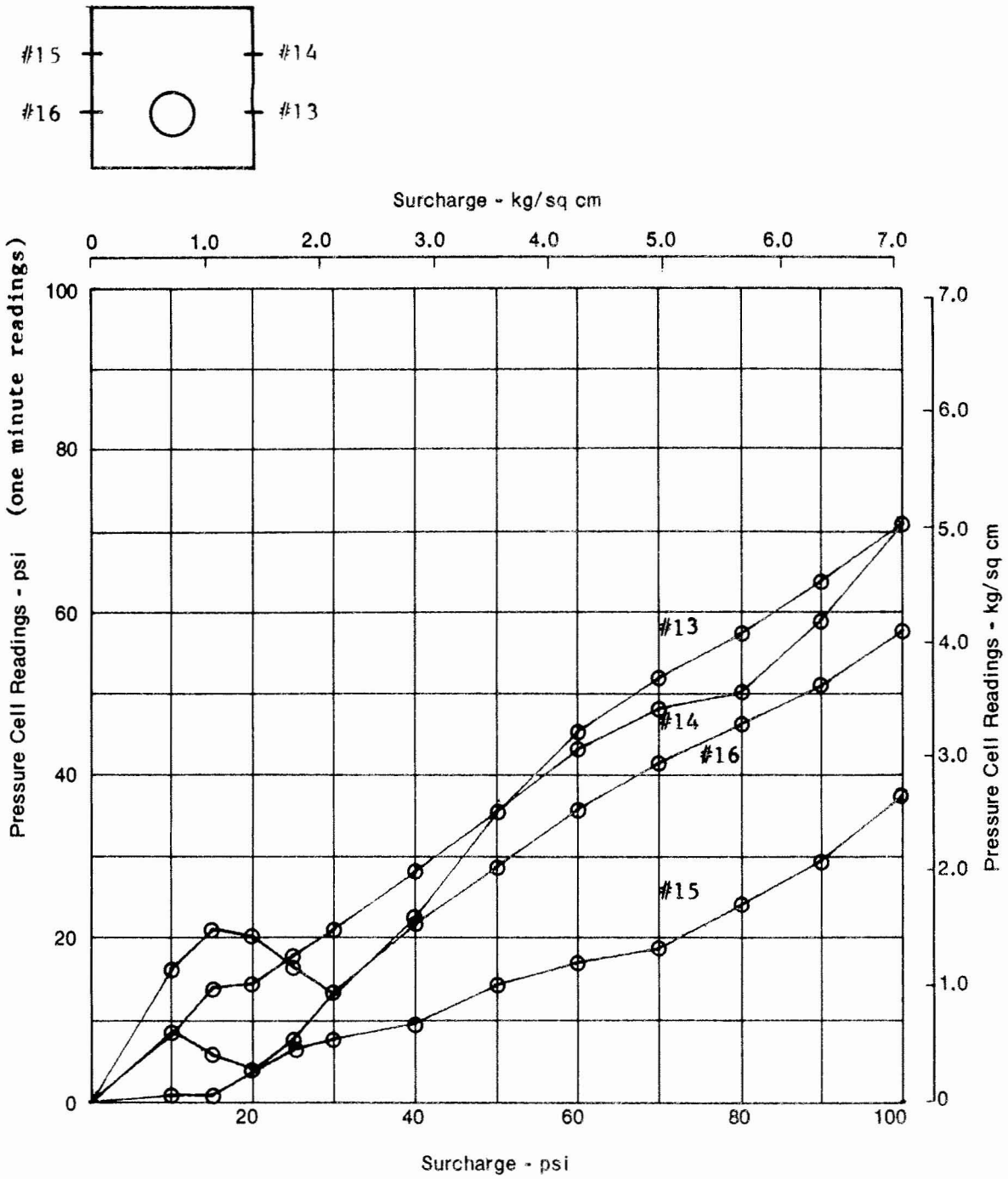


Figure B--12. Soil pressures on container walls, PA-18-F.

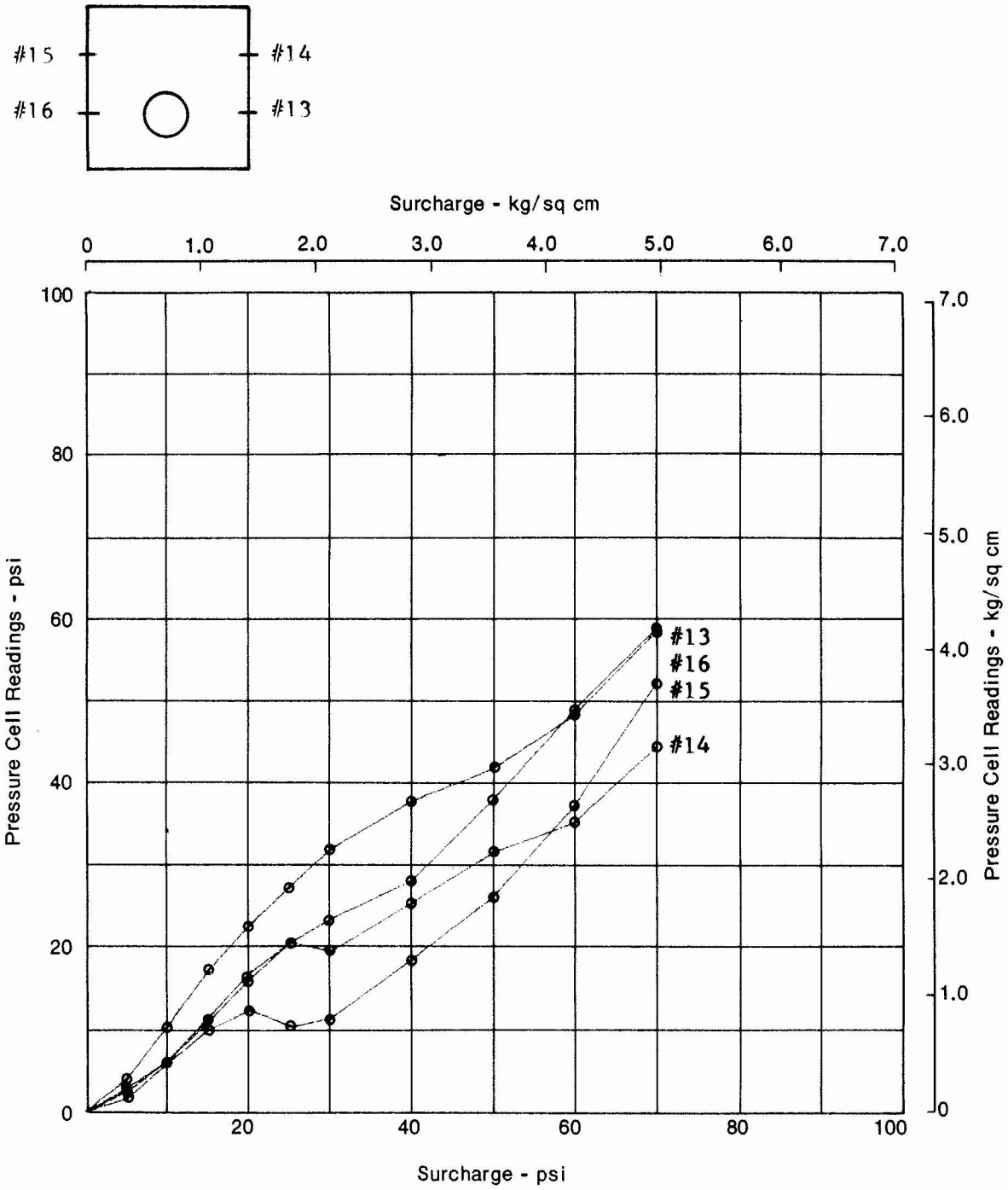


Figure B–13. Soil pressures on soil container wall, PA-24.

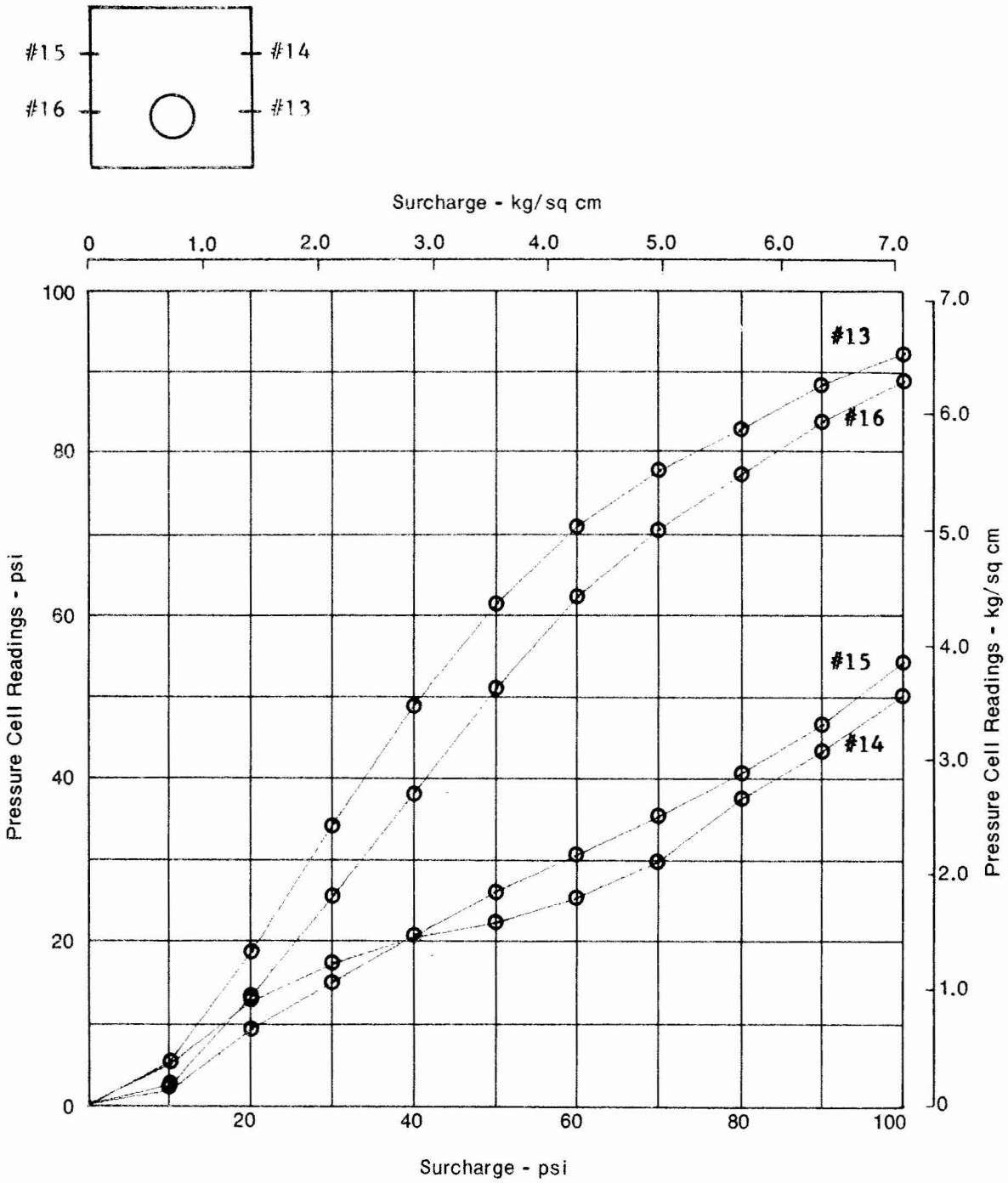


Figure B–14. Soil pressures on container wall, PB-18.

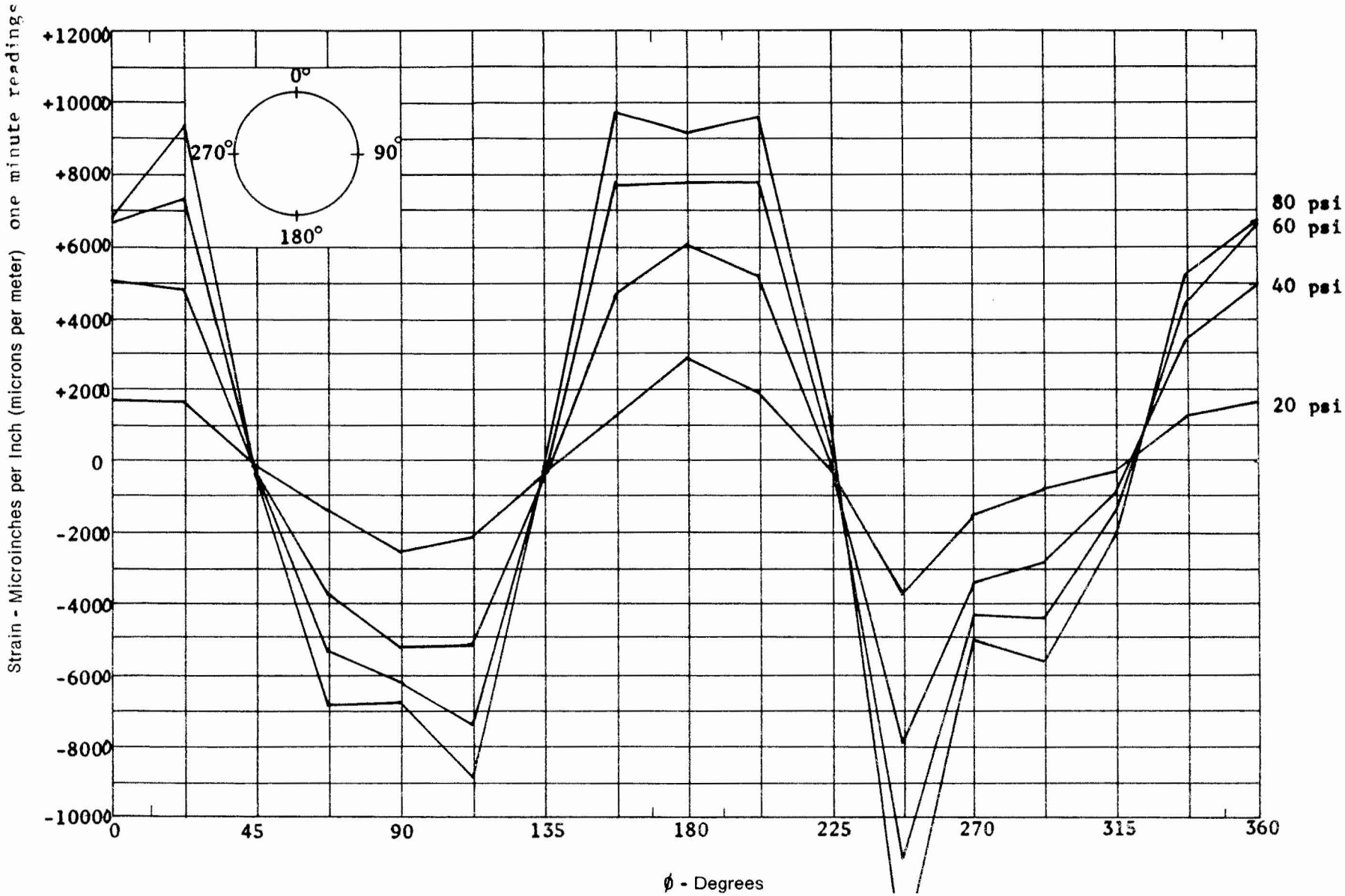


Figure B–15. Strain gage readings around inside pipe circumference, PA-18-A.

