Evaluation of Hydraulic Plate Compactor

Morgan State University
The Pennsylvania State University
University of Maryland
University of Virginia
Virginia Polytechnic Institute & State University
West Virginia University

The Pennsylvania State University
The Thomas D. Larson Pennsylvania Transportation Institute
Transportation Research Building ❖ University Park, PA 16802-4710
Phone: 814-865-1891 ❖ Fax: 814-863-3707
www.mautc.psu.edu

Evaluation of Hydraulic Plate Compactor

FINAL REPORT

December 26, 2014

By Tong Qiu
The Thomas D. Larson
Pennsylvania Transportation Institute

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

CONTRACT # 4400008014
WORK ORDER # PSU 12A

Technical Report Documentation Page

1. Report No.
FHWA-PA-2014-008-PSU WO 12A

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Evaluation of Hydraulic Plate Compactor

5. Report Date
December 26, 2014

6. Performing Organization Code

7. Author(s)
Tong Qiu, Ming Xiao, and Chaoyi Wang

8. Performing Organization Report No.
LTI 2015-12

9. Performing Organization Name and Address
The Thomas D. Larson Pennsylvania Transportation Institute
The Pennsylvania State University
201 Transportation Research Building
University Park, PA 16802

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
4400008014, PSU 12A

12. Sponsoring Agency Name and Address
The Pennsylvania Department of Transportation
Bureau of Planning and Research
Commonwealth Keystone Building
400 North Street, 6th Floor
Harrisburg, PA 17120-0064

13. Type of Report and Period Covered
Final Report: 8/26/14 – 12/26/2014

14. Sponsoring Agency Code

15. Supplementary Notes
COTR: Joseph F. Cribben, jcribben@pa.gov, 717-783-9759

16. Abstract
This report presents the results of two parallel field investigations consisting of utility trench backfill compaction tests. The field investigation at State College, Pa. was conducted to establish baseline measurements using a walk-behind vibratory roller compactor and a lift thickness of 8 inches. These baseline measurements were compared to measurements from a field investigation at Harrisburg, Pa. using a hydraulic plate compactor and varied lift thicknesses. The effects of hydraulic plate compactor use and lift thickness on the ability to consistently achieve a minimum specified standard Proctor density of trench backfill, compaction-induced downward earth pressure in the backfill zone, and compaction-induced longitudinal and hoop strains in typical pipes are discussed. A recommendation regarding the lift thickness for hydraulic plate compactors is provided.

17. Key Words
Backfill, compaction, construction, hydraulic plate compactor, lift thickness, pipes, utility trench, vibratory roller compactor

18. Distribution Statement
No restrictions. This document is available from the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	99	N/A

Form DOT F 1700.7 **(8-72)** **Reproduction of completed page authorized**

This work was sponsored by the Pennsylvania Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the Federal Highway Administration, U.S. Department of Transportation, or the Commonwealth of Pennsylvania at the time of publication. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 INTRODUCTION

1.1 Scope of Work and Objectives

Hydraulic plate compactors have been increasingly used for soil or material compaction in trenching, street repair, or site preparation. Compared to traditional compaction tools such as roller compactors, hydraulic plate compactors are advantageous for backfill compaction in utility trench, as they can be mounted on excavators and backhoes. However, uncertainty remains with regard to the maximum lift thickness to consistently achieve desired compacted dry mass density using hydraulic plate compactors. The large impulse energy and downward pressure exerted by hydraulic plate compactors also raise concerns about potential damage to utility pipes.

The objective of this research project was to assess the capability of vibratory hydraulic plate compactors for aggregate compaction in utility trench backfill. Specifically, the project aim was to investigate: (1) the maximum lift thickness to consistently achieve the minimum specified Standard Proctor Density (SPD) of trench backfill in the cover zone as per the Pennsylvania Department of Transportation (PennDOT) Publication 408 (2011.5), Section 206.3(b)1; (2) the effect of lift thickness on compaction-induced downward earth pressure in the backfill zone; and (3) the effect of lift thickness on compaction-induced longitudinal and hoop strains in typical pipes.

To achieve the research objective, two parallel field investigations consisting of backfill compaction tests were performed at the following sites:

State College Site: Test Track Facility, The Larson Institute, The Pennsylvania State University, University Park, PA 16802.
Contractor: Ameron Construction Co., Inc.

Harrisburg Site: Lower Paxton Township Public Works Facility, 5993 Locust Lane, Harrisburg, PA 17109.
Contractor: Joao & Bradley Construction Co., Inc.

Maps of the two test sites are shown in Figures 1.1 and 1.2. The purpose of the field investigation at the State College site was to establish baseline measurements using a walk-behind vibratory roller compactor in accordance with current PennDOT specifications in Publication 408/2011. These baseline measurements were compared to measurements from the field investigation at the Harrisburg site using a hydraulic plate compactor.

Three types of pipes were utilized: 450-mm (18-inch) diameter HDPE drainage pipe (flexible pipe), 150-mm (6-inch) diameter SDR-35 (PVC) sewer pipe (flexible pipe), and 450-mm (18-inch) concrete pipe (rigid pipe). These pipes represent typical flexible and rigid pipes of interest to PennDOT. The HDPE drainage pipe and PVC sewer pipe were 6 m (20 ft) long, and the concrete pipe consisted of two 2.4-m (8-ft) long sections.

Backfill materials were 2A aggregates in general accordance with Publication 408/2011 from Eastern Industries Inc. (EAF44B14) Naginey – Milroy, PA. A 50-50 blend of PennDOT 2A and

2RC materials was used so that (1) the standard Proctor compaction test could be performed on the mix to determine the moisture-density relationships according to the Pennsylvania Test Method (PTM) No. 106, and (2) the nuclear density gauge tests could be utilized to verify the compacted dry mass density according to AASHTO T 310 specifications. Figure 1.3 shows the grain size distribution curve of the mix. Based on the standard Proctor compaction test conducted by the quarry (PTM No. 106), the mix had a maximum dry density of 2.17 gram/cm^3 (135.2 pcf) and an optimum moisture content of 7.7%.