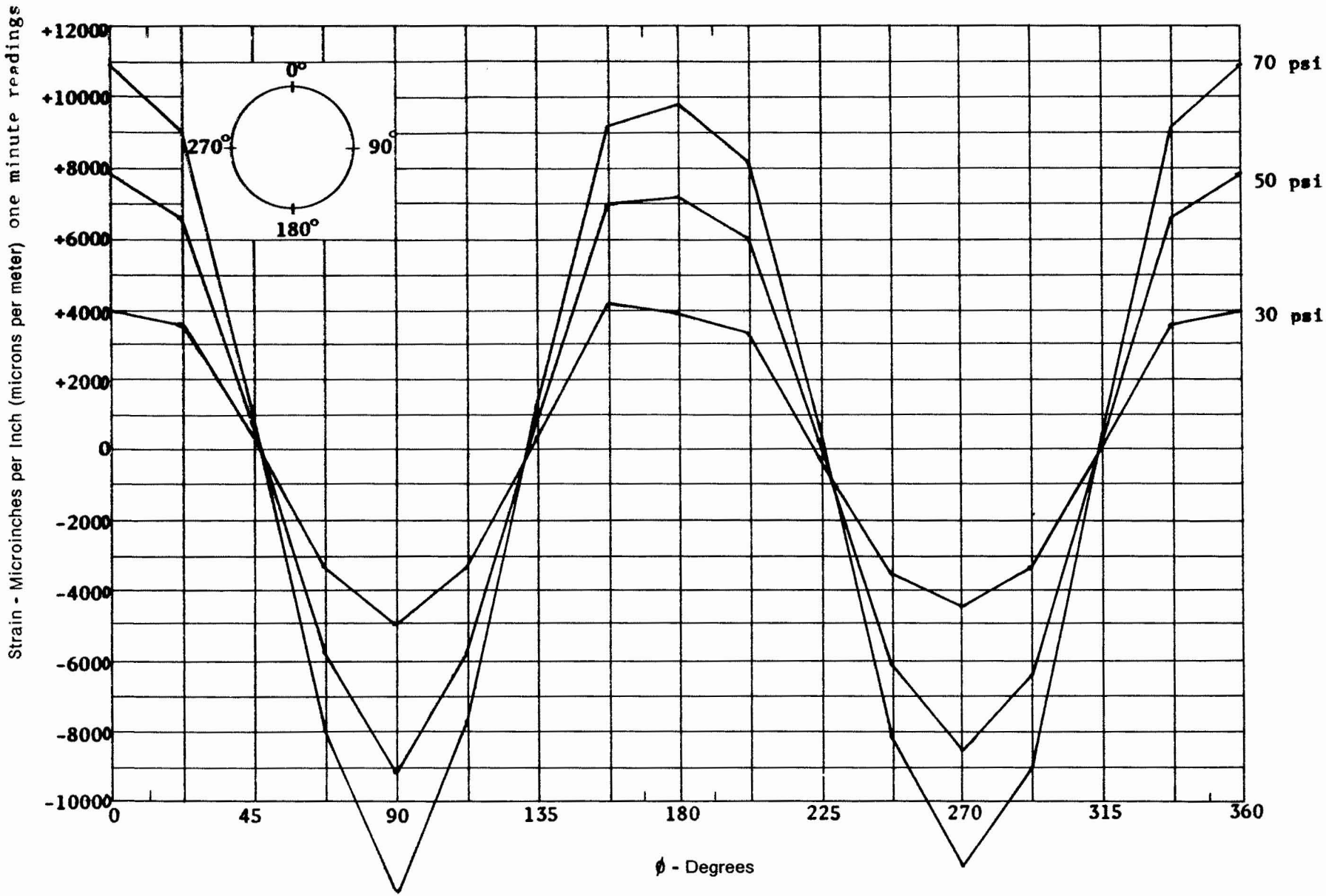


Figure B–16. Strain gage readings around inside pipe circumference, PA-18-B.

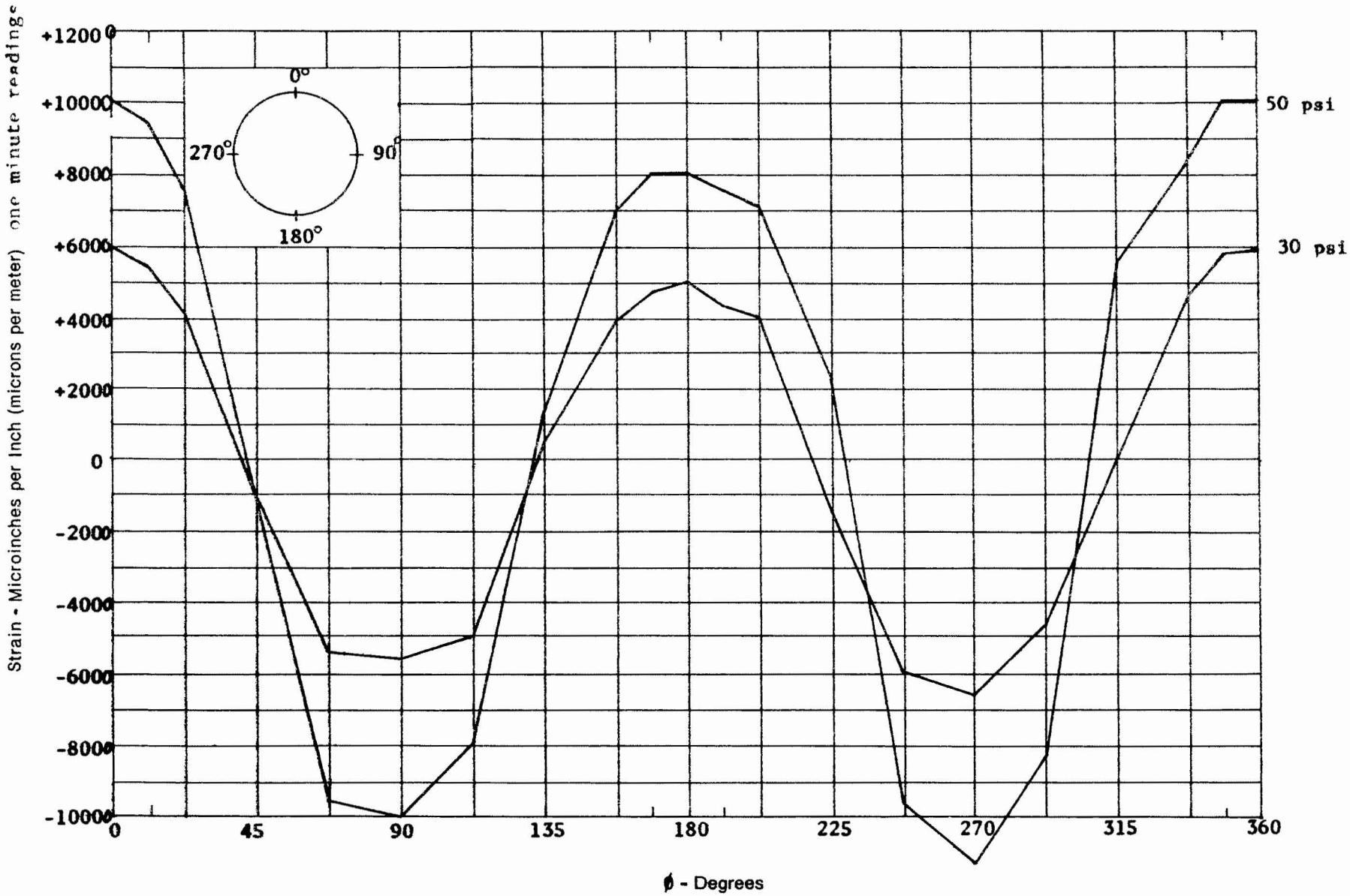


Figure B–17. Strain gage readings around inside pipe circumference, PA-18-D.

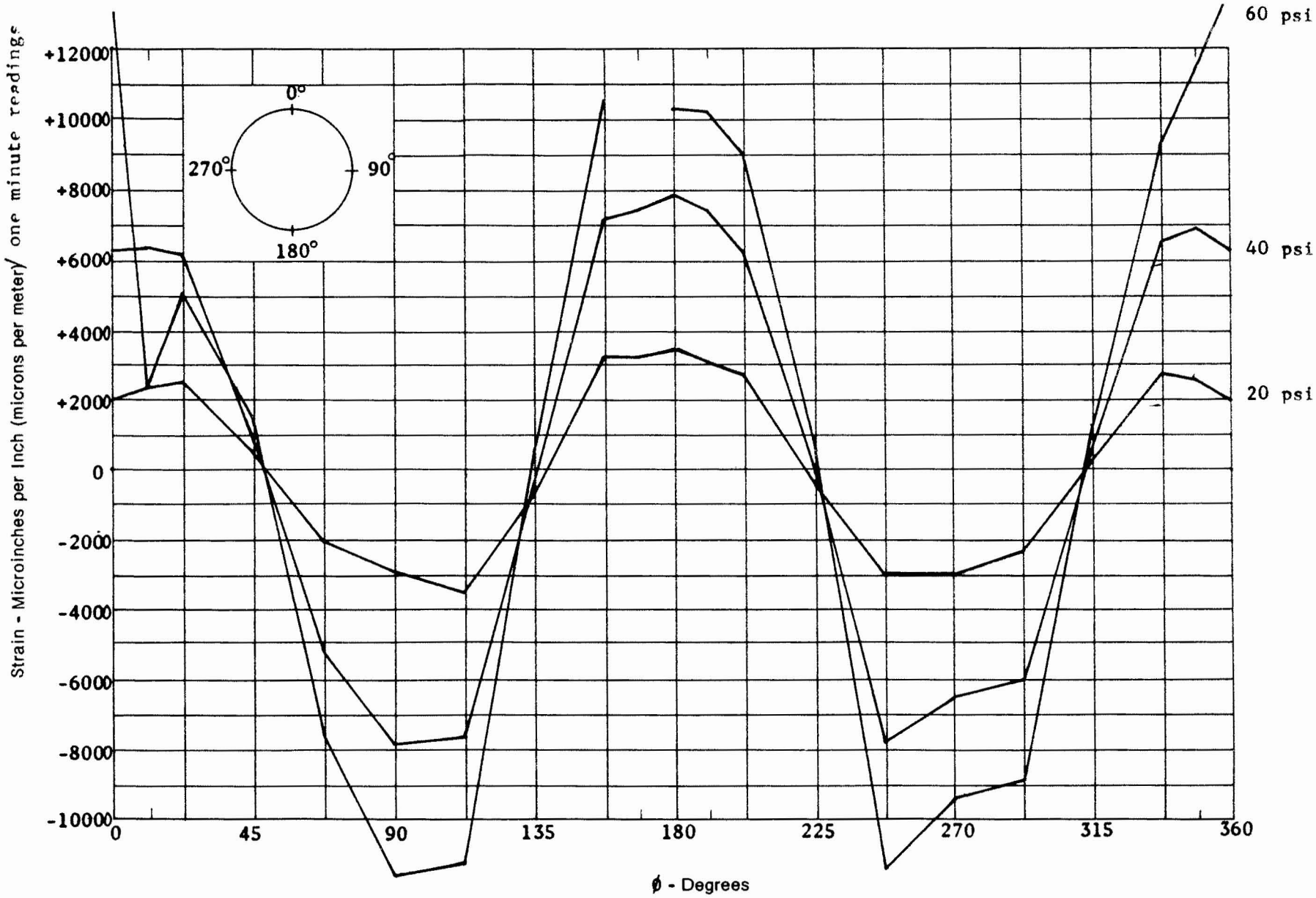


Figure B—18. Strain gage readings around inside pipe circumference, PA-18-F.

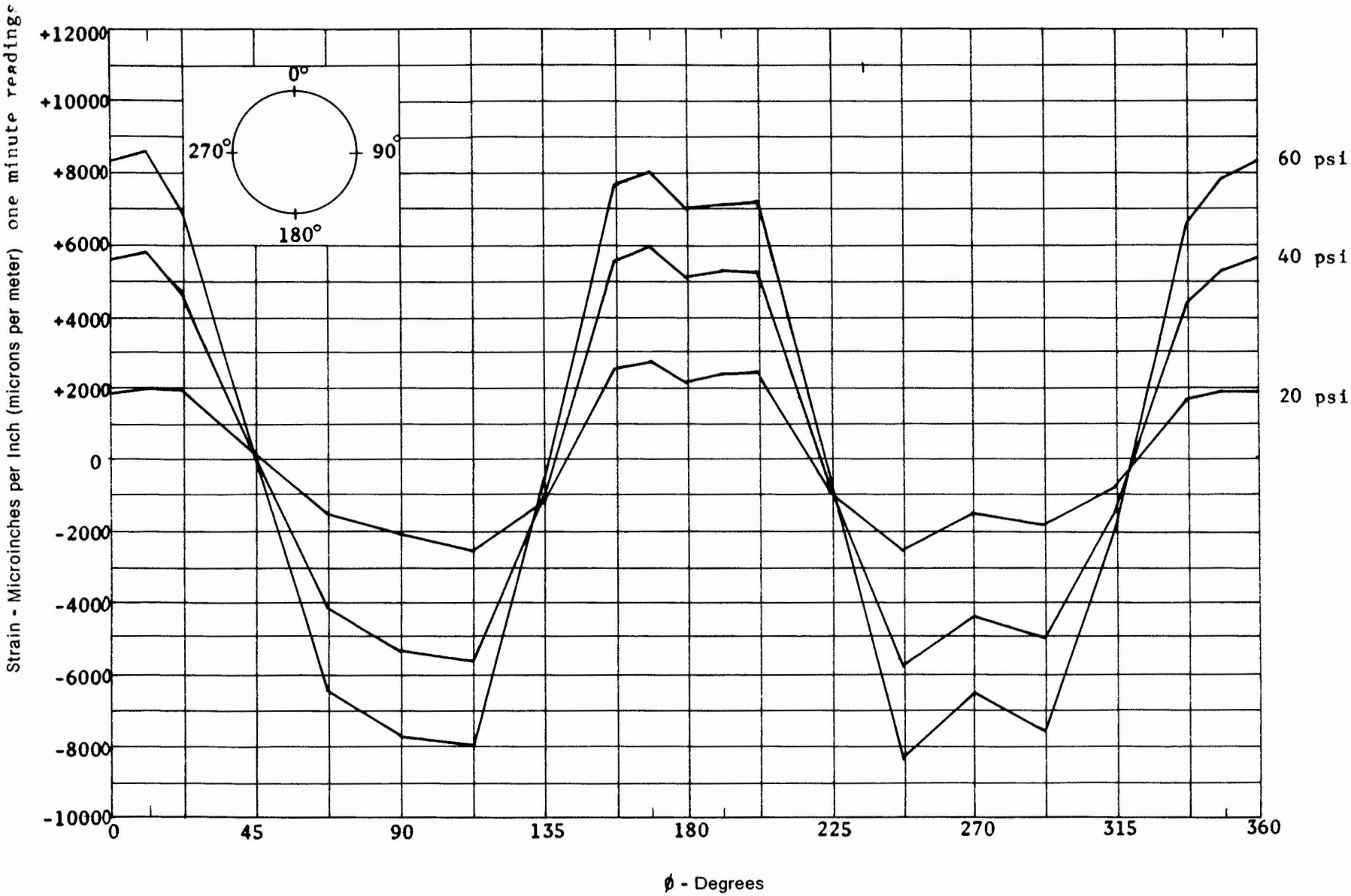


Figure B–19. Strain gage readings around inside pipe circumference, PA-24.

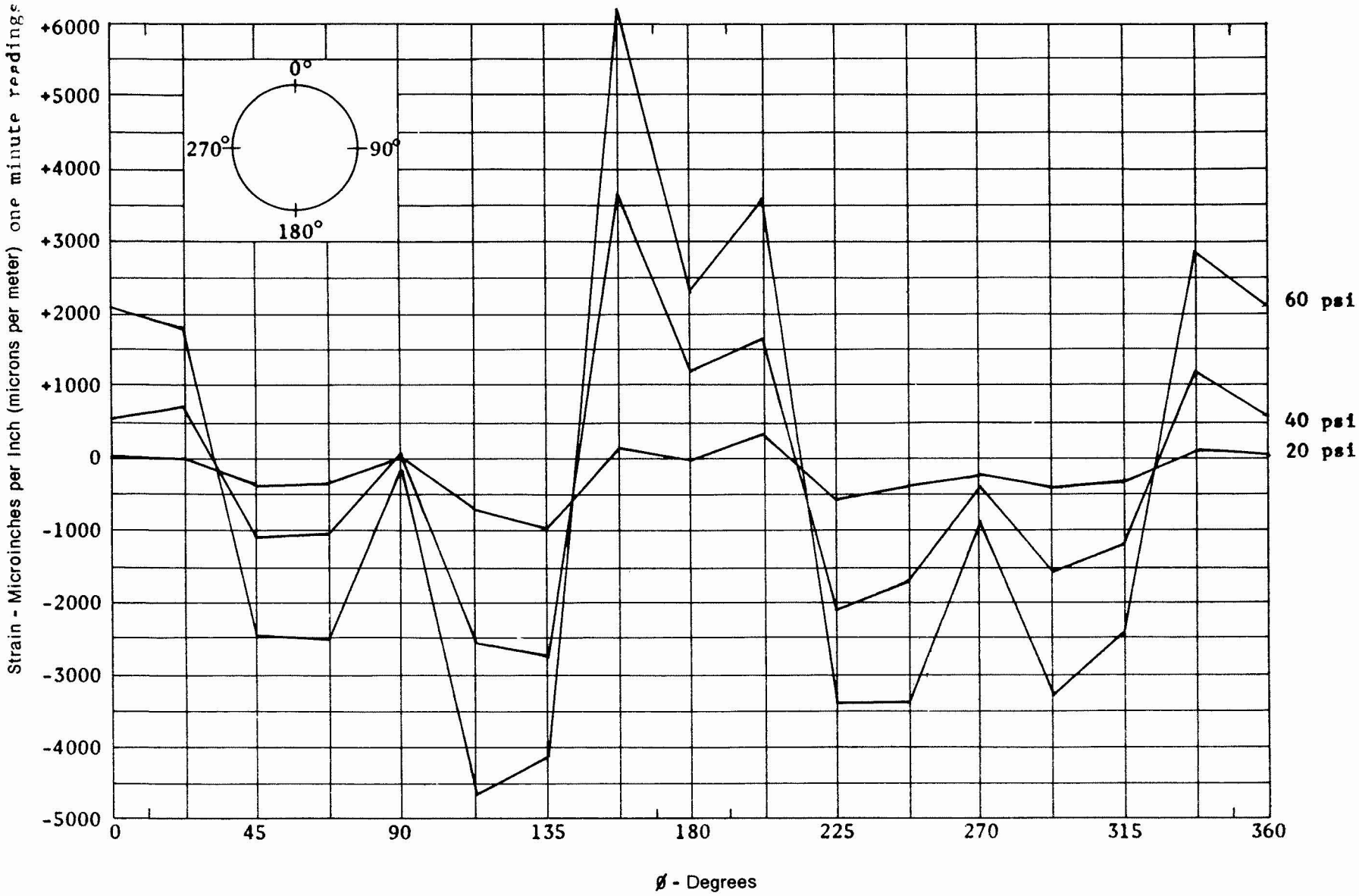


Figure B—20, Strain gage readings around inside pipe circumference, PB-18.