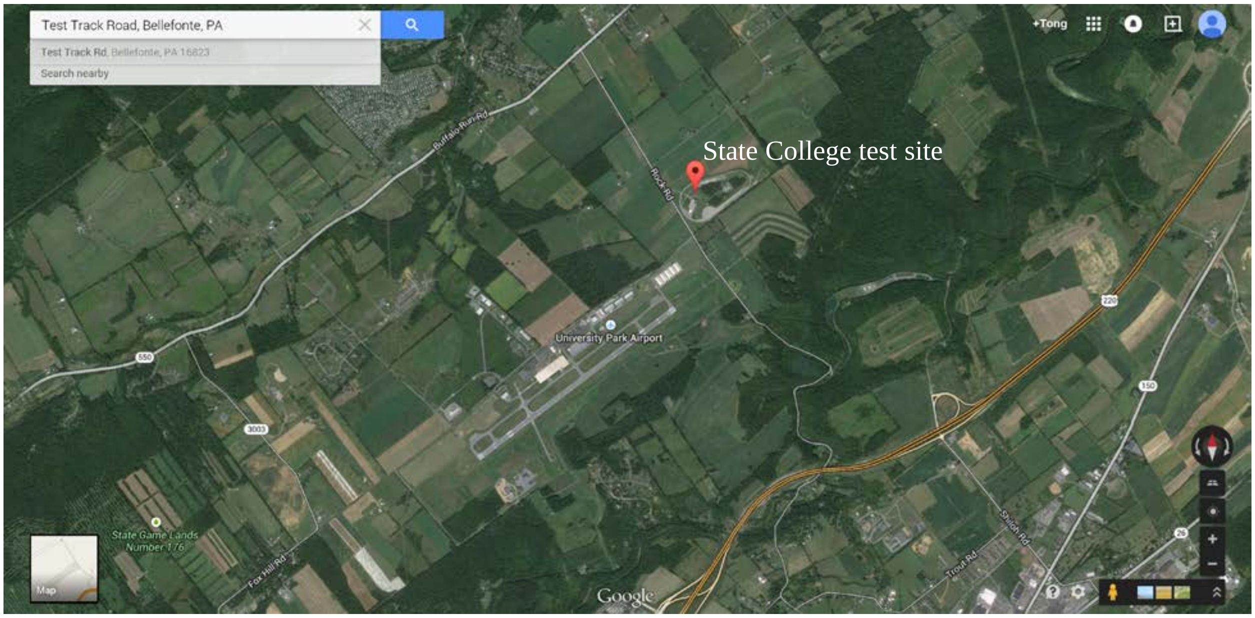

Figure 1.1 Map of State College test site

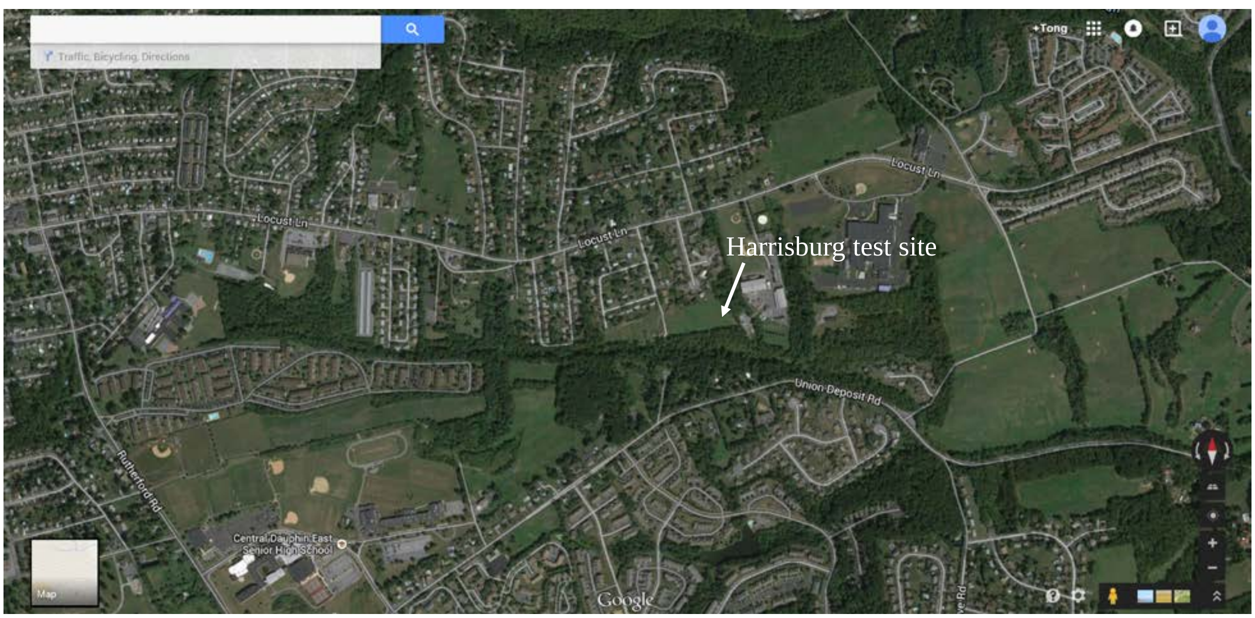

Figure 1.2 Map of Harrisburg test site

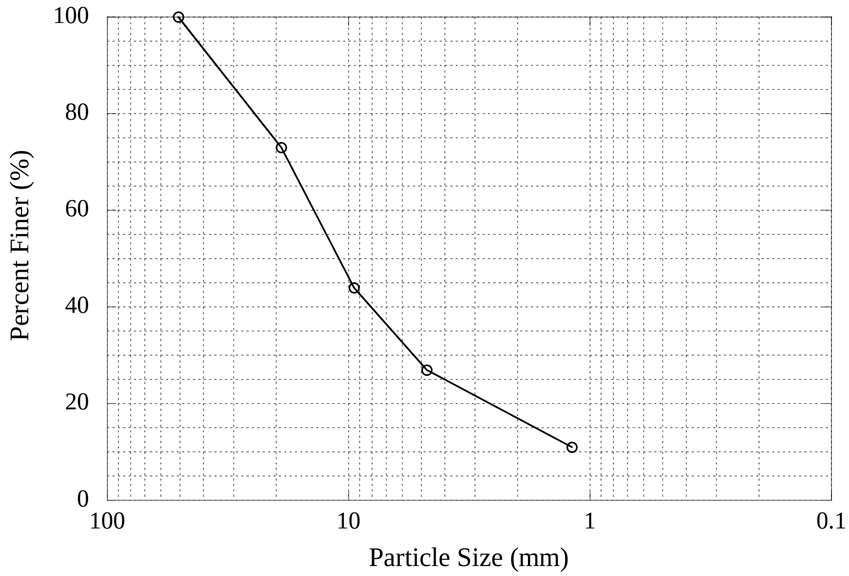

Figure 1.3 Grain size distribution of 2A aggregates

The backfill compaction tests were instrumented with dynamic earth pressure cells and strain gages to measure compaction-induced downward earth pressure in backfill and strains along pipe, respectively. A total of six 225-mm (9-inch) diameter dynamic earth pressure cells were embedded in the backfill for each pipe. These pressure cells were utilized to measure the downward earth pressure generated by compaction. Strain gages were mounted on each pipe to measure the axial strain and hoop strain developed in the pipe due to compaction. For each test, pressure cells and strain gages were instrumented at three sections along the pipe to assess repeatability of the measurements.

1.2 Organization of Report

This report consists of five chapters. Chapter 1 presents the scope of work and research objectives. Chapter 2 presents a summary of the literature review of available research data and reports concerning the use of hydraulic plate compactors currently used in highway and utility construction. The selection of hydraulic plate compactors that may best fit the needs of PennDOT is discussed. Chapter 3 presents the test procedures and data collected for the field investigation at the State College site. Chapter 4 presents the test procedures and data collected for the field investigation at the Harrisburg site. Chapter 5 presents the effects of hydraulic plate compactor and lift thickness on trench backfill compaction based on the data collected from the field investigations. A recommendation regarding the lift thickness for hydraulic plate compactors is also provided.

2 LITERATURE REVIEW

This chapter provides a summary of the literature review of available research data and reports concerning the use of hydraulic plate compactor equipment currently used in highway and utility construction. The review focuses on hydraulic plate compactors that are used for aggregate compaction in utility trench backfill construction. Factors impacting the performance of hydraulic plate compactors, including impulse force, vibration frequency, and baseplate dimensions, etc., are discussed. The selection of hydraulic plate compactors that may best fit the needs of PennDOT is discussed.

2.1 Working Theory of Hydraulic Plate Compactor

Compacting equipment compacts soil by applying one or a combination of the following types of compaction effort: static pressure, impact, vibration, and kneading. These different types of effort are found in the following two principal types of compaction forces: static and vibratory (Multiquip 2011).

S*tatic force* is often the deadweight of the machine, applying downward force on the soil surface, compressing the soil. The effective compaction force can be changed by adding to or reducing the weight of the machine. Static compaction is typically limited to soils/materials near the surface and is most effective for thin layers of non-granular materials and asphalt (Allied 2004). Kneading and static pressure are two examples of static compaction.

Vibratory force uses impact or vibration, usually engine-driven, to create a downward dynamic force in addition to the machine's static weight. The mechanism is usually a rotating eccentric weight or piston/spring combination (in rammers). Impact compaction equipment (e.g., rammers, tampers) generates a low-frequency, long-stroke motion, which can break soil "clumps" into smaller pieces and rearrange the pieces together. Impact compaction is effective for soils with less than 50% granular content (i.e., fine-grained soils). On the other hand, vibration compaction equipment generates a higher-frequency, shorter-stroke motion, resulting in stress waves propagating through the soil, setting particles in motion and rearranging them into a higher density. Vibration compaction is effective for soils with 50% or more granular content (i.e., coarse-grained soils) (Allied 2004).

Factors such as soil type, degree of compaction required, moisture content, etc., must be taken into consideration when choosing among various compactors. A comparison of the relative performance of typical compaction equipment for different soil types is presented in Table 2.1. Table 2.1 indicates that vibration is effective in densifying granular soils (e.g., sand and gravel). In addition, vibratory compaction can work in materials with some cohesion (Selig and Yoo 1977). When vibration is added to a static component, compaction is significantly increased, as shown in Figure 2.1. For soils compacted on the dry side of optimum, adding the dynamic component results in increased density (Holtz and Kovacs 1981).

Table 2.1 Relative performance of typical compaction equipment for different soil types (after Multiquip 2011)

Soil Types	Vibrating Sheepsfoot Rammer	Static Sheepsfoot Grid Roller Scraper	Vibrating Plate Compactor Vibrating Roller Vibrating Sheepsfoot	Scraper Rubber-tired Roller Loader Grid Roller
	Impact	Static Pressure with kneading	Vibration	Kneading with static pressure
Gravel	Poor	Not used	Good	Very good
Sand	Poor	Not used	Excellent	Good
Silt	Good	Good	Poor	Excellent
Clay	Excellent	Very Good	Not used	Good

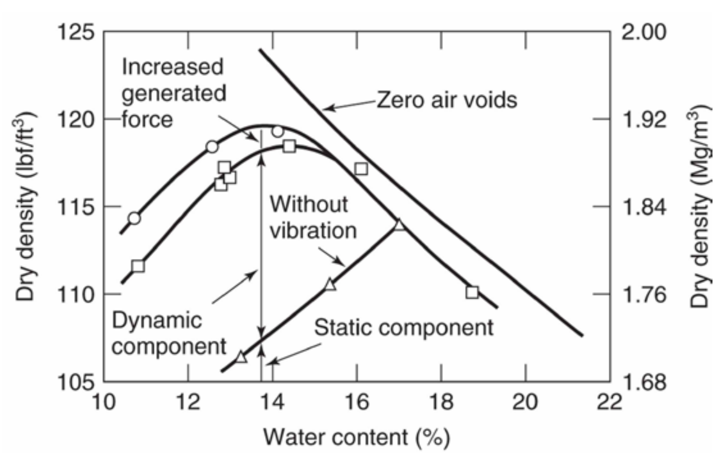

Figure 2.1 Compaction results on 30-cm (12-inch) layers of silty sand, with and without vibration, using a 7,700-kg (17,000-lb) towed vibratory roller (after Parsons et al. 1962, as cited by Selig and Yoo 1977)

Hydraulic plate compactors utilize a combination of static pressure and vibration to compact granular soils. The static pressure is applied by the hydraulic system and extended arm of the carrier (e.g., excavator); the vibration and impulse energy are applied using eccentric weight rotating at a high rpm (revolutions per minute) rate. The rate and density of compaction depend on factors such as moisture content of the soil, condition of the compactor and carrier, and the skill of the operator. The following factors are discussed.

Vibration Frequency: The effect of vibration frequency on compaction by smooth-drum vibratory rollers for different soils is shown in Figure 2.2. Figure 2.2 indicates that a peak in the density-frequency curve develops for most soils, including clays. The frequency at which a maximum density is achieved is called the optimum frequency (or resonant frequency), which is a function of the compactor-soil system, and it changes as the density increases during the process of compaction (Converse 1952; Holtz and Kovacs 1981). Granular soil particles (e.g., sand and gravel) respond differently to different vibration frequencies depending on particle size. The smaller the particle, the higher the frequency necessary to move/excite it. For compacting soils consisting of large particles, moving up to a larger compactor with a lower frequency and higher vibration force may be advantageous. Therefore, it is desirable for a compactor to have the capability to vary its operating frequency and have the range required to obtain maximum density. However, the peaks are gentle, as shown in Figure 2.2, and a wide frequency range may not be important (Holtz and Kovacs 1981). For utility trench backfill, 2A aggregates (sandy gravel) are used according to PennDOT Publication 408/2011. Figure 2.2 suggests that vibration frequencies at about 2,000 cpm (cycles per minute) are effective for compacting this material.

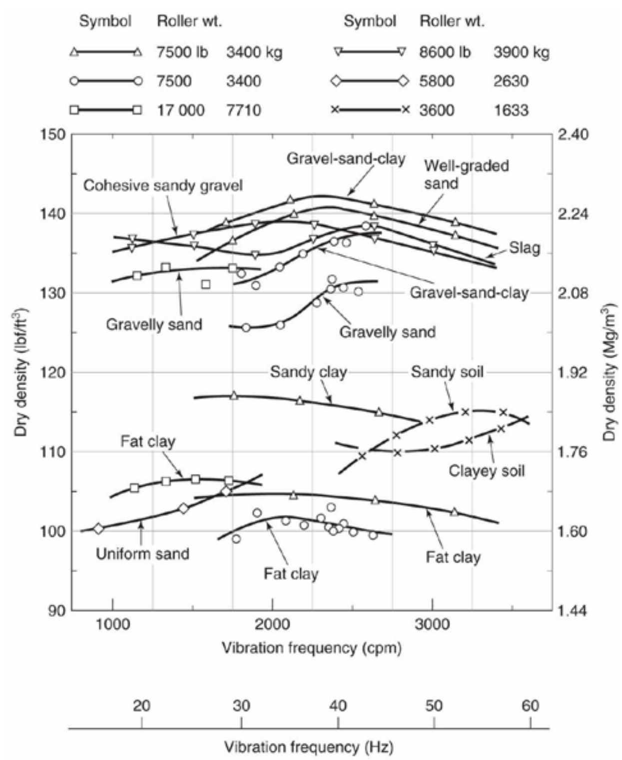

Figure 2.2 Effect of vibration frequency on compaction by smooth-drum vibratory rollers (after several sources as cited by Selig and Yoo 1977)

For hydraulic plate compactors, the vibration frequency is controlled by the hydraulic flow input to the compactor. A higher flow rate results in a higher vibration frequency but does not necessarily improve performance; on the contrary, it may result in fluid overheating, and contributes to early bearing failure.

Impulse Force and Downward Pressure: The impulse force is proportional to the product of eccentric mass and eccentric distance for a given vibration frequency. An increase in impulse force and downward pressure results in higher compaction energy delivered to the soil and a greater effective compaction depth; however, fines content, location of ground water, the presence of a hard underlying layer that reflects vibrations, and other factors can all have a significant impact on the maximum depth and effectiveness of densification (Whetten and Weaver 1991).

Baseplate Dimensions: An increase in baseplate dimensions results in a greater effective compaction depth. Some field compaction tests have indicated that excellent compacted dry densities were obtained to depths of 1.5 times the width of the surface plate (e.g., Converse 1952). For utility trench backfill, the closer the width of the baseplate is to the width of the trench, the higher the delivered compactive effort due to the effect of confinement from the trench. Adjacent compacted sections should overlap slightly; excessive overlap may loosen the soil previously compacted.

2.2 Specifications of Common Models of Hydraulic Plate Compactors

Table 2.2 presents specifications of common models of hydraulic plate compactors from major manufacturers. Table 2.2 indicates that most models come with a fixed vibration frequency at about 2,000 cpm, which is effective for compacting granular materials including 2A aggregates (see Figure 2.2). Several manufacturers offer adjustable vibration frequencies in their models (e.g., Tramac by Montabert, Astec - Breaker Technology, Inc.). As previously discussed, the advantage of adjustable vibration frequency may not be important for compacting 2A aggregate materials.