*Original Distance to Side of Pipe

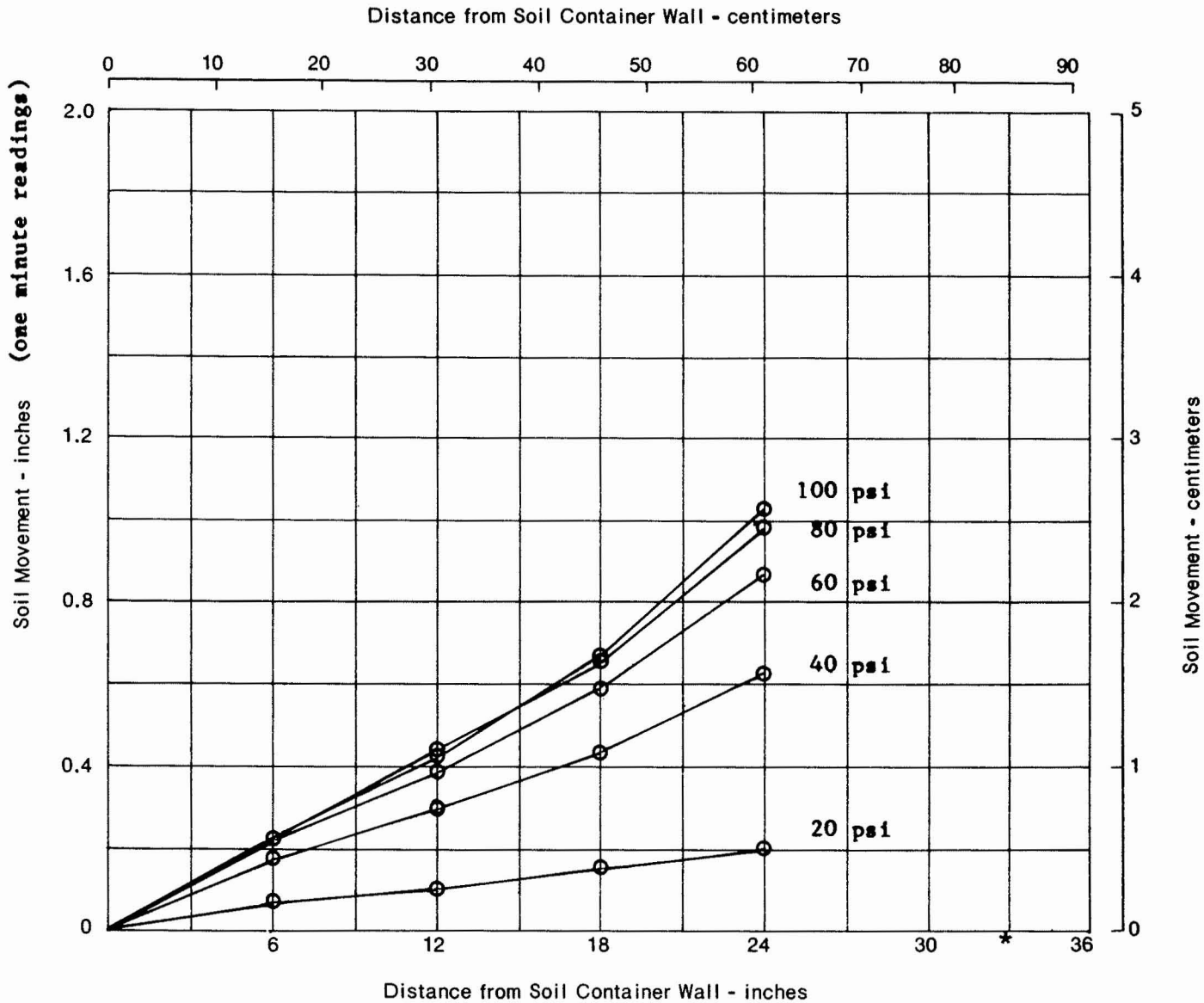


Figure B—21. Soil movement between pipe and soil container wall, PA-18-A.

*Original Distance to Side of Pipe

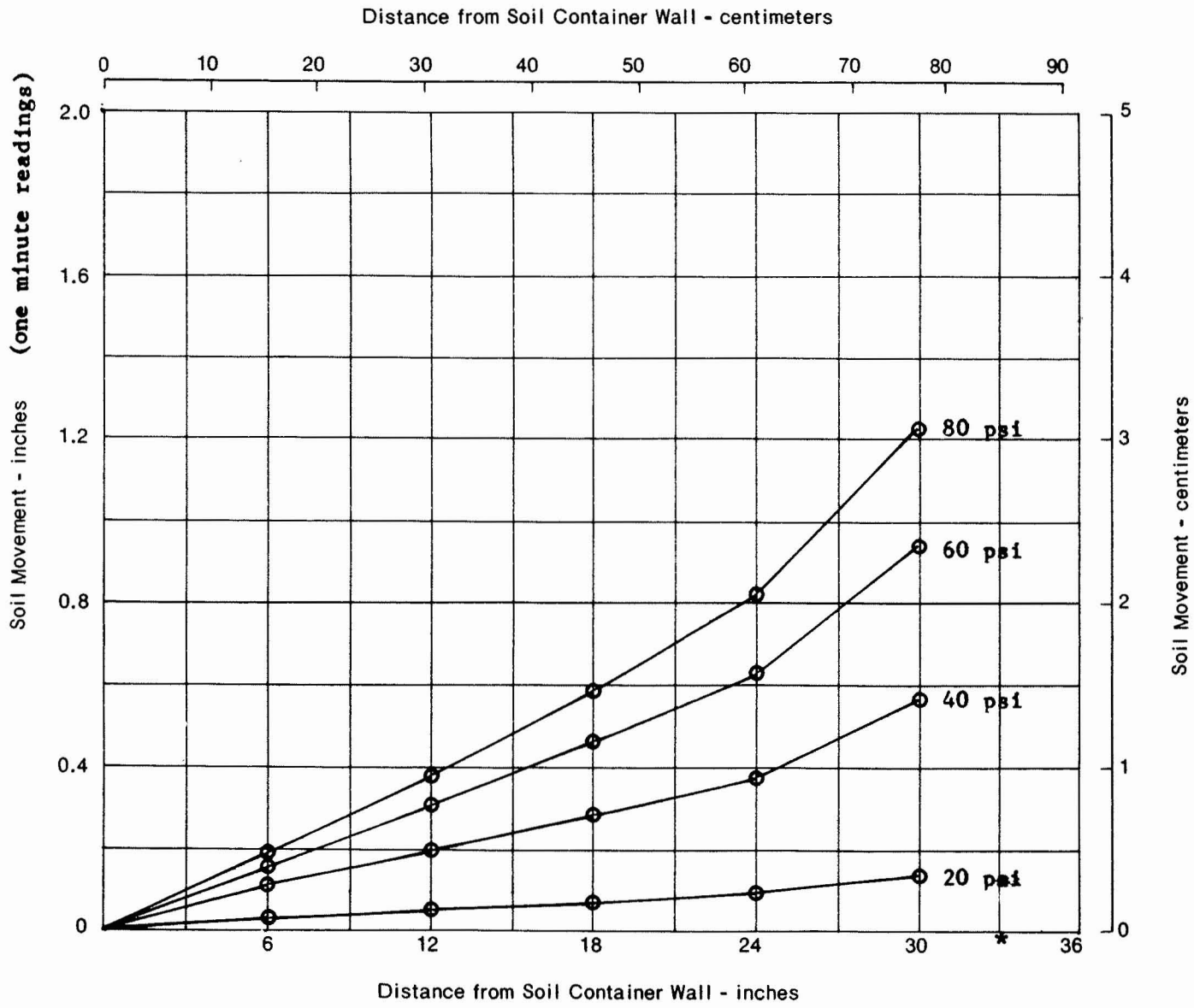


Figure B—22. Soil movement between pipe and soil container wall, PA-18-B.

*Original Distance to Side of Pipe

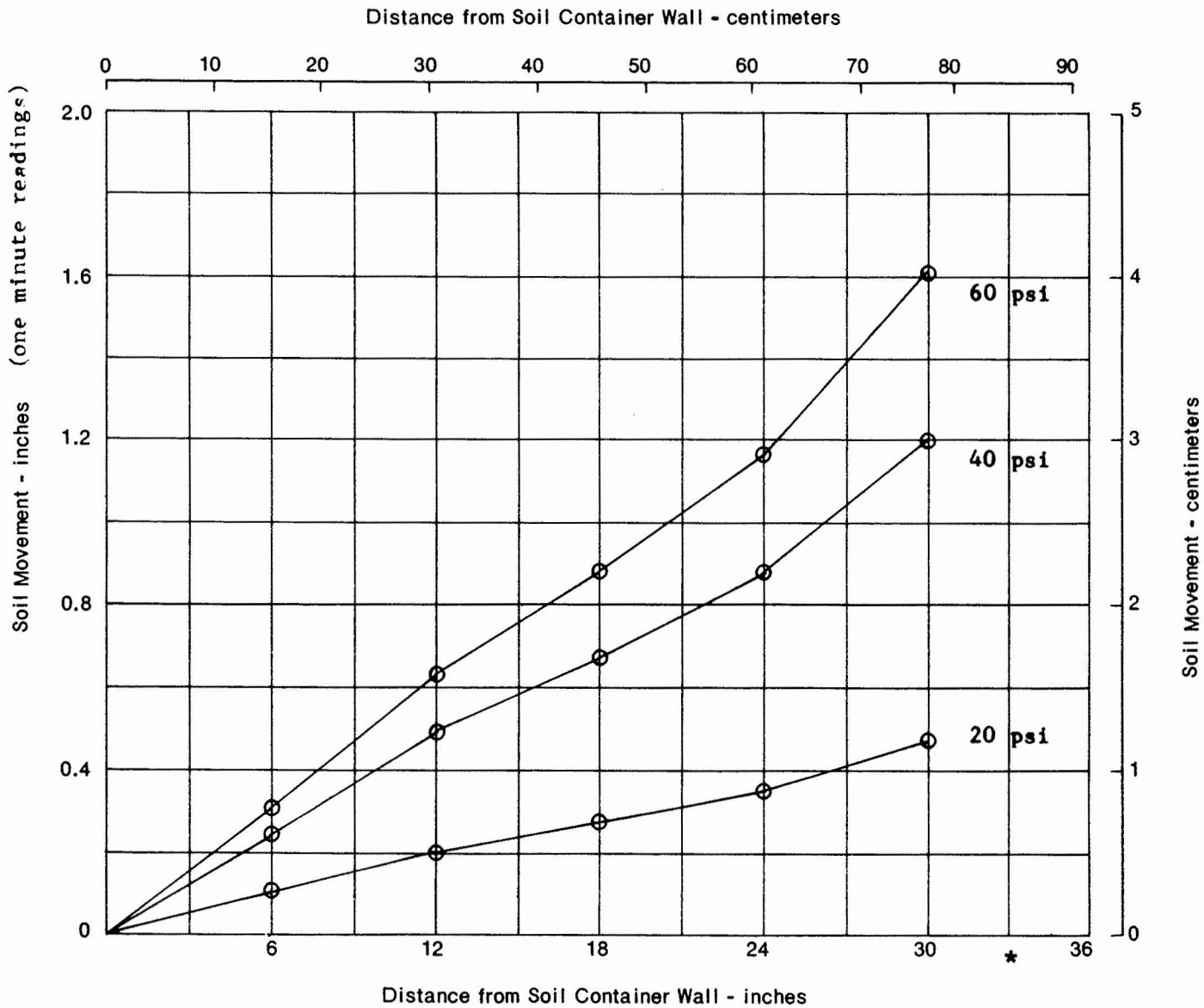


Figure B–23. Soil movement between pipe and soil container wall, PA-18-C.

*Original Distance to Side of Pipe

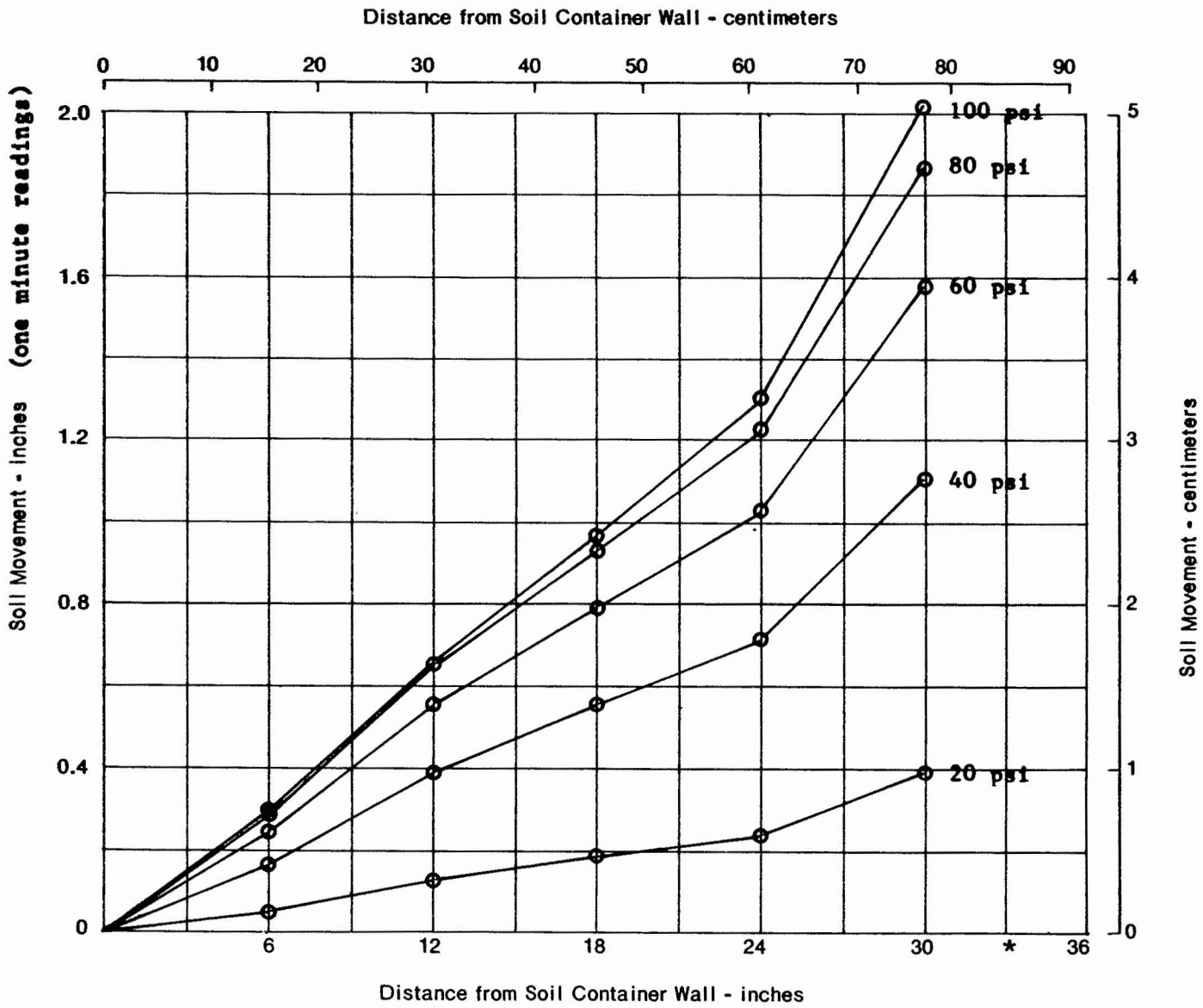


Figure B—24. Soil movement between pipe and soil container wall, PA-18-D.

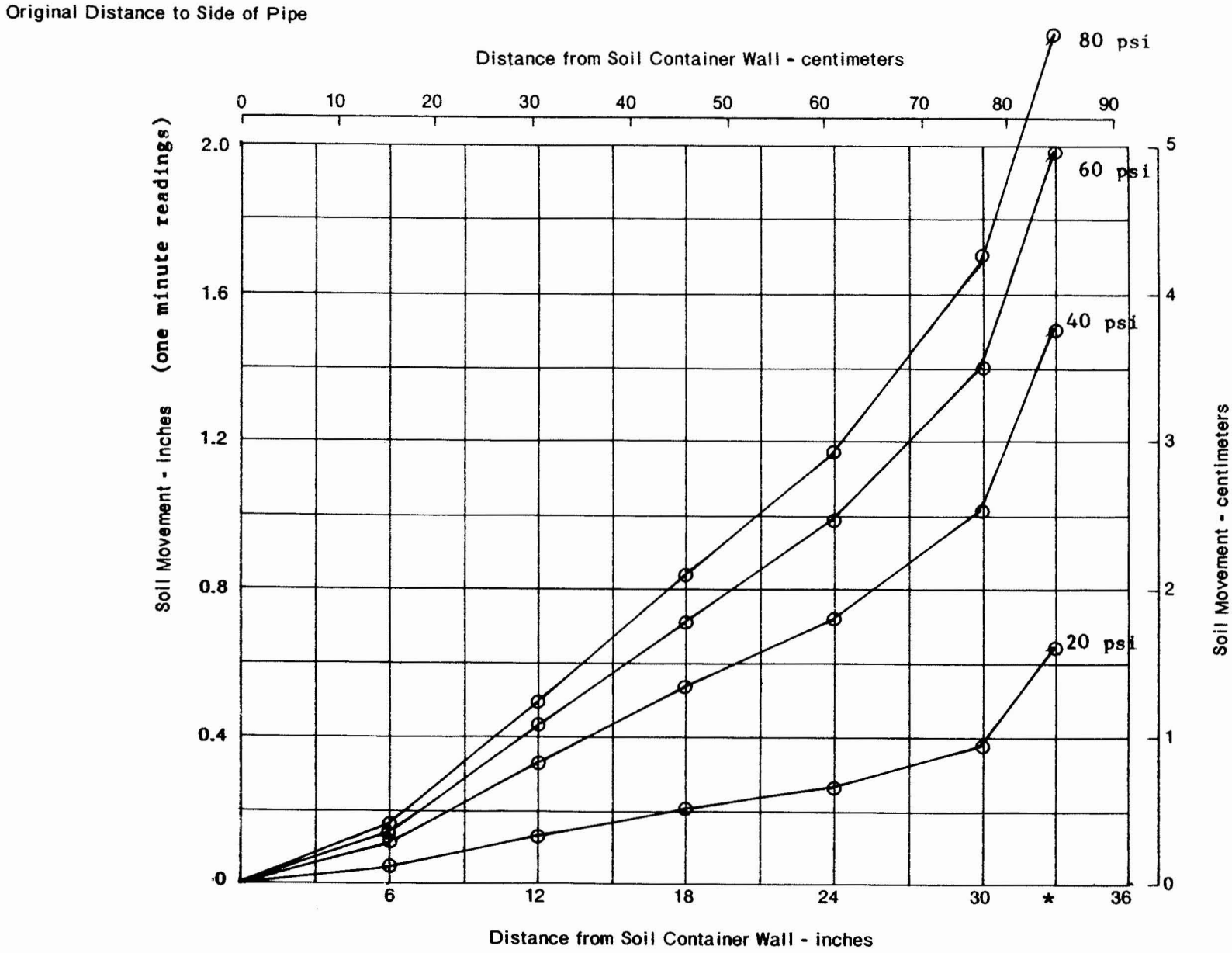


Figure B—25. Soil movement between pipe and soil container wall, PA-18-F.

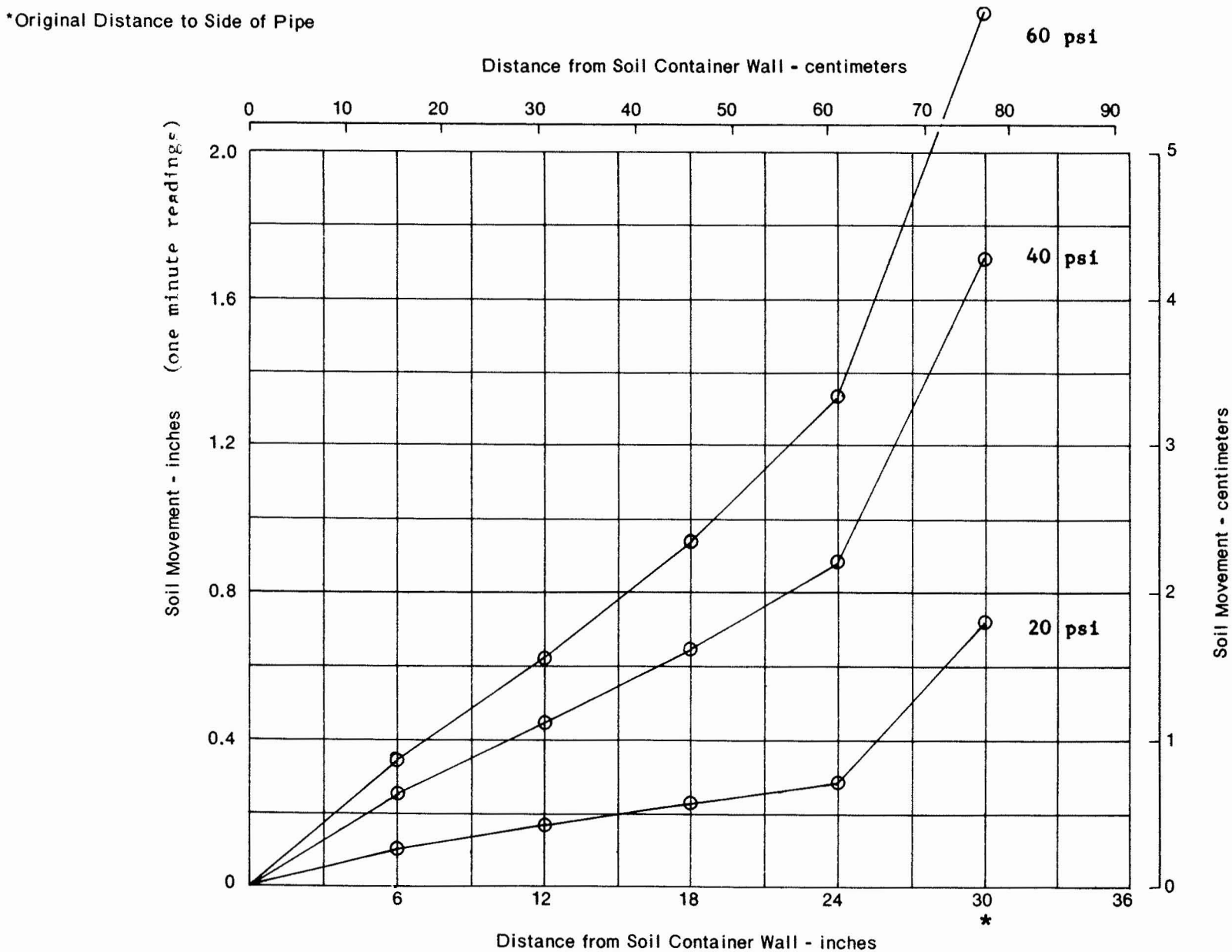


Figure B–26. Soil movement between pipe and soil container wall, PA-24.

*Original Distance to Side of Pipe

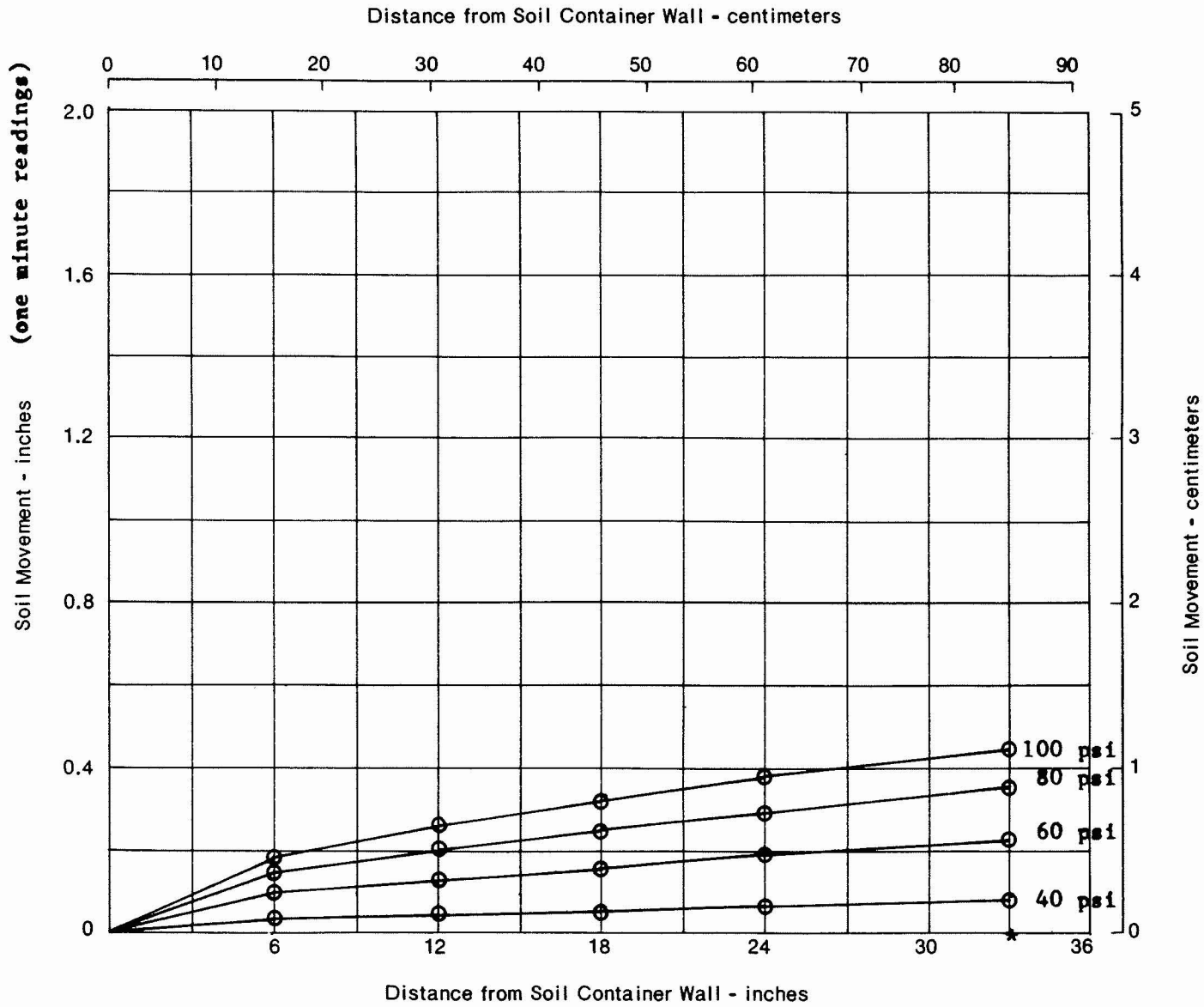


Figure B–27. Soil movement between pipe and soil container wall, PB-18.

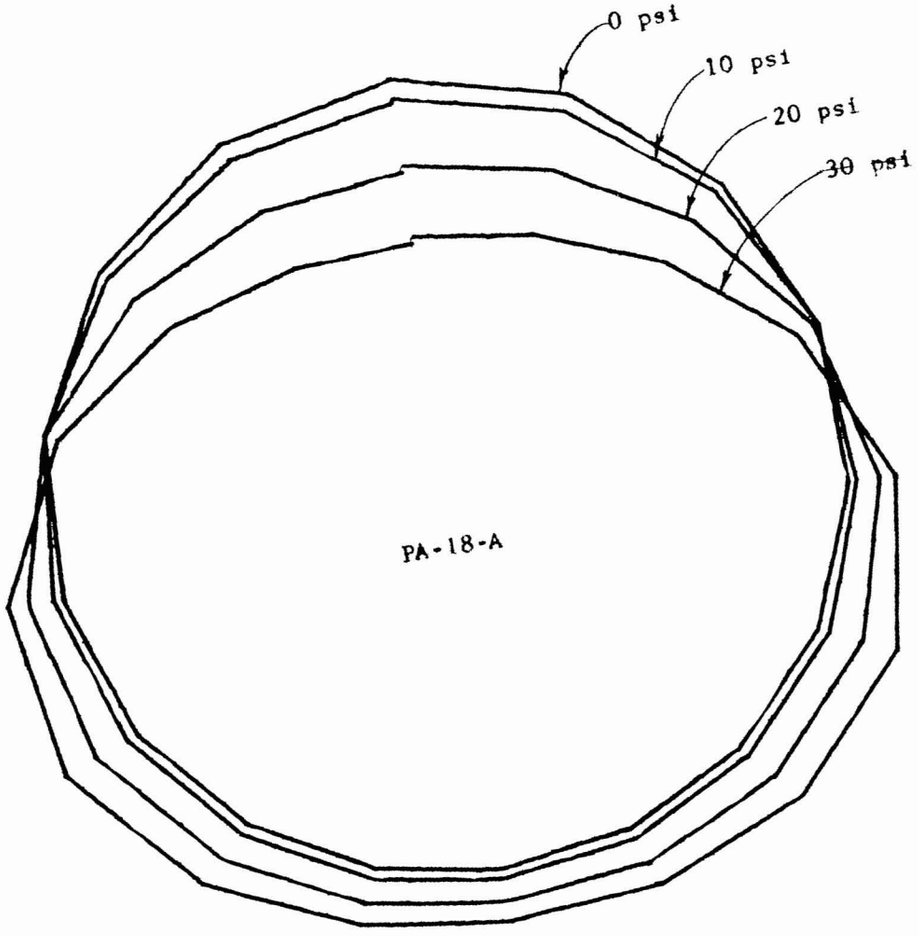


Figure B–28. Cross section of pipe under load, RPM pipe test, PA-18-A.

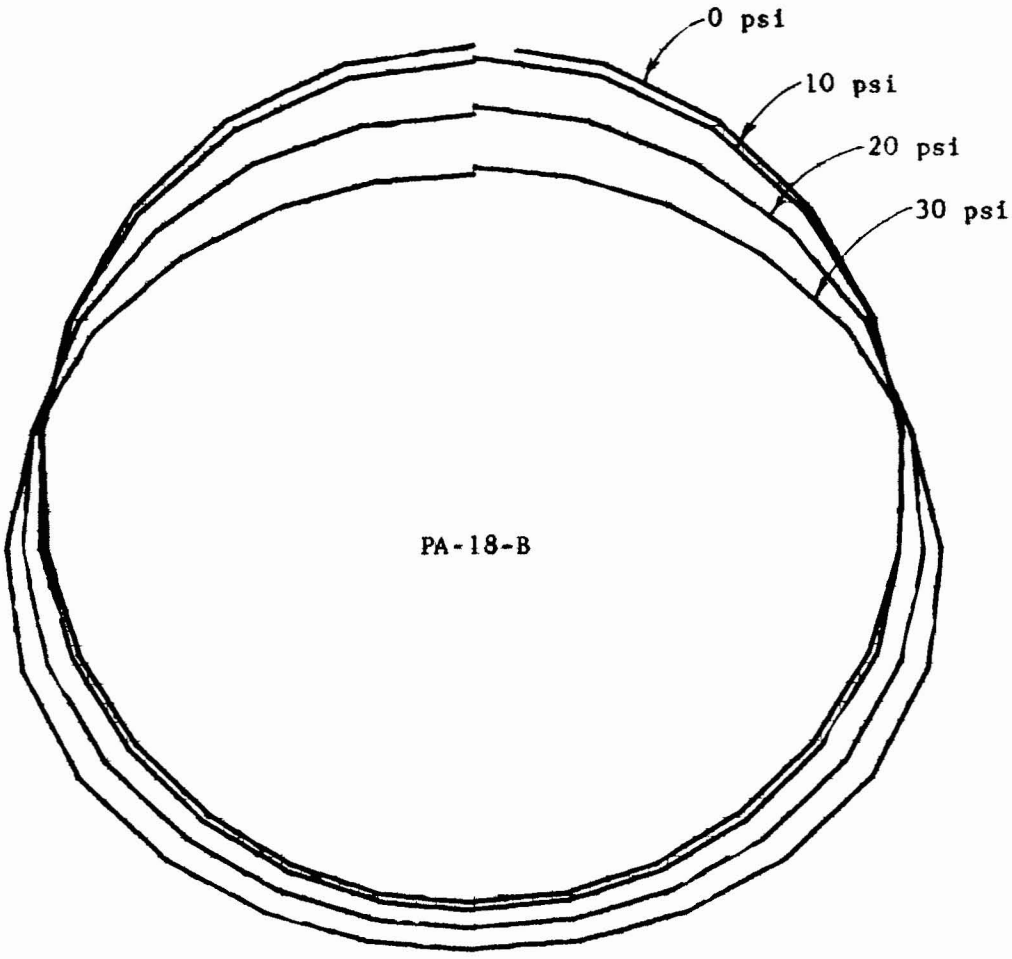


Figure B–29. Cross section of pipe under load, RPM pipe test, PA-18-B.