Table 2.2 Specifications of Common Models of Hydraulic Plate Compactors

Specifications	**Allied Construction Products, LLC**				
	300B	500B	1000B	1600B	2300B
Impulse Force (lb)	3,000	5,000	8,000	16,000	24,000
CPM	2,000	2,000	2,000	2,100	2,100
Baseplate Dimensions (in)	12×22	13×27	24×28	29×32	34×36
Weight (lb)	162	162	200	320	N/A

Source: Allied (2014)

Specifications	**Astec – Breaker Technology, Inc.**				
	TC51	TC71	TC92	TC152	TC301
Impulse Force (lb)	1,930 – 3,000	2,600 – 5,000	5,500 – 8,200	11,130 – 16,630	16,330 – 24,400
CPM	1,800 – 2,240	1,800 – 2,500	1,800 – 2,200	1,800 – 2,200	1,800 – 2,200
Baseplate Dimensions (in)	12.5×28	15×31.5	23×34.9	28×45.7	34×48.4
Weight (lb)	295	610	1130	1820	2150

Source: Rock Breaker (2014)

Specifications	**Caterpillar**			
	CVP16	CVP40	CVP75	CVP110
Impulse Force (lb)	3,650	8,928	16,508	24,669
CPM	2,200	2,200	2,200	2,200
Baseplate Dimensions (in)	12×24	23×38	29×43	34×47
Weight (lb)	474	884	1,765	2,319

Source: CAT (2014)

Specifications	Furukawa Rock Drill				
	HP35ME	HP65II	HP75	HP135II	HP210II
Impulse Force (lb)	3,000	6,500	7,800	13,500	21,000
CPM	2,000	2,000	2,000	2,000	2,000
Baseplate Dimensions (in)	12×26	24×34	24×34	28×40	34×46
Weight (lb)	350	850	850	1,335 – 1,770	2,150 – 2,730

Source: FRD (2014)

Specifications	Hudco Manufacturing, Inc.						
	HC-10	HC-12	HC-15	HC-20	HC-30	HC-40	HC-50
Impulse Force (lb)	3,000	3,500	5,000	6,500	13,500	20,000	22,000
CPM	2,100	2,100	2,100	2,000	2,000	2,000	2,100
Baseplate Dimensions (in)	12×30	12×31	16×36	24×34	29×40	34×47	34×47
Weight (lb)	280	350	700	900	1,600	2,600	2,600

Source: Hudco (2014)

Specifications	Kenco					
	KC-12	KC-15	KC-20	KC-30	KC-40	KC-50
Impulse Force (lb)	3,500	5,000	6,500	13,500	20,000	22,000
CPM	2,100	2,100	2,000	2,000	2,000	2,100
Baseplate Dimensions (in)	12×31	16×36	24×34	29×40	34×47	34×47
Weight (lb)	350	700	900	1,600	2,600	2,600

Source: Kenco (2014)

Specifications	Stanley Black & Decker, Inc.			
	HSX3	HSX6	HSX11	HSX22
Impulse Force (lb)	3,400	6,400	11,350	22,000
CPM	2,100	2,000	2,000	2,100
Baseplate Dimensions (in)	19×20	24×26	27×30	32×42
Weight (lb)	370	850	1,425	2,200

Source: Stanley (2014)

Specifications	Tramac by Montabert				
	TR-6	TR-9	TR-14	TR-21	TR-40TM
Impulse Force (lb)	1,800 – 3,200	3,800 - 7000	7,000 – 14,500	15,000 – 21,500	21,000 – 40,000
CPM	2,600 – 3,740	1,800 – 2,600	1,800 – 2,600	2,000 – 2,300	1,500 – 2,100
Baseplate Dimensions (in)	12×18	23×31	23×35	23.5×41	35×41
Weight (lb)	250	715	850	1,500	2,500

Source: Tramac (2014)

2.3 Selection of Hydraulic Plate Compactors

The hydraulic plate compactor should be selected properly for the carrier on which it is mounted and the compaction work it needs to perform. For utility trench backfill with 2A aggregate materials, most compactor models can provide good compaction if proper lift thickness is used. If the lift is too thick, it will either take a long compaction time to reach the desired level of compaction, or the desired level will be unattainable. If the lift is too thin, soil may be over-compacted, thereby wasting time, causing “cracking” of the compacted layers, and creating unnecessary wear on the compaction equipment as excessive impact force is transferred back into the compactor (Allied 2004). Generally speaking, compactors with higher impulse energy can use a higher lift of materials to achieve the same compacted dry density, which increases productivity. However, higher impulse energy and downward pressure may potentially damage utility pipes beneath the soil being compacted, particularly during the compaction of the first lift above the pipe at the crown (Demartini et al. 1997; Kararam 2004). It may be necessary to try different lift heights to determine the most effective lift to achieve the desired level of compaction and productivity. An instrumented field study is hence warranted to investigate the effect of lift thickness on the level of compaction attained and compaction-induced downward pressure in compacted fill and strains developed in utility pipes.

Generally speaking, the amount of impulse force necessary to achieve desired compaction depends on soil particle size. For compacting soils consisting of large particles, moving up to a larger compactor with a higher impulse force may be advantageous. For 2A aggregates (sandy gravel) used in utility trench backfill, a large percentage of the mixture has particle sizes between 50 mm and 4.75 mm (#4 sieve). For this range of particle sizes, a moderate level of impulse force is necessary for effective compaction. Therefore, hydraulic plate compactors with mid-range impulse forces may be desirable. The top three hydraulic plate compactors that may best fit the needs of PennDOT are considered to be: Model 1000B from Allied Construction Products LLC, Model CVP40 from Caterpillar, and Model KC-20 from Kenco (see Table 2.2).

3 TRENCH BACKFILL COMPACTION TESTS AT STATE COLLEGE

Four trench backfill compaction tests were conducted at State College between November 4, 2014 and November 6, 2014. These four tests are listed in Table 3.1. The compaction tests were instrumented with dynamic earth pressure cells and strain gages to measure compaction-induced downward earth pressure in backfill and strains in pipe, respectively. This chapter documents the test procedures and data collected. Analyses of the test data are also provided.

Table 3.1 Four compaction tests at State College

Test	Pipe	Lift Thickness (inch)	Test Date
SC-1	6 inch diameter SDR-35 pipe in 2B stone	8	November 4, 2014
SC-2	6 inch diameter SDR-35 pipe in 2A aggregates	8	November 4, 2014
SC-3	18 inch reinforced concrete pipe	8	November 5, 2014
SC-4	18 inch diameter HDPE drainage pipe	8	November 6, 2014

3.1 Test SC-1: 6-inch Diameter SDR-35 Pipe in 2B Stone

Figure 3.1 shows the cross-sectional view of trench and instrumentation for the 6-inch diameter SDR-35 pipe in 2B stone. Figure 3.2 shows a detailed view of instrumentation, including the pressure cells and strain gages. Figure 3.3 presents a photo showing a fully instrumented SDR-35 pipe. To avoid damage to wires during compaction, wires were taped along the pipe and collected at one end of the pipe, as shown in Figure 3.3. Figure 3.4 presents a photo showing placement of a pressure cell that was 6 inches above pipe. To avoid rough contact between the pressure cell and 2B stone and for more reliable earth pressure measurement, a thin layer (less than 1 inch) of the finer fraction of excavated soil was used as a seating material (i.e., cushion) between the pressure cell and 2B stone, as shown in Figure 3.4. A similar procedure was followed for placement of pressure cells for all trench backfill tests at the State College and Harrisburg sites. Backfill procedures for the backfill zone and cover zone are summarized below.