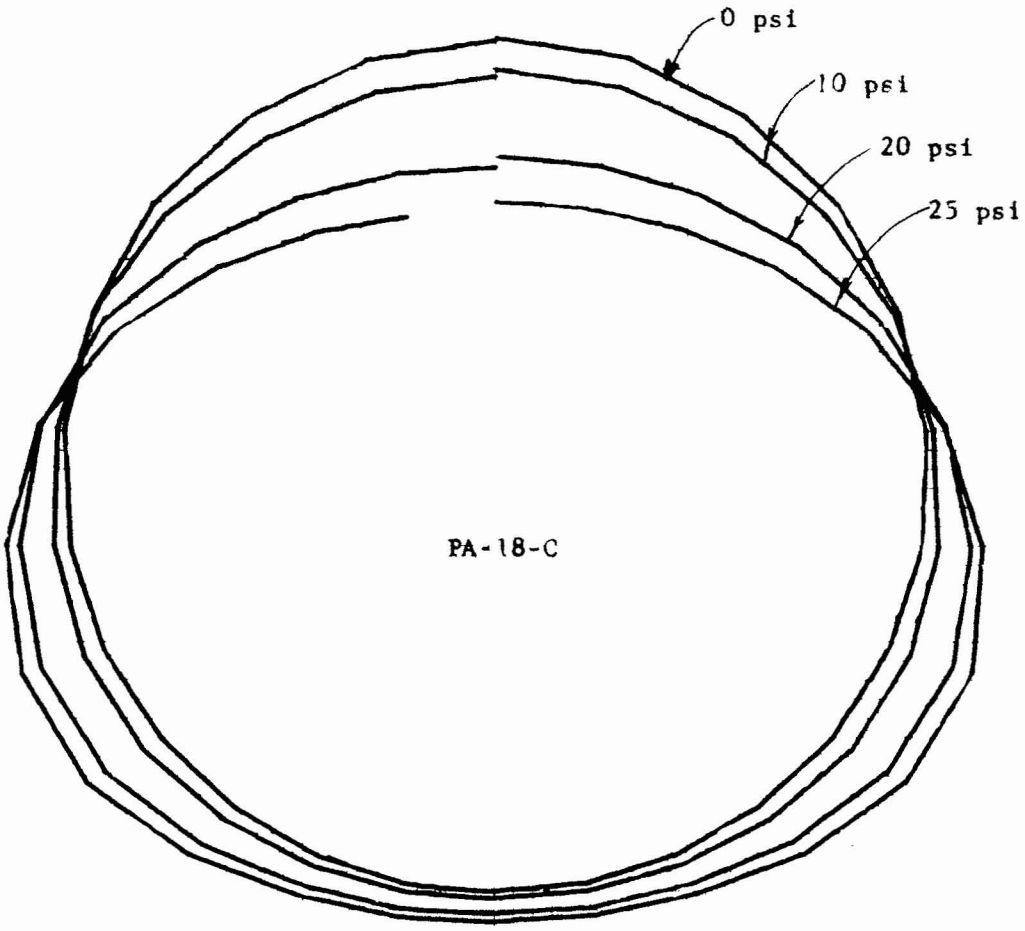


Figure B—30. Cross section of pipe under load, RPM pipe test, PA-18-C.

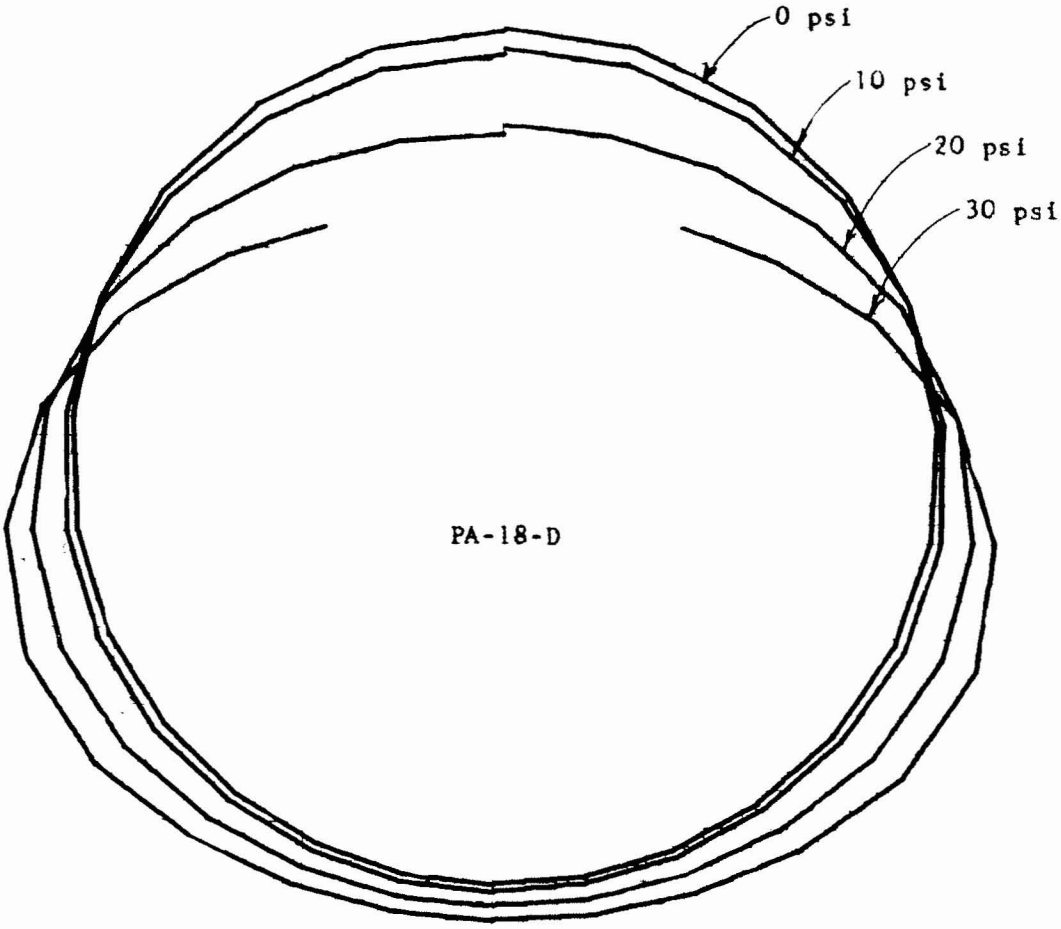


Figure B–31. Cross section of pipe under load, RPM pipe test, PA-18-D.

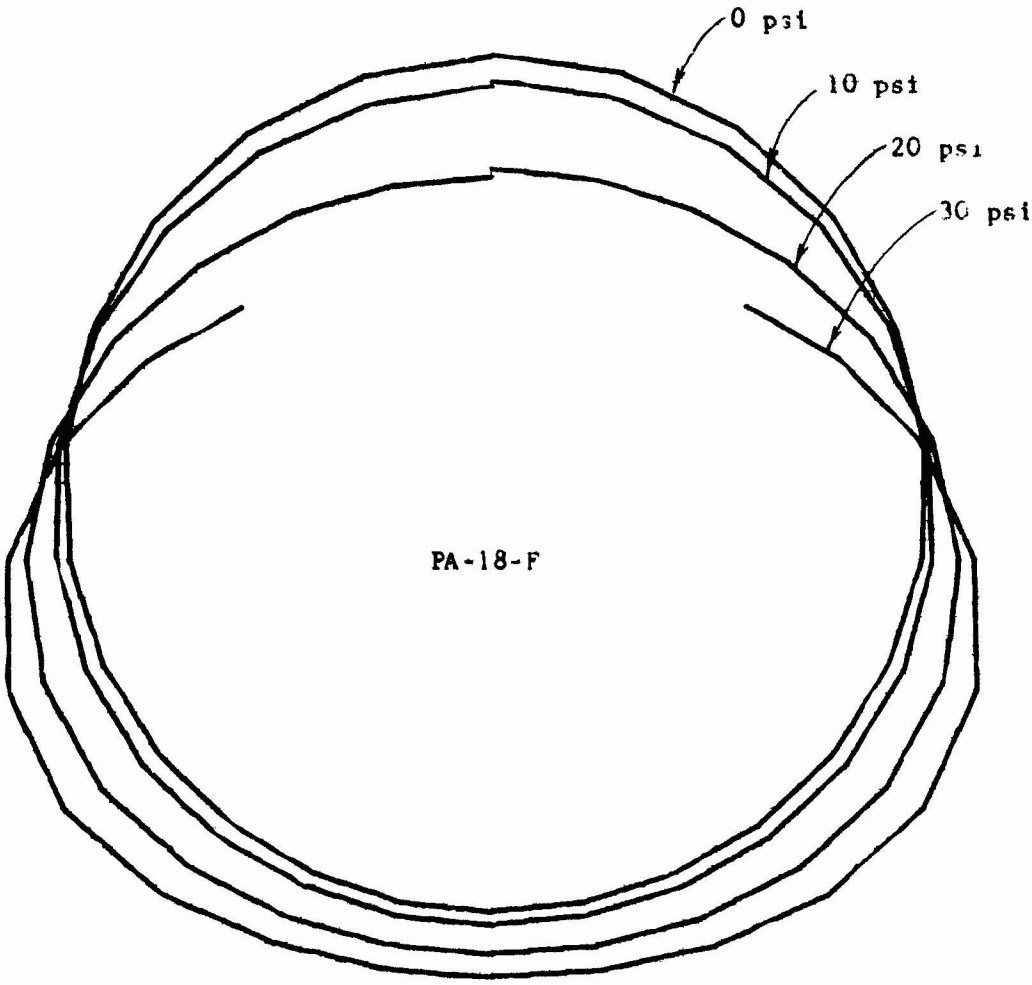


Figure B–32. Cross section of pipe under load, RPM pipe test, PA-18-F.

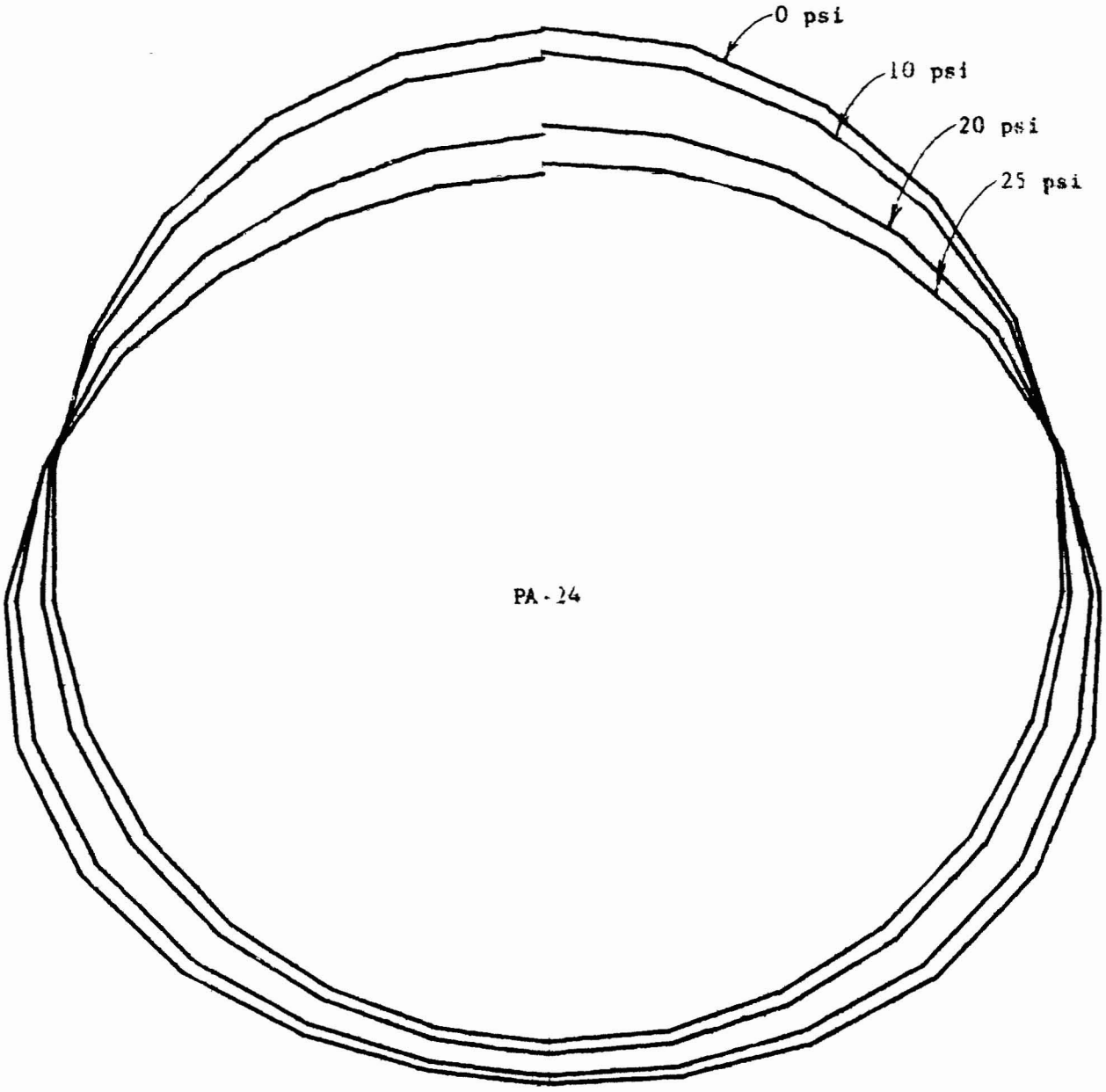


Figure B–33. Cross section of pipe under load, RPM pipe test, PA-24.

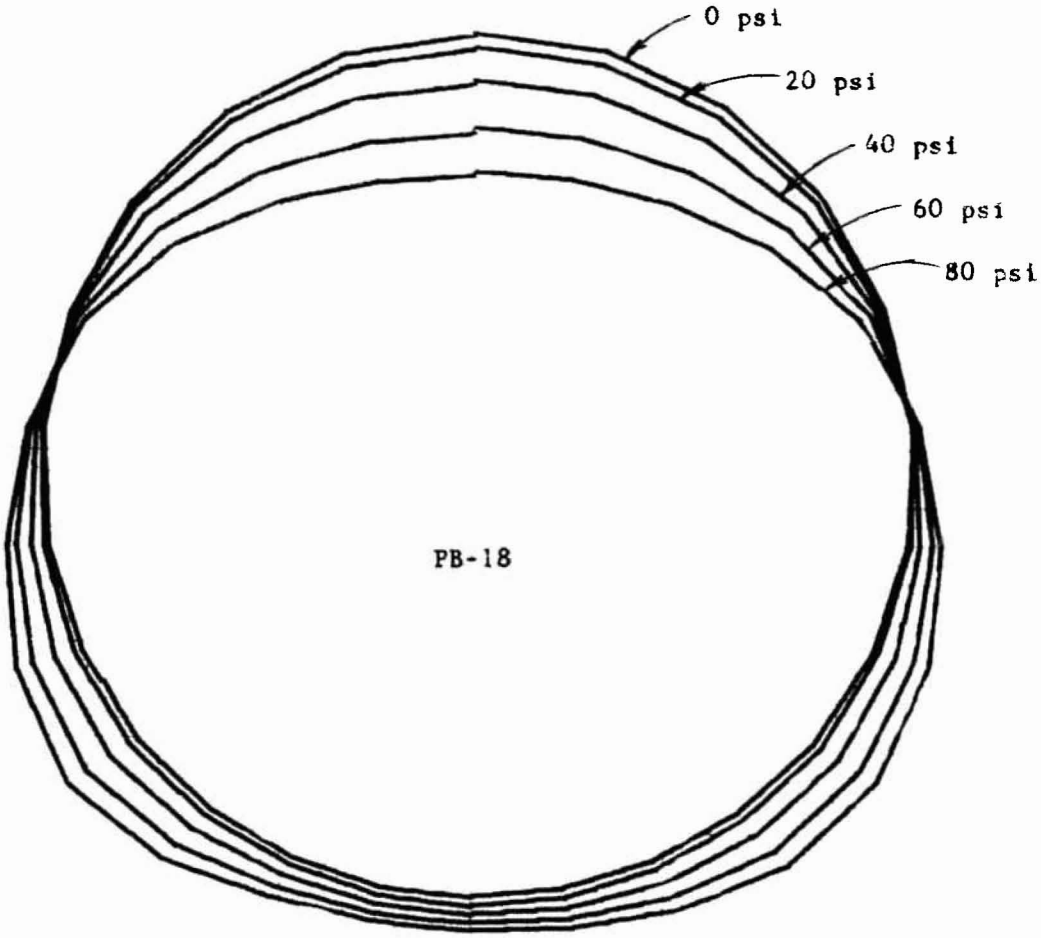


Figure B–34. Cross section of pipe under load, RPM pipe test, PB-18.

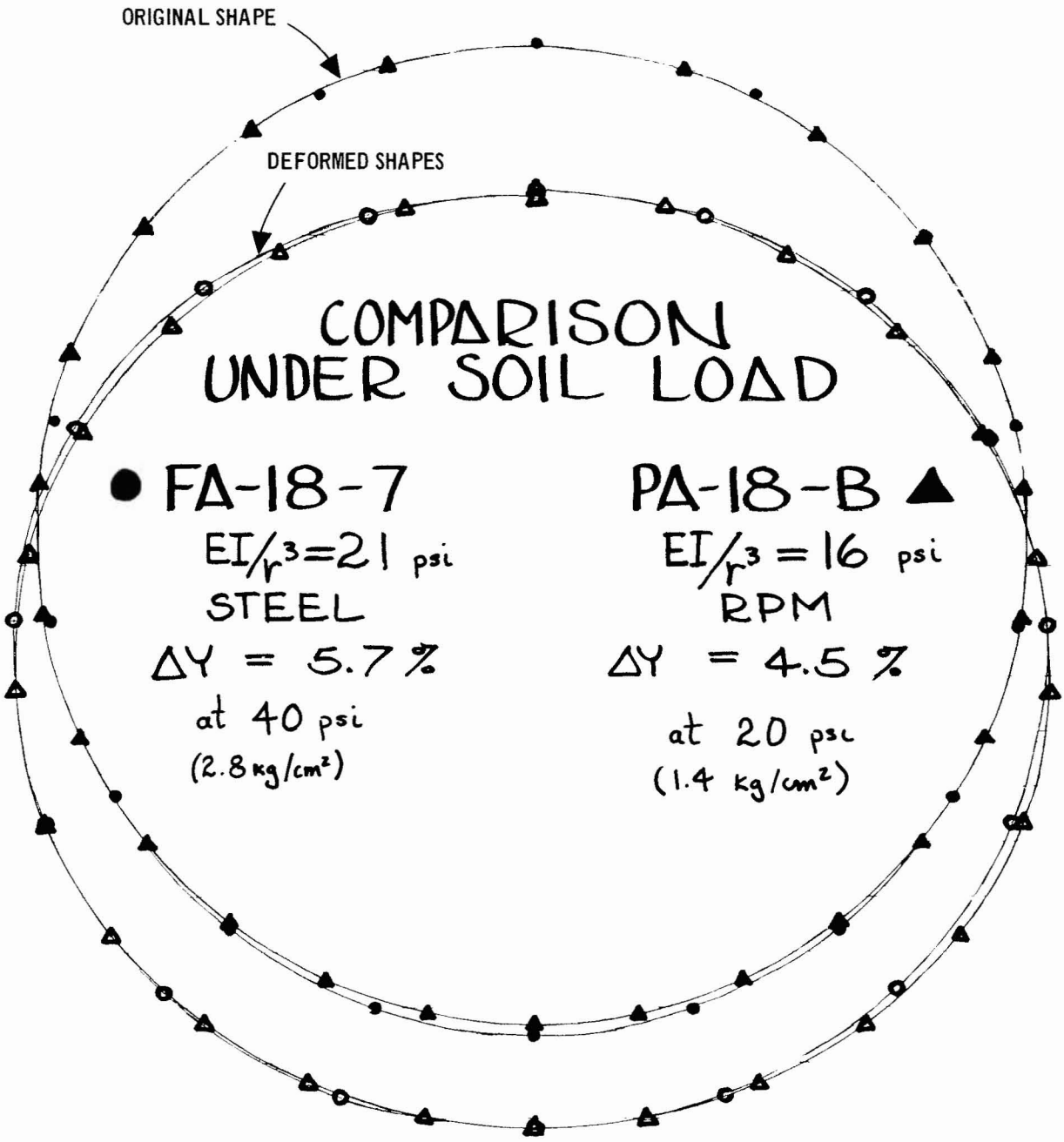
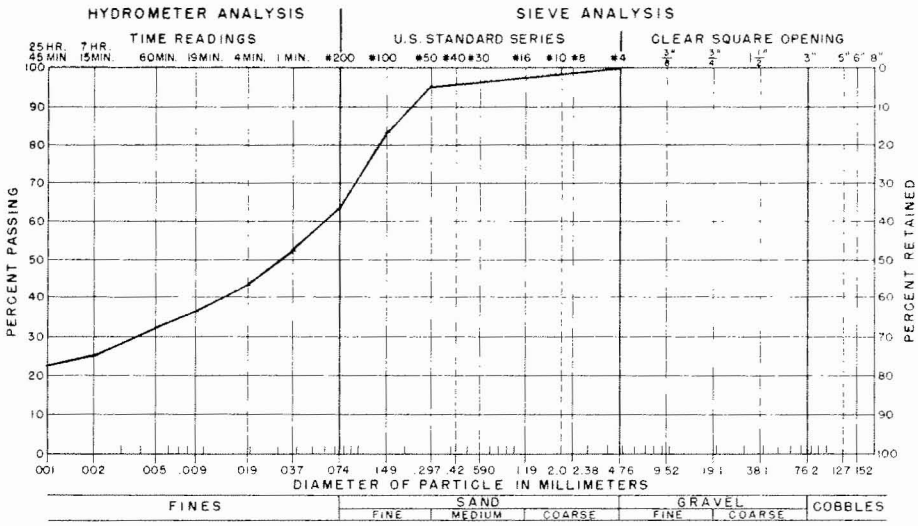
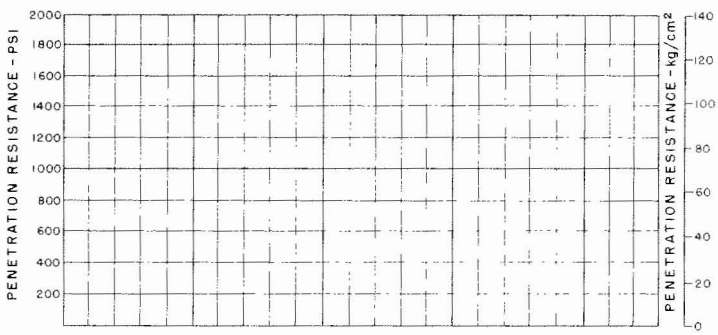

ORIGINAL SHAPE
DEFORMED SHAPES
COMPARISON
UNDER SOIL LOAD
● FA-18-7
EI/r³=21 psi
STEEL
ΔY = 5.7%
at 40 psi
(2.8 kg/cm²)
PA-18-B ▲
EI/r³ = 16 psi
RPM
ΔY = 4.5%
at 20 psi
(1.4 kg/cm²)

Figure B–35.

7-1565 (8-70)
Bureau of Reclamation

PHYSICAL PROPERTIES SUMMARY PLOT (Compaction)





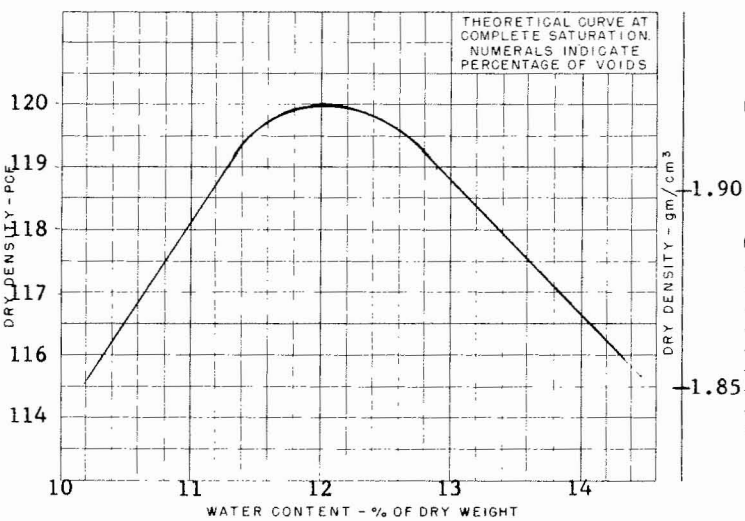
CLASSIFICATION SYMBOL CL

GRADATION SUMMARY
- GRAVEL 0 %
- SAND 36 %
- FINES 64 %

ATTERBERG LIMITS
- LIQUID LIMIT 27 %
- PLASTICITY INDEX 15
- SHRINKAGE LIMIT ____ %

SPECIFIC GRAVITY
- MINUS NO 4 2.69
- PLUS NO 4 ____
- BULK ____
- APPARENT ____
- ABSORPTION ____ %

COMPACTION
- % LARGER THAN TESTED ____
- MAX. DRY DENSITY 120.0 PCF (1.92 gm/cm²)
- OPTIMUM WATER CONT. 12 %
- PENETRATION RESISTANCE ____ PSI (____ kg/cm²)



COMPACTION - PENETRATION RESISTANCE CURVES

PERMEABILITY SETTLEMENT
- PLACEMENT CONDITION ____
- COEF OF PERMEABILITY ____ FT/YR (____ cm/sec)
- SETTLEMENT UNDER ____ PSI LOAD ____ % (____ kg/cm²)

NOTES:

tests run Nov. 1969

compaction curve based on average of 5 tests

SAMPLE NO. 24G-103 HOLE NO. ____ DEPTH ____ FT (____ m)

Figure B–36.

APPENDIX C

FAILURE CHARACTERISTICS OF RPM PIPE

INTRODUCTION

Structural failure of RPM pipe begins with a crazing of the inner liner and ends with separation of the fiberglass in the tension areas of the pipe. The inner liner of the pipes tested was a sand-rich resin layer. A fine random network of hairline cracks, called crazing, occurs in this liner in the areas on the interior of the pipe that are in tension. In pressure pipe, water could seep into these cracks and cause deterioration of the fiberglass. A typical crazing pattern is shown in Figure C–1.

Under the high surcharges in the load test with high pipe deflections, observers could hear the strands of fiberglass breaking with a sound similar to popcorn popping. Separation of the fiberglass strands could be seen on some of the pipe on the exterior in the areas that had been under tension. Figure C–2 shows a typical separation on the exterior of the pipe and Figure C–3 shows the depth of the separation through the wall thickness of one of the pipes.

INDIVIDUAL TEST PIPE PERFORMANCE

PA-18-A

Test pipe PA-18-A was a standard production pipe with a wall thickness of 0.27 inch (0.69 cm) and a Ring Stiffness Factor, EI/r^3, of about 3 psi (0.21 kg/sq cm). It deflected 45 percent vertically without any interior cracking under a 100 psi (7.03 kg/sq cm) soil surcharge load. After the test, soil over the pipe was removed in two steps, first from 4 feet (1.2 meters) of the length of the pipe and then from the remaining 2 feet (0.6 meter) of length. Between these two steps, the pipe was unrestrained over the 4-foot length, but was still deformed 45 percent where the soil remained over the pipe. A 6-inch (15-cm) long longitudinal exterior crack appeared on one side of the pipe at the transitional zone between the restrained and unrestrained portions of the pipe. The remaining 2 feet of soil was then removed. As the pipe was lifted out of the test container, the exterior cracking increased until 4-foot-long longitudinal cracks appeared on both sides of the pipe where the pipe had been unrestrained, as shown in Figure C–4.

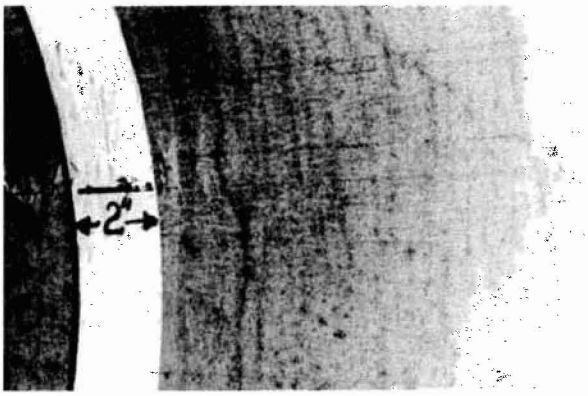


Figure C–1. Typical crazing pattern on interior surface of RPM pipe. Photo PX-D-72193

Figure C–2. Separation of fiberglass strands on exterior of RPM pipe. Photo PX-D-72185

Figure C–3. Separation of laminations in wall of RPM pipe. Photo PX-D-72194

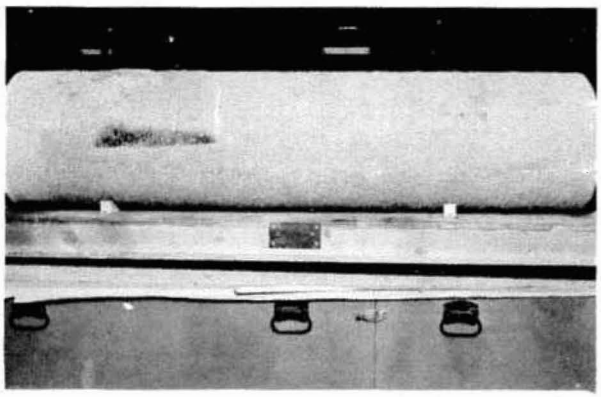


Figure C–4. Four-foot-long longitudinal exterior crack of Test Pipe PA-18-A. Photo PX-D-72179

Figure C–5 shows the unrestrained end of the pipe where the laminations of the pipe wall have separated at about half the wall thickness. These cracks were at 105° and 255° where the maximum tension occurred on the outer edge of the pipe wall.

After removal from the container, the pipe returned to 95 percent of its original diameter.

PA-18-B

This pipe was 18 inches (45.7 cm) in diameter and had a wall thickness of about 0.40 inch (1.02 cm). It was the stiffest RPM pipe tested and had a Ring Stiffness Factor of 15 to 17 psi (1.05 to 1.20 kg/sq cm). It was loaded to 80 psi (5.63 kg/sq cm) on the soil surface resulting in a deflection of 27 percent vertically. The pipe at this deflection is shown in Figure C–6. There were no interior cracks. On the exterior of the pipe,

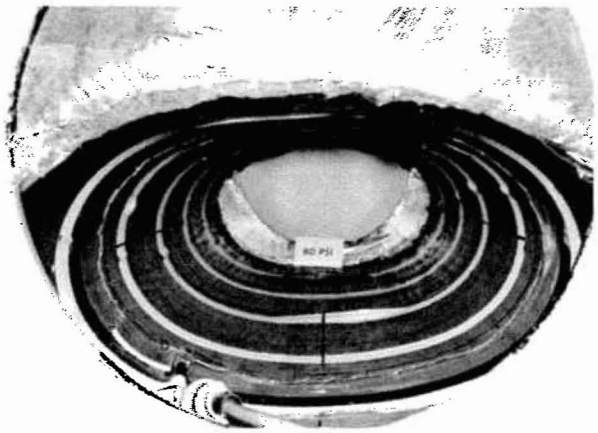


Figure C–6. Test Pipe PA-18-B with 27 percent vertical deflection. Photo PX-D-72186

separation of the fiberglass occurred at 90° for about 3 feet (0.9 meter) on one end of the pipe, as shown in Figure C–7. At 270°, separation occurred for about 10 inches (25 cm) in the center of the pipe. After removal from the soil container, the pipe returned to 96 percent of its original diameter.