Backfill Zone:
1) Set 6 inch 2B stone bedding, no compaction
2) Lay pipe
3) Add 3 inch 2B stone, no compaction, lay three pressure cells on side of pipe
4) Add 9 inch 2B stone, no compaction, lay three pressure cells on top of pipe
5) Add 6 inch 2B stone (reach top of backfill zone), compact using a small tamper (no density measurement)

Cover Zone:
6) 8 inches/lift, 6 lifts total
7) Nuclear density gauge testing after compaction of each lift, two density measurements per lift at approximately 4 ft from each end of pipe (i.e., above Sections 1 and 3, see Figure 3.2)

Figure 3.5 presents photos showing various stages of the field test. Table 3.2 presents results of nuclear density gauge tests for all six lifts. Figure 3.6 shows the downward earth pressure versus time recorded by the embedded pressure cells. Figure 3.7 shows the strains along pipe versus time recorded by the mounted strain gages.

Table 3.2 Results of nuclear density gauge tests for SC-1 (SDR-35 pipe in 2B stone)

Lifts	Location 1 (Above Section #1)		Location 2 (Above Section #3)	
	Relative Density	Moisture Content	Relative Density	Moisture Content
1 (Bottom)	99.0%	7.0%	No measurements were taken	
2	101.2%	7.6%	103.7%	7.3%
3	102.1%	6.2%	102.9%	6.5%
4	101.5%	7.1%	102.6%	5.8%
5	104.8%	4.1%	101.7%	6.5%
6 (Top)	101.1%	4.7%	104.1%	6.0%

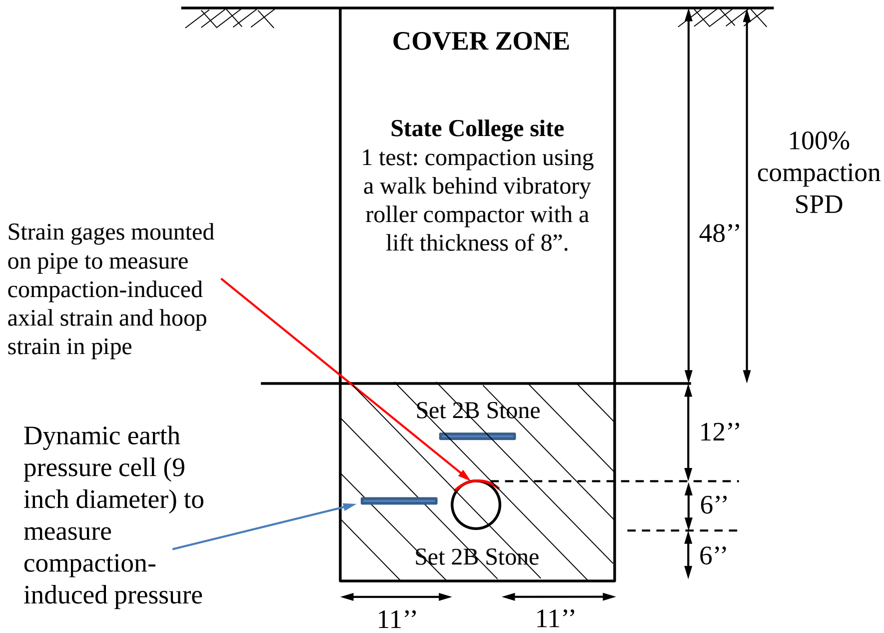

Figure 3.1 Cross-sectional view of trench and instrumentation for 6-inch diameter SDR-35 pipe in 2B stone (not to scale)

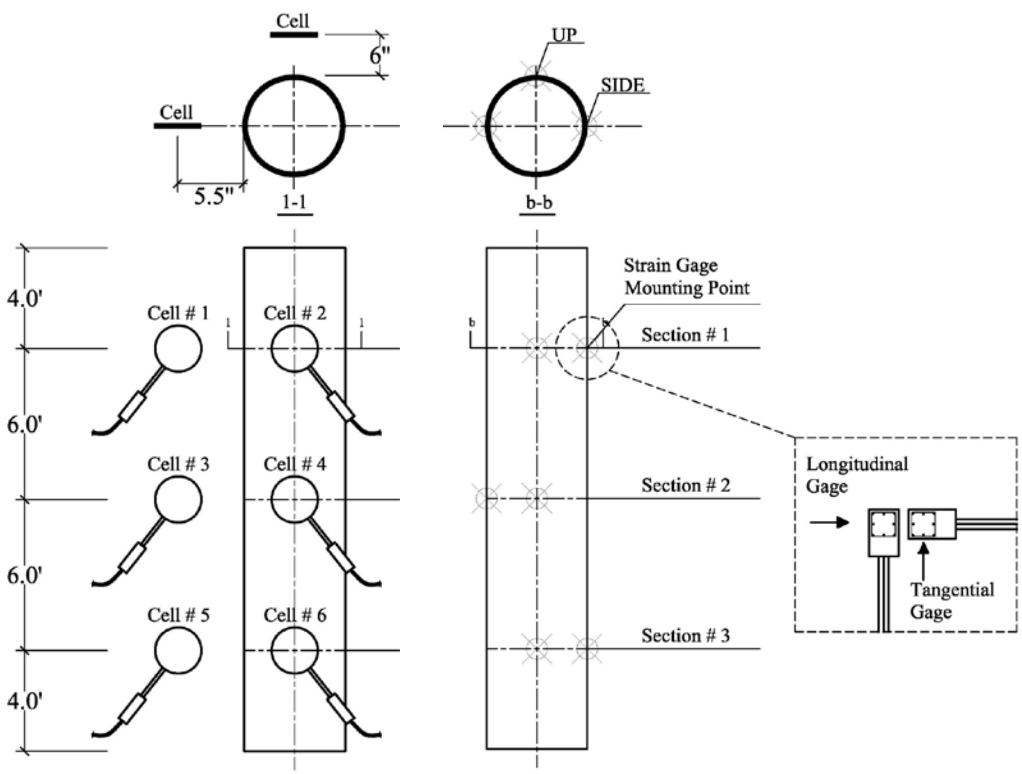

Figure 3.2 Detailed view of instrumentation for 6-inch diameter SDR-35 pipe in 2B stone (not to scale)

Figure 3.3 A photo showing a fully instrumented 6-inch diameter SDR-35 pipe prior to placement

Figure 3.4 A photo showing placement of a pressure cell 6 inches above pipe

Figure 3.5 Photos showing various stages of field testing: a) a fully excavated trench; b) laying instrumented pipe on 2B stone; c) placement of pressure cells on side along mid elevation of pipe; d) compaction using a small tamper at top of backfill zone; e) compaction using a walk-behind vibratory roller compactor in cover zone; f) nuclear density gauge testing after compaction of a lift; g) compaction at top of trench after last lift; h) excavation of compacted fill to retrieve pressure cells

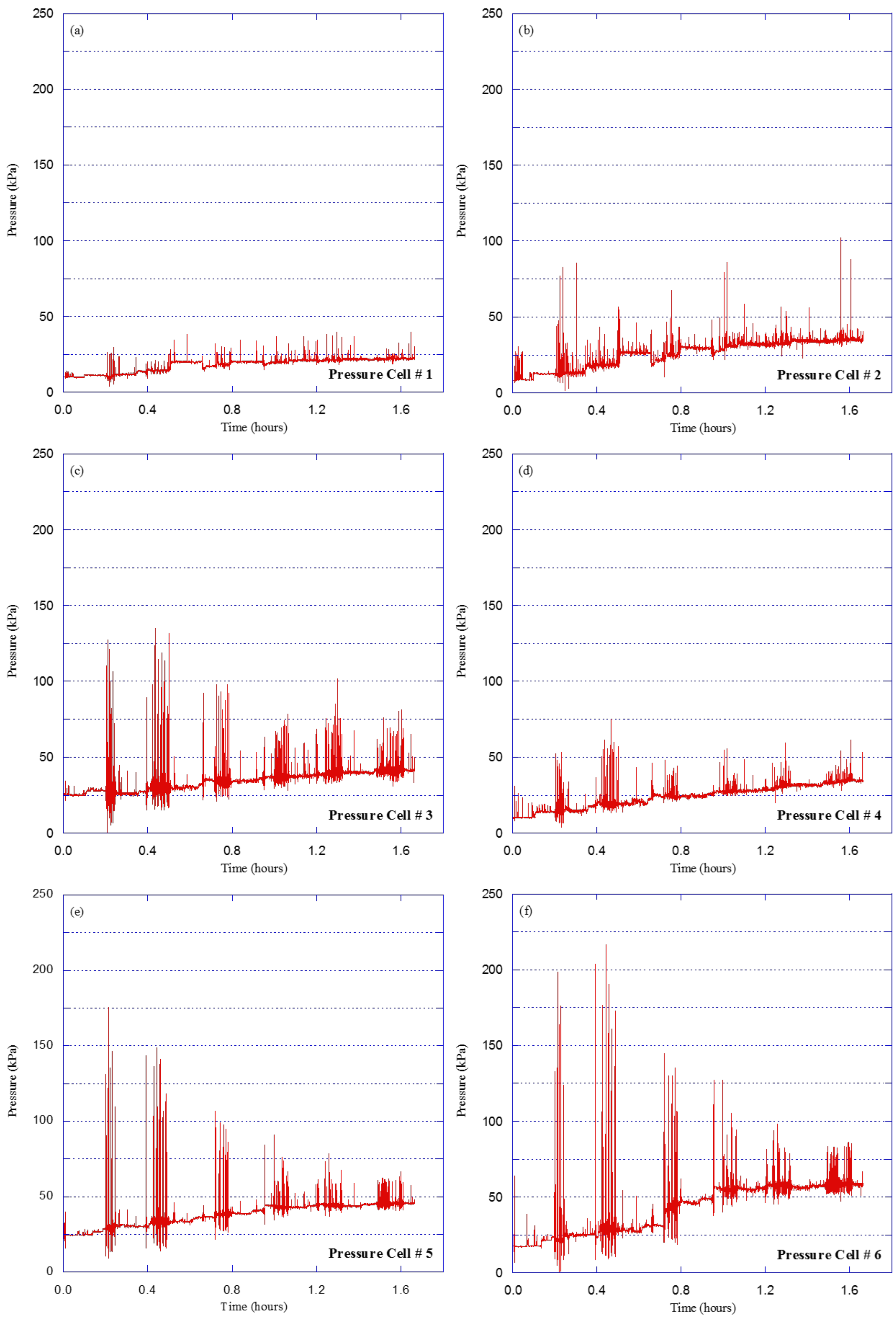

Figure 3.6 Downward earth pressures versus time for Test SC-1 (SDR-35 pipe in 2B stone)

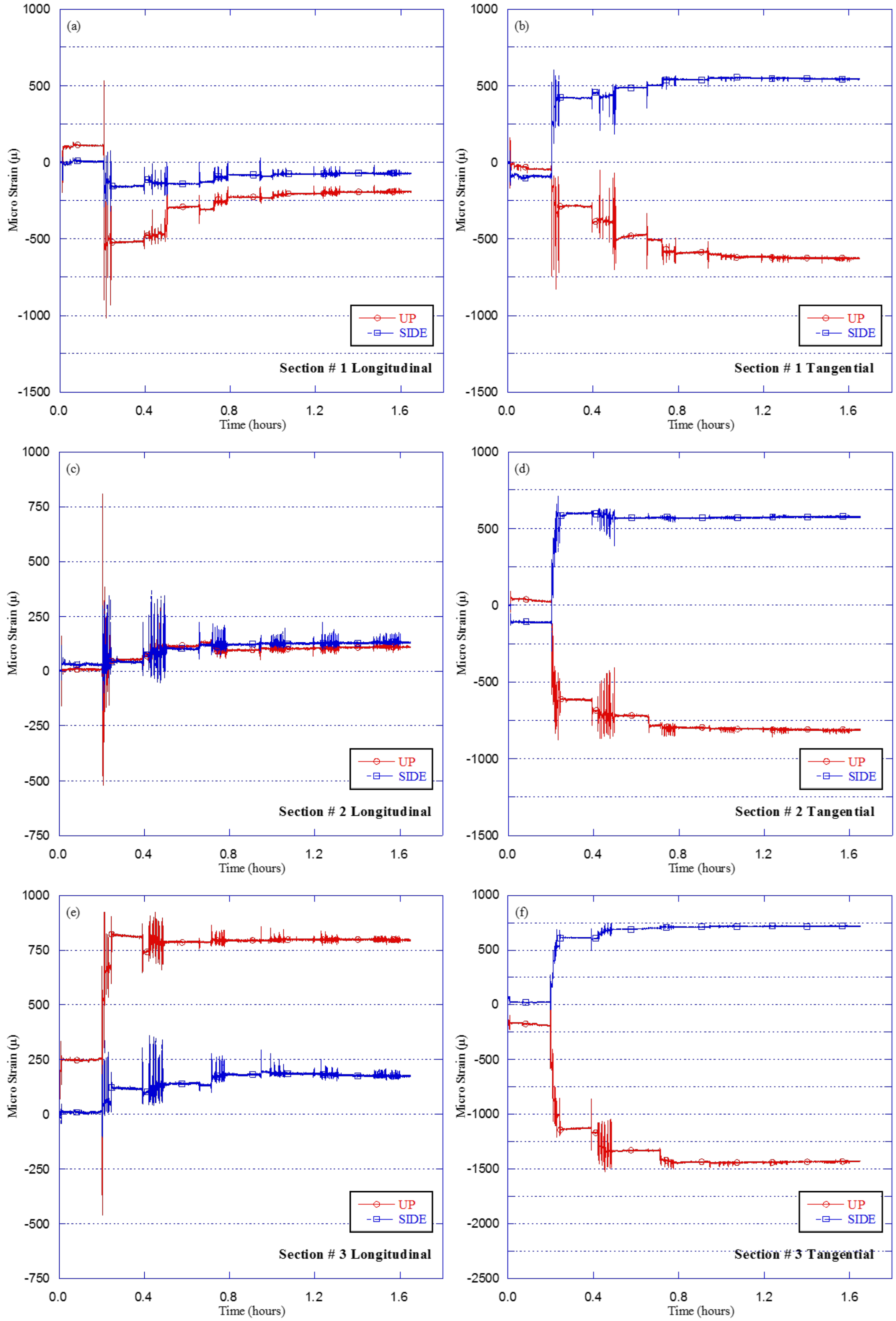

Figure 3.7 Strains along pipe versus time for Test SC-1 (SDR-35 pipe in 2B stone)

3.2 Test SC-2: 6-inch Diameter SDR-35 Pipe in 2A Aggregates

Figure 3.8 shows the cross-sectional view of trench and instrumentation for the 6-inch diameter SDR-35 pipe in 2A aggregates. Figure 3.9 shows a detailed view of instrumentation, including the pressure cells and strain gages. Backfill procedures for the backfill zone and cover zone are summarized below.

Backfill Zone:
1) Set 6 inch 2B stone bedding, no compaction
2) Lay pipe
3) Add 3 inch 2A aggregates, no compaction, lay three pressure cells on side of pipe
4) Add 9 inch 2A aggregates, compact using a small tamper, lay three pressure cells on top of pipe, conduct nuclear density gage test at middle section of trench (relative density 97.5%, moisture content 5.7%)
5) Add 6 inch 2A aggregates (reach top of backfill zone), compact using a small tamper, conduct nuclear density gage test at middle section of trench (relative density 98.3%, moisture content 5.2%)

Cover Zone:
6) 8 inches/lift, 6 lifts total
7) Nuclear density gauge testing after compaction of each lift, two density measurements per lift at approximately 4 feet from each end of pipe (i.e., above Sections 1 and 3, see Figure 3.9)

Figure 3.10 presents photos showing various stages of the field test. Table 3.3 presents results of nuclear density gauge tests for all 6 lifts. Figure 3.11 shows the downward earth pressure versus time recorded by the embedded pressure cells. Figure 3.12 shows the strains along pipe versus time recorded by the mounted strain gages.