PA-18-C

This pipe was the thinnest 18-inch (45.7-cm) diameter pipe tested. It had a wall thickness of about 0.23 inch (0.58 cm) with a Ring Stiffness Factor of about 2 psi (0.14 kg/sq cm). With 60 psi (4.22 kg/sq cm) on the soil surface, the pipe deflection was 36 percent vertically. When the pipe was loaded to 70 psi (4.92 kg/sq cm), a reverse curvature of the top of the pipe occurred in the center, as shown in Figure C–8. Separation of the fiberglass occurred on the interior

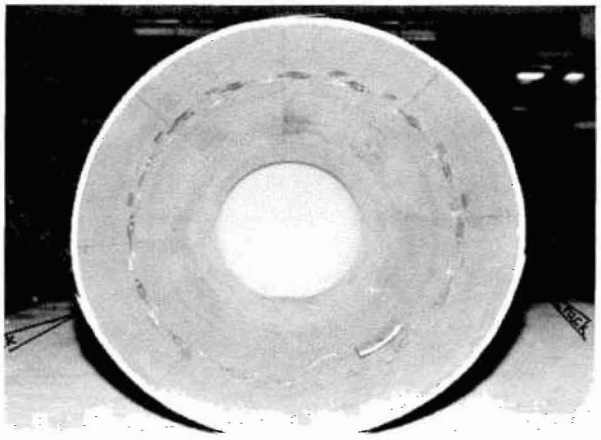


Figure C–5. Circumferential location of exterior cracks on Test Pipe PA-18-A. Photo PX-D-72180

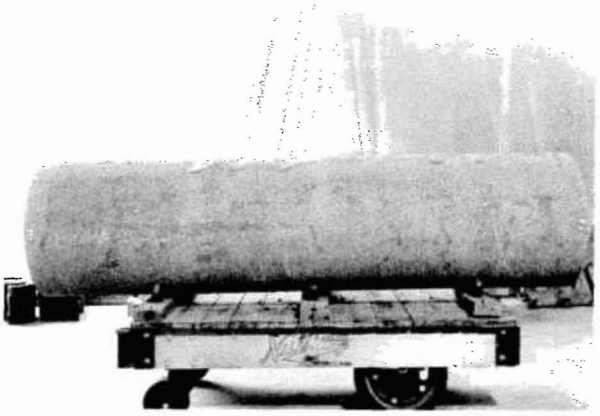


Figure C–7. Three-foot longitudinal crack at south end of Test Pipe PA-18-B at 90°. Photo PX-D-72187

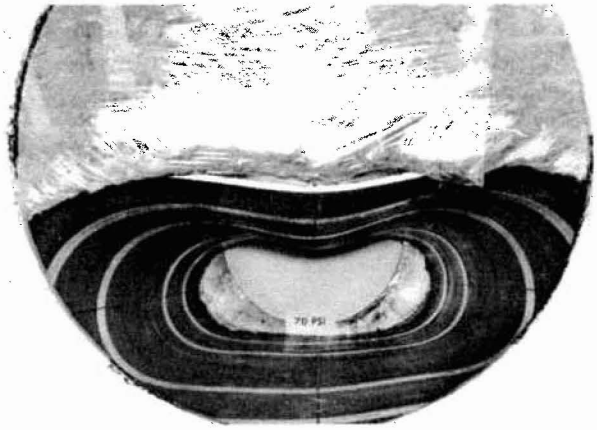


Figure C–8. Test Pipe PA-18-C showing reverse curvature at 0°. Photo PX-D-72188

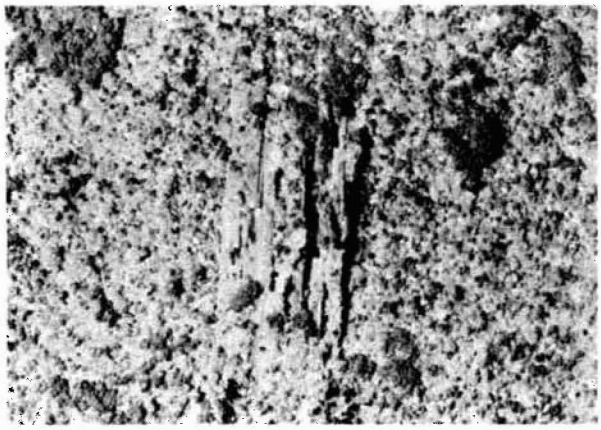


Figure C–10. Closeup of exterior cracking of Test Pipe PA-18-C. Photo PX-D-72331

and the exterior of the pipe at the top (0°). The cracking was in an intermittent pattern, with separation occurring for about 2-inch (5-cm) widths every 6 to 8 inches (15 to 20 cm). The exterior cracking pattern is shown in Figure C–9 with a closeup of the separation shown in Figure C–10.

PA-18-D

This 18-inch (45.7-cm) diameter pipe was manufactured similar to pipe PA-18-A except that the exterior sand coating was omitted from the pipe. Its wall thickness was about 0.24 inch (0.61 cm) with a Ring Stiffness Factor of 3 psi (0.21 kg/sq cm). At 90 psi (6.33 kg/sq cm) surcharge, the pipe had deflected 46 percent. As 100 psi (7.03 kg/sq cm) was being applied, reverse curvature occurred at the top of the pipe resulting in severe cracking on the interior of the pipe at 0°, as shown in Figure C–11. The cracking pattern is shown in Figures C–12 and C–13. Exterior cracking of the pipe occurred at 90° and 270° for the length of the pipe. The separation at 270° is shown in Figure C–14 and a closeup of the separation in Figure C–2.

PA-18-F

This test was of an 18-inch (45.7-cm) diameter standard production pipe by a different manufacturer than the other pipe. Its wall thickness was about 0.30 inch (0.76 cm) with a Ring Stiffness Factor of about 6 psi (0.42 kg/sq cm). As shown in Figure C–15, the vertical deflection was almost 50 percent under 100 psi (7.03 kg/sq cm) surcharge. There was a compressive crushing of the interior wall of the pipe at 110° as shown in Figure C–16. There were separations on the exterior of the pipe at 110° and 260° for the entire

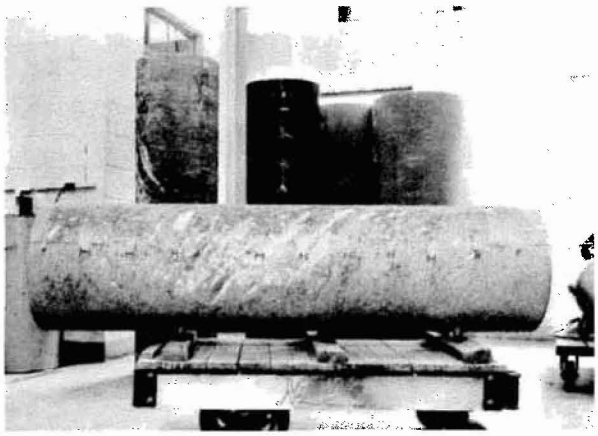


Figure C–9. Exterior cracking of Test Pipe PA-18-C. Photo PX-D-72330

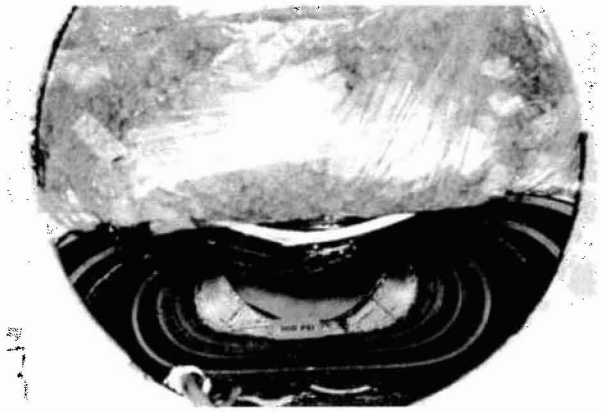


Figure C–11. Test Pipe PA-18-D showing reverse curvature at 0°. Photo PX-D-72181

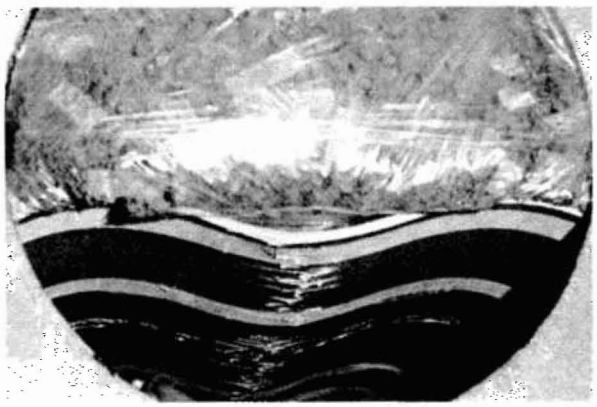


Figure C–12. Interior cracking of Test Pipe PA-18-D at 0°. Photo PX-D-72182

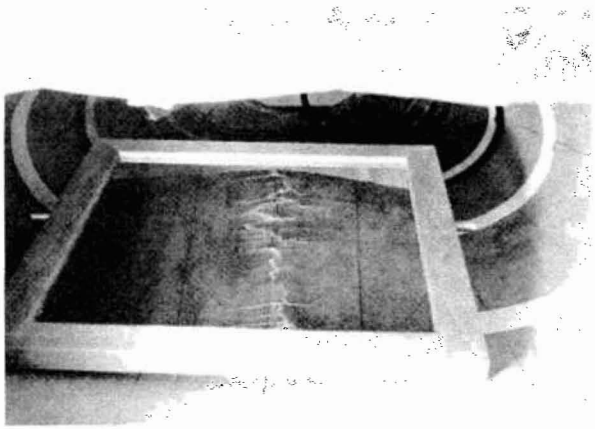


Figure C–13. Interior cracking pattern of Test Pipe PA-18-D at 0°. Photo PX-D-72183

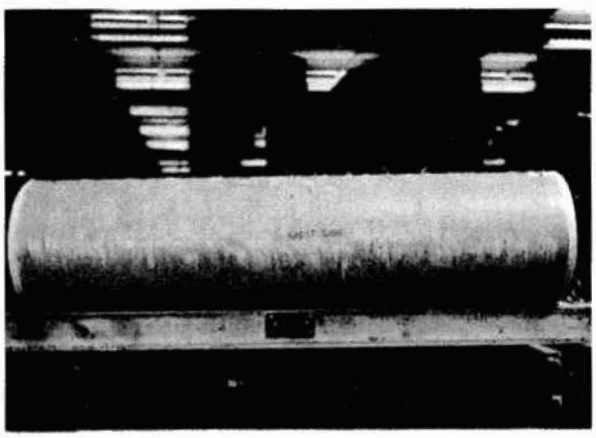


Figure C–14. Exterior longitudinal cracking of Test Pipe PA-18-D at 270°. Photo PX-D-72184

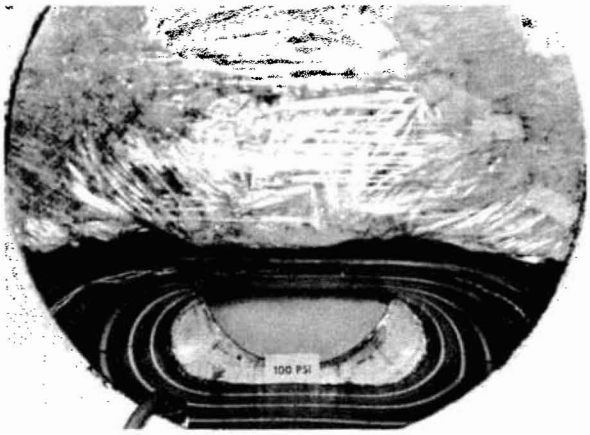


Figure C–15. Test Pipe PA-18-F with 50 percent vertical deflection. Photo PX-D-72189

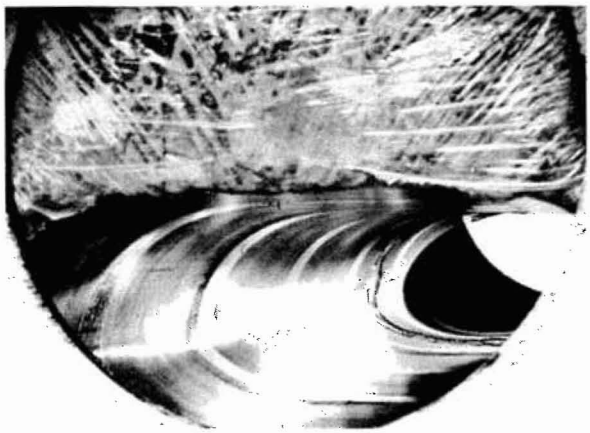


Figure C–16. Compressive crushing of interior wall of Test Pipe PA-18-F at 110°. Photo PX-D-72190

length of the pipe and about 12 inches (30 cm) of separation at 180° at one end of the pipe. Figure C–17 shows the overall separation and a closeup is shown in Figure C–18.

PA-24

This piece of 24-inch (61.0 cm) diameter RPM pipe had a wall thickness of about 0.35 inch (0.89 cm) with a Ring Stiffness Factor of 4 psi (0.28 kg/sq cm). As shown in Figure C–19, at 70 psi (4.92 kg/sq cm) surcharge the vertical deflection was 31 percent. There were no interior cracks. On the exterior, the fiberglass strands pulled loose from the pipe at 90° to 120° for about 4 inches (10 cm) on one end of the pipe, as shown in Figure C–20.

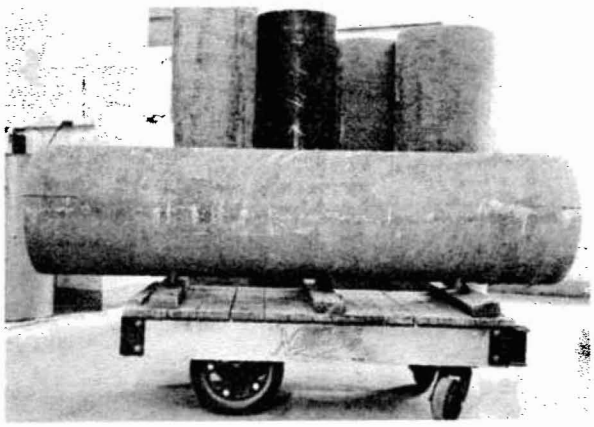


Figure C–17. Exterior cracking of Test Pipe PA-18-F at 110°. Photo PX-D-72192

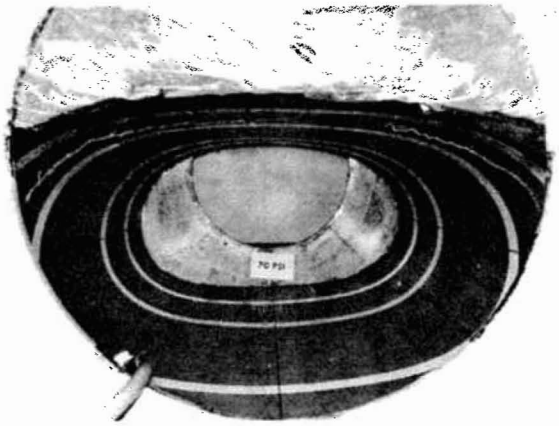


Figure C–19. Test Pipe PA-24 with 31 percent vertical deflection. Photo PX-D-72191

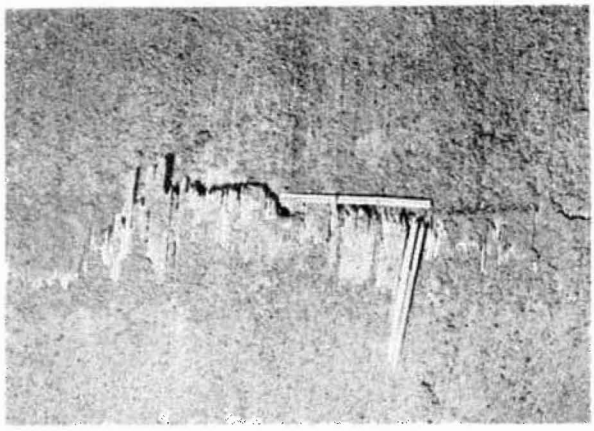


Figure C–18. Closeup of exterior cracking of Test Pipe PA-18-F. Photo PX-D-72194

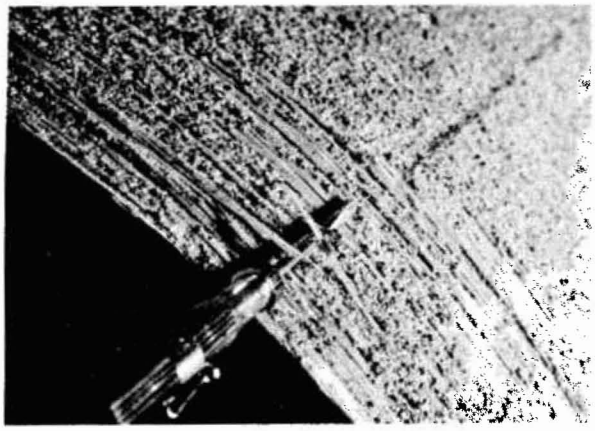


Figure C–20. Fiberglass strands pulled loose from one end of Test Pipe PA-24. Photo PX-D-72196

PB-18

This 18-inch (45.7-cm) diameter pipe was a standard production pipe with a wall thickness of 0.28 inch (0.71 cm) and a Ring Stiffness Factor of about 3 (0.21 kg/sq cm). It was backfilled with soil placed at 100 percent of Proctor maximum density. It deflected 17 percent vertically under 100-psi (7.03-kg/ sq cm) surcharge and no interior or exterior cracking was evident.

7-1750 (3-71)
Bureau of Reclamation

CONVERSION FACTORS—BRITISH TO METRIC UNITS OF MEASUREMENT

The following conversion factors adopted by the Bureau of Reclamation are those published by the American Society for Testing and Materials (ASTM Metric Practice Guide, E 380-68) except that additional factors (*) commonly used in the Bureau have been added. Further discussion of definitions of quantities and units is given in the ASTM Metric Practice Guide.