Table 3.3 Results of Nuclear Density Gauge Tests for Test SC-2 (SDR-35 Pipe in 2A Aggregates)

Lifts	Location 1 (Above Section #1)		Location 2 (Above Section #3)	
	Relative Density	Moisture Content	Relative Density	Moisture Content
1 (Bottom)	102.6%	5.2%	101.2%	3.8%
2	101.7%	4.7%	102.2%	4.2%
3	100.4%	4.0%	103.2%	4.2%
4	N/A*		102.7%	7.0%
5	102.5%	6.4%	101.6%	6.6%
6 (Top)	100.2%	5.2%	101.9%	5.1%

*Only compacted 4 inches at this end of trench to even the bottom of entire trench (no nuclear density gauge measurements were taken at this location).

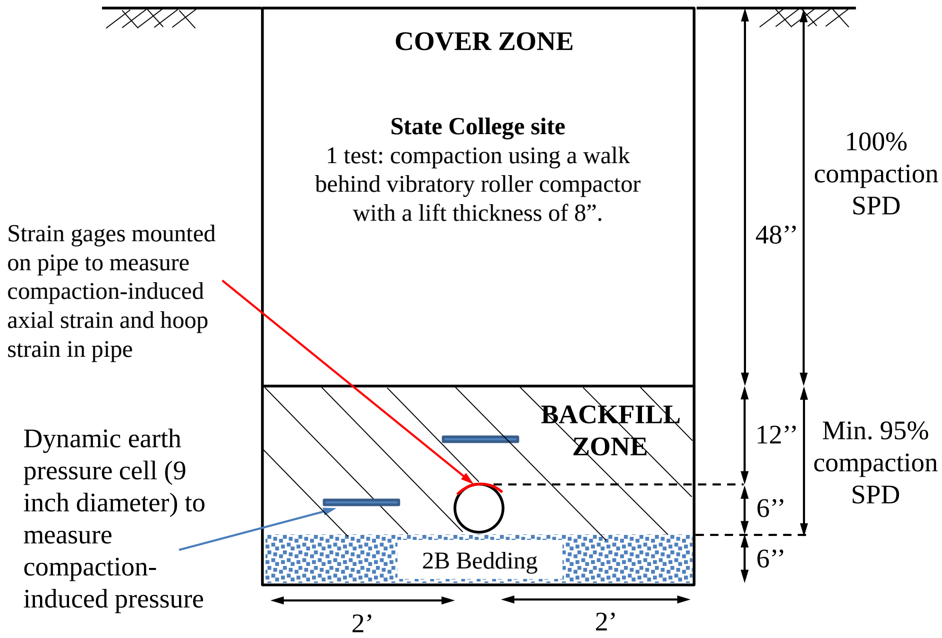

Figure 3.8 Cross-sectional view of trench and instrumentation for 6-inch diameter SDR-35 pipe in 2A aggregates (not to scale)

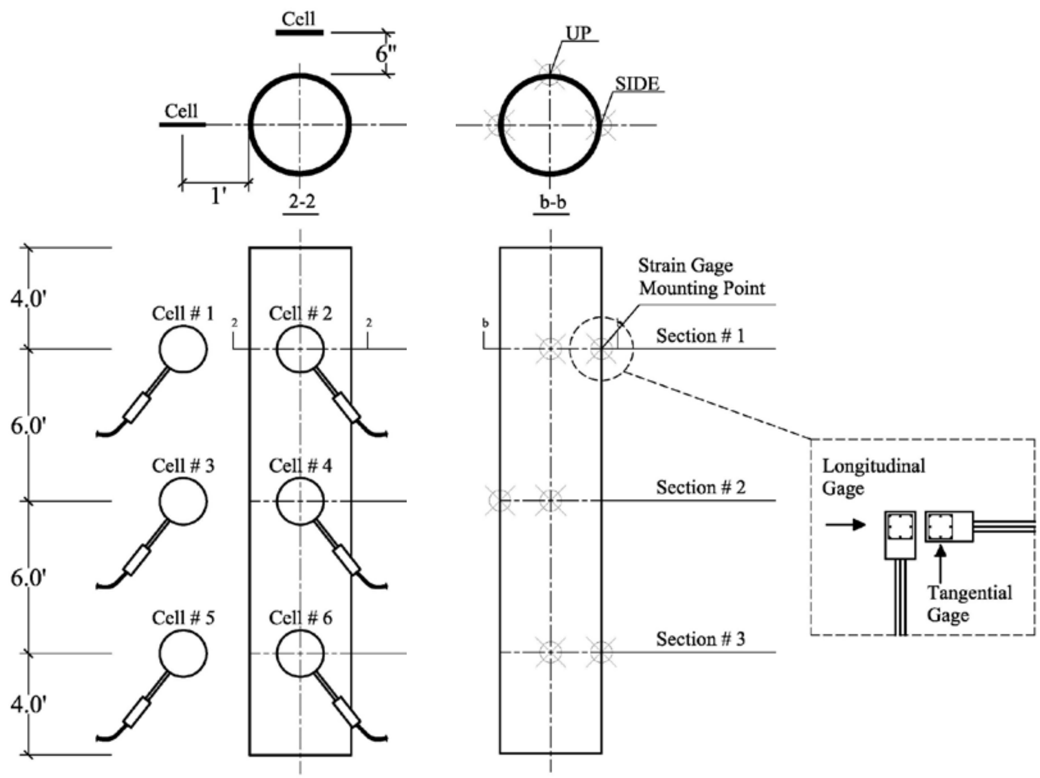

Figure 3.9 Detailed view of instrumentation for 6-inch diameter SDR-35 pipe in 2A aggregates (not to scale)

Figure 3.10 Photos showing various stages of field test: a) add 2A aggregates to mid elevation of pipe; b) placement of pressure cells on side along mid elevation of pipe; c) compaction using a small tamper at top of backfill zone; d) compaction using a walk-behind vibratory roller compactor in cover zone