The metric units and conversion factors adopted by the ASTM are based on the "International System of Units" (designated SI for Systeme International d'Unites), fixed by the International Committee for Weights and Measures; this system is also known as the Giorgi or MKSA (meter-kilogram (mass)-second-ampere) system. This system has been adopted by the International Organization for Standardization in ISO Recommendation R-31.

The metric technical unit of force is the kilogram-force; this is the force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 9.80665 m/sec/sec, the standard acceleration of free fall toward the earth's center for sea level at 45 deg latitude. The metric unit of force in SI units is the newton (N), which is defined as that force which, when applied to a body having a mass of 1 kg, gives it an acceleration of 1 m/sec/sec. These units must be distinguished from the (inconstant) local weight of a body having a mass of 1 kg, that is, the weight of a body is that force with which a body is attracted to the earth and is equal to the mass of a body multiplied by the acceleration due to gravity. However, because it is general practice to use "pound" rather than the technically correct term "pound-force," the term "kilogram" (or derived mass unit) has been used in this guide instead of "kilogram-force" in expressing the conversion factors for forces. The newton unit of force will find increasing use, and is essential in SI units.

Where approximate or nominal English units are used to express a value or range of values, the converted metric units in parentheses are also approximate or nominal. Where precise English units are used, the converted metric units are expressed as equally significant values.

Table I

QUANTITIES AND UNITS OF SPACE

Multiply	By	To obtain
	LENGTH	
Mil	25.4 (exactly)	Micron
Inches	25.4 (exactly)	Millimeters
Inches	2.54 (exactly)*	Centimeters
Feet	30.48 (exactly)	Centimeters
Feet	0.3048 (exactly)*	Meters
Feet	0.0003048 (exactly)*	Kilometers
Yards	0.9144 (exactly)	Meters
Miles (statute)	1,609.344 (exactly)*	Meters
Miles	1.609344 (exactly)	Kilometers
	AREA	
Square inches	6.4516 (exactly)	Square centimeters
Square feet	*929.03	Square centimeters
Square feet	0.092903	Square meters
Square yards	0.836127	Square meters
Acres	*0.40469	Hectares
Acres	*4,046.9	Square meters
Acres	*0.0040469	Square kilometers
Square miles	2.58999	Square kilometers
	VOLUME	
Cubic inches	16.3871	Cubic centimeters
Cubic feet	0.0283168	Cubic meters
Cubic yards	0.764555	Cubic meters
	CAPACITY	
Fluid ounces (U.S.)	29.5737	Cubic centimeters
Fluid ounces (U.S.)	29.5729	Milliliters
Liquid pints (U.S.)	0.473179	Cubic decimeters
Liquid pints (U.S.)	0.473166	Liters
Quarts (U.S.)	*946.358	Cubic centimeters
Quarts (U.S.)	*0.946331	Liters
Gallons (U.S.)	*3,785.43	Cubic centimeters
Gallons (U.S.)	3.78543	Cubic decimeters
Gallons (U.S.)	3.78533	Liters
Gallons (U.S.)	*0.00378543	Cubic meters
Gallons (U.K.)	4.54609	Cubic decimeters
Gallons (U.K.)	4.54596	Liters
Cubic feet	28.3160	Liters
Cubic yards	*764.55	Liters
Acre-feet	*1,233.5	Cubic meters
Acre-feet	*1,233,500	Liters

Table II

QUANTITIES AND UNITS OF MECHANICS

Multiply	By	To obtain
MASS		
Grains (1/7,000 lb)	64.79891 (exactly)	Milligrams
Troy ounces (480 grains)	31.1035	Grams
Ounces (avdp)	28.3495	Grams
Pounds (avdp)	0.45359237 (exactly)	Kilograms
Short tons (2,000 lb)	907.185	Kilograms
Short tons (2,000 lb)	0.907185	Metric tons
Long tons (2,240 lb)	1,016.05	Kilograms
FORCE/AREA		
Pounds per square inch	0.070307	Kilograms per square centimeter
Pounds per square inch	0.689476	Newtons per square centimeter
Pounds per square foot	4.88243	Kilograms per square meter
Pounds per square foot	47.8803	Newtons per square meter
MASS/VOLUME (DENSITY)		
Ounces per cubic inch	1.72999	Grams per cubic centimeter
Pounds per cubic foot	16.0185	Kilograms per cubic meter
Pounds per cubic foot	0.0160185	Grams per cubic centimeter
Tons (long) per cubic yard	1.32894	Grams per cubic centimeter
MASS/CAPACITY		
Ounces per gallon (U.S.)	7.4893	Grams per liter
Ounces per gallon (U.K.)	6.2362	Grams per liter
Pounds per gallon (U.S.)	119.829	Grams per liter
Pounds per gallon (U.K.)	99.779	Grams per liter
BENDING MOMENT OR TORQUE		
Inch-pounds	0.011521	Meter-kilograms
Inch-pounds	1.12985×10^6	Centimeter-dynes
Foot-pounds	0.138255	Meter-kilograms
Foot-pounds	1.35582×10^7	Centimeter-dynes
Foot-pounds per inch	5.4431	Centimeter-kilograms per centimeter
Ounce-inches	72.008	Gram-centimeters
VELOCITY		
Feet per second	30.48 (exactly)	Centimeters per second
Feet per second	0.3048 (exactly)*	Meters per second
Feet per year	$*0.965873 \times 10^{-6}$	Centimeters per second
Miles per hour	1.609344 (exactly)	Kilometers per hour
Miles per hour	0.44704 (exactly)	Meters per second
ACCELERATION*		
Feet per second^2	*0.3048	Meters per second^2
FLOW		
Cubic feet per second (second-feet)	*0.028317	Cubic meters per second
Cubic feet per minute	0.4719	Liters per second
Gallons (U.S.) per minute	0.06309	Liters per second
FORCE*		
Pounds	*0.453592	Kilograms
Pounds	*4.4482	Newtons
Pounds	$*4.4482 \times 10^5$	Dynes

Table II—Continued

Multiply	By	To obtain
WORK AND ENERGY*		
British thermal units (Btu)	*0.252	Kilogram calories
British thermal units (Btu)	1,055.06	Joules
Btu per pound	2.326 (exactly)	Joules per gram
Foot-pounds	*1.35582	Joules
POWER		
Horsepower	745.700	Watts
Btu per hour	0.293071	Watts
Foot-pounds per second	1.35582	Watts
HEAT TRANSFER		
Btu in./hr ft^2 degree F (k, thermal conductivity)	1.442	Milliwatts/cm degree C
Btu in./hr ft^2 degree F (k, thermal conductivity)	0.1240	Kg cal/hr m degree C
Btu ft/hr ft^2 degree F	*1.4880	Kg cal m/hr m^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	0.568	Milliwatts/cm^2 degree C
Btu/hr ft^2 degree F (C, thermal conductance)	4.882	Kg cal/hr m^2 degree C
Degree F hr ft^2/Btu (R, thermal resistance)	1.761	Degree C cm^2/milliwatt
Btu/lb degree F (c, heat capacity)	4.1868	J/g degree C
Btu/lb degree F	*1.000	Cal/gram degree C
Ft^2/hr (thermal diffusivity)	0.2581	Cm^2/sec
Ft^2/hr (thermal diffusivity)	*0.09290	M^2/hr
WATER VAPOR TRANSMISSION		
Grains/hr ft^2 (water vapor transmission)	16.7	Grams/24 hr m^2
Perms (permeance)	0.659	Metric perms
Perm-inches (permeability)	1.67	Metric perm-centimeters

Table III

OTHER QUANTITIES AND UNITS

Multiply	By	To obtain
Cubic feet per square foot per day (seepage)	*304.8	Liters per square meter per day
Pound-seconds per square foot (viscosity)	*4.8824	Kilogram second per square meter
Square feet per second (viscosity)	*0.092903	Square meters per second
Fahrenheit degrees (change)*	5/9 exactly	Celsius or Kelvin degrees (change)*
Volts per mil	0.03937	Kilovolts per millimeter
Lumens per square foot (foot-candles)	10.764	Lumens per square meter
Ohm-circular mils per foot	0.001662	Ohm-square millimeters per meter
Millicuries per cubic foot	*35.3147	Millicuries per cubic meter
Milliamps per square foot	*10.7639	Milliamps per square meter
Gallons per square yard	*4.527219	Liters per square meter
Pounds per inch	*0.17858	Kilograms per centimeter

GPO 846-302

ABSTRACT

Reinforced Plastic Mortar (RPM) pipe 18 and 24 inches in diameter with different wall thicknesses was buried in a large soil container and load tested. Surcharge loads were applied to the soil surface over the pipe with a large testing machine. For each test, pipe cross sectional deflections and shape, strain on the inner surface, soil movement around the pipe, and soil pressures on the container walls were measured during a 1-day period. Six RPM pipes were tested with the surrounding lean clay backfill placed at 90 percent Proctor maximum dry density and one at 100 percent. Behavior was compared with steel pipe tested under similar conditions. Conclusions are: (1) in high density clay backfill tests (100 percent Proctor), the RPM pipe was more resistant to elastic buckling than steel pipe of similar stiffness, deflecting about the same as steel pipe of much greater stiffness. (2) In low density clay backfill tests (90 percent Proctor), the RPM pipe deflected 2 to 3 times more than steel pipe of similar stiffnesses. (3) For RPM pipe manufactured with the same fiberglass-resin ratio, the pipe deflection varied inversely with the Ring Stiffness Factor. (4) RPM pipe without exterior sand coating deflected the same as RPM pipe of similar stiffness with the coating.

ABSTRACT

Reinforced Plastic Mortar (RPM) pipe 18 and 24 inches in diameter with different wall thicknesses was buried in a large soil container and load tested. Surcharge loads were applied to the soil surface over the pipe with a large testing machine. For each test, pipe cross sectional deflections and shape, strain on the inner surface, soil movement around the pipe, and soil pressures on the container walls were measured during a 1-day period. Six RPM pipes were tested with the surrounding lean clay backfill placed at 90 percent Proctor maximum dry density and one at 100 percent. Behavior was compared with steel pipe tested under similar conditions. Conclusions are: (1) in high density clay backfill tests (100 percent Proctor), the RPM pipe was more resistant to elastic buckling than steel pipe of similar stiffness, deflecting about the same as steel pipe of much greater stiffness. (2) In low density clay backfill tests (90 percent Proctor), the RPM pipe deflected 2 to 3 times more than steel pipe of similar stiffnesses. (3) For RPM pipe manufactured with the same fiberglass-resin ratio, the pipe deflection varied inversely with the Ring Stiffness Factor. (4) RPM pipe without exterior sand coating deflected the same as RPM pipe of similar stiffness with the coating.

ABSTRACT

Reinforced Plastic Mortar (RPM) pipe 18 and 24 inches in diameter with different wall thicknesses was buried in a large soil container and load tested. Surcharge loads were applied to the soil surface over the pipe with a large testing machine. For each test, pipe cross sectional deflections and shape, strain on the inner surface, soil movement around the pipe, and soil pressures on the container walls were measured during a 1-day period. Six RPM pipes were tested with the surrounding lean clay backfill placed at 90 percent Proctor maximum dry density and one at 100 percent. Behavior was compared with steel pipe tested under similar conditions. Conclusions are: (1) in high density clay backfill tests (100 percent Proctor), the RPM pipe was more resistant to elastic buckling than steel pipe of similar stiffness, deflecting about the same as steel pipe of much greater stiffness. (2) In low density clay backfill tests (90 percent Proctor), the RPM pipe deflected 2 to 3 times more than steel pipe of similar stiffnesses. (3) For RPM pipe manufactured with the same fiberglass-resin ratio, the pipe deflection varied inversely with the Ring Stiffness Factor. (4) RPM pipe without exterior sand coating deflected the same as RPM pipe of similar stiffness with the coating.

ABSTRACT

Reinforced Plastic Mortar (RPM) pipe 18 and 24 inches in diameter with different wall thicknesses was buried in a large soil container and load tested. Surcharge loads were applied to the soil surface over the pipe with a large testing machine. For each test, pipe cross sectional deflections and shape, strain on the inner surface, soil movement around the pipe, and soil pressures on the container walls were measured during a 1-day period. Six RPM pipes were tested with the surrounding lean clay backfill placed at 90 percent Proctor maximum dry density and one at 100 percent. Behavior was compared with steel pipe tested under similar conditions. Conclusions are: (1) in high density clay backfill tests (100 percent Proctor), the RPM pipe was more resistant to elastic buckling than steel pipe of similar stiffness, deflecting about the same as steel pipe of much greater stiffness. (2) In low density clay backfill tests (90 percent Proctor), the RPM pipe deflected 2 to 3 times more than steel pipe of similar stiffnesses. (3) For RPM pipe manufactured with the same fiberglass-resin ratio, the pipe deflection varied inversely with the Ring Stiffness Factor. (4) RPM pipe without exterior sand coating deflected the same as RPM pipe of similar stiffness with the coating.

REC-ERC-72-38
Howard, A K
LABORATORY LOAD TESTS ON BURIED FLEXIBLE PIPE—PROGRESS REPORT NO. 4—REINFORCED PLASTIC MORTAR (RPM) PIPE
Bur Reclam Rep REC-ERC-72-38, Div Gen Res, Nov 1972. Bureau of Reclamation, Denver, 75p, 77 fig, 8 tab, 9 ref, 3 append

DESCRIPTORS—/ pipelines/ backfills/ soil mechanics/ loading tests/ test procedures/ cohesive soils/ pressure cells/ *buried pipes/ strain gages/ *flexible pipes/ pressure measuring instruments/ *soil pressure/ lateral forces/ pressure sensors/ steel pipes/ strain/ *deflection/ deformation/ laboratory tests/ plastics/ *plastic pipes/ polymers/ stiffness/ resins
IDENTIFIERS—/ Iowa Formula/ soil-structure interaction/ *reinforced plastic mortar pipe/ glass reinforced plastics/ deflection measurement

REC-ERC-72-38
Howard, A K
LABORATORY LOAD TESTS ON BURIED FLEXIBLE PIPE—PROGRESS REPORT NO. 4—REINFORCED PLASTIC MORTAR (RPM) PIPE
Bur Reclam Rep REC-ERC-72-38, Div Gen Res, Nov 1972. Bureau of Reclamation, Denver, 75p, 77 fig, 8 tab, 9 ref, 3 append

DESCRIPTORS—/ pipelines/ backfills/ soil mechanics/ loading tests/ test procedures/ cohesive soils/ pressure cells/ *buried pipes/ strain gages/ *flexible pipes/ pressure measuring instruments/ *soil pressure/ lateral forces/ pressure sensors/ steel pipes/ strain/ *deflection/ deformation/ laboratory tests/ plastics/ *plastic pipes/ polymers/ stiffness/ resins
IDENTIFIERS—/ Iowa Formula/ soil-structure interaction/ *reinforced plastic mortar pipe/ glass reinforced plastics/ deflection measurement

REC-ERC-72-38
Howard, A K
LABORATORY LOAD TESTS ON BURIED FLEXIBLE PIPE—PROGRESS REPORT NO. 4—REINFORCED PLASTIC MORTAR (RPM) PIPE
Bur Reclam Rep REC-ERC-72-38, Div Gen Res, Nov 1972. Bureau of Reclamation, Denver, 75p, 77 fig, 8 tab, 9 ref, 3 append

DESCRIPTORS—/ pipelines/ backfills/ soil mechanics/ loading tests/ test procedures/ cohesive soils/ pressure cells/ *buried pipes/ strain gages/ *flexible pipes/ pressure measuring instruments/ *soil pressure/ lateral forces/ pressure sensors/ steel pipes/ strain/ *deflection/ deformation/ laboratory tests/ plastics/ *plastic pipes/ polymers/ stiffness/ resins
IDENTIFIERS—/ Iowa Formula/ soil-structure interaction/ *reinforced plastic mortar pipe/ glass reinforced plastics/ deflection measurement

REC-ERC-72-38
Howard, A K
LABORATORY LOAD TESTS ON BURIED FLEXIBLE PIPE—PROGRESS REPORT NO. 4—REINFORCED PLASTIC MORTAR (RPM) PIPE
Bur Reclam Rep REC-ERC-72-38, Div Gen Res, Nov 1972. Bureau of Reclamation, Denver, 75 p, 77 fig, 8 tab, 9 ref, 3 append

DESCRIPTORS—/ pipelines/ backfills/ soil mechanics/ loading tests/ test procedures/ cohesive soils/ pressure cells/ *buried pipes/ strain gages/ *flexible pipes/ pressure measuring instruments/ *soil pressure/ lateral forces/ pressure sensors/ steel pipes/ strain/ *deflection/ deformation/ laboratory tests/ plastics/ *plastic pipes/ polymers/ stiffness/ resins
IDENTIFIERS—/ Iowa Formula/ soil-structure interaction/ *reinforced plastic mortar pipe/ glass reinforced plastics/ deflection measurement