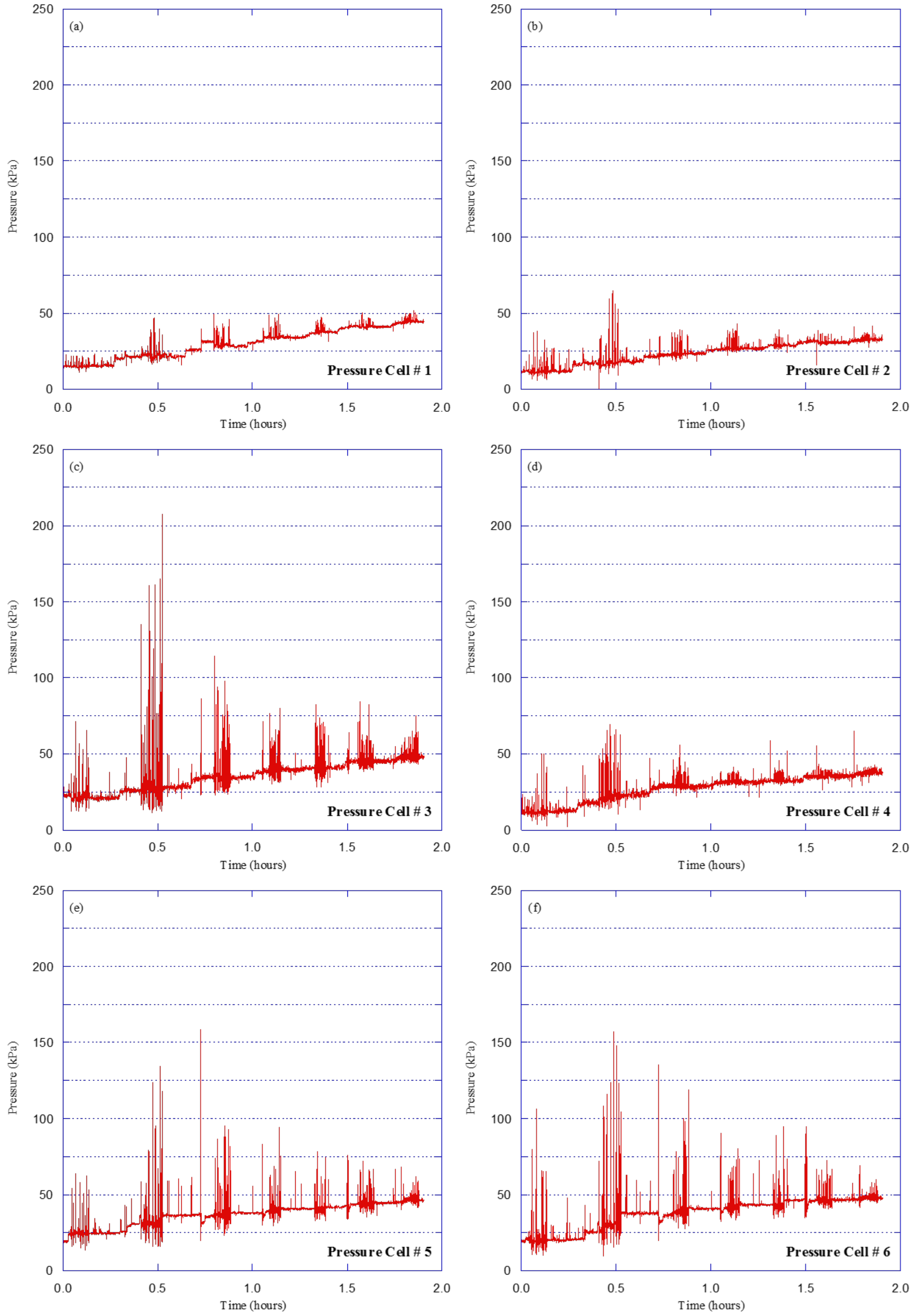

Figure 3.11 Downward earth pressures versus time for Test SC-2 (SDR-35 pipe in 2A aggregates)

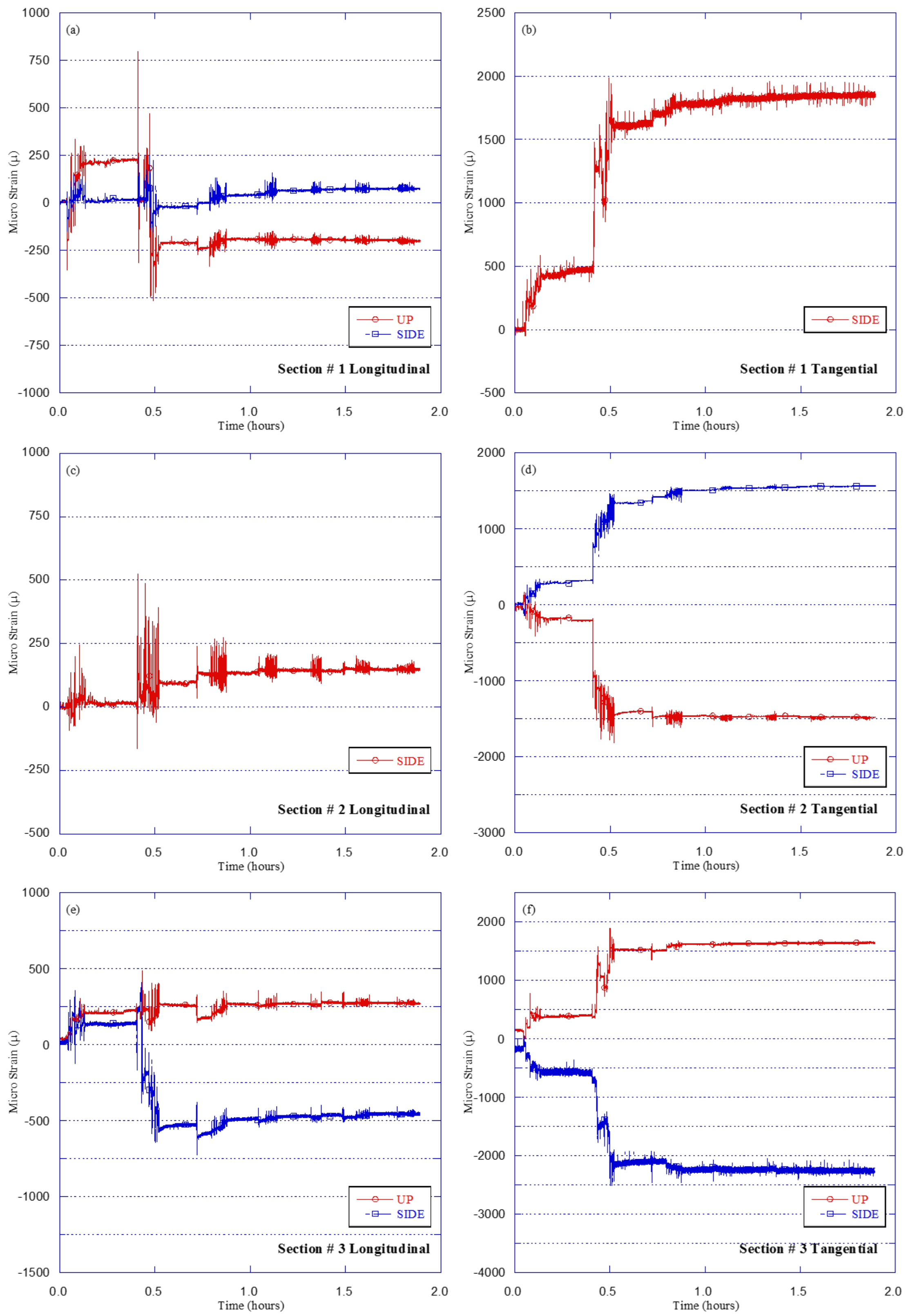

Figure 3.12 Strains along pipe versus time for Test SC-2 (SDR-35 pipe in 2A aggregates)

3.3 Test SC-3: 18-inch Diameter Reinforced Concrete Pipe

Figure 3.13 shows a cross-sectional view of trench and instrumentation for the 18-inch diameter reinforced concrete pipe. Figure 3.14 shows a detailed view of instrumentation, including the pressure cells and strain gages. Backfill procedures for the backfill zone and cover zone are summarized below.

Backfill Zone:
1) Set 6 inch AASHTO #8 bedding, no compaction
2) Lay pipe: each section of pipe is 8 ft long, two sections are connected first on ground using rubber seal gasket, then the entire 16-ft pipe is carefully laid in trench
3) Add 9 inch 2A aggregates on both sides of pipe, compact (away from pipe) using a small tamper, lay three pressure cells on side of pipe, conduct nuclear density gage test at middle section of trench (relative density 99.5%, moisture content 5.9%)
4) Add 9 inch 2A aggregates on both sides of pipe, compact (away from pipe) using a small tamper, lay three pressure cells on opposite side of pipe, conduct nuclear density gage test at middle section of trench (relative density 96.8%, moisture content 5.6%)
5) Add 24 inch 2A aggregates at once (reach top of backfill zone), compact using a small tamper (stay away from backfill directly above pipe), conduct nuclear density gage test at two locations approximately 4 ft from each end of pipe (relative density 98.1%, moisture content 6.1%; relative density 97.4%, moisture content 6.4%)

Cover Zone:
6) 4 lifts total (first three lifts: 8 inches/lift; last lift: 12 inches)
7) Nuclear density gauge testing after compaction of each lift, two density measurements per lift at approximately 4 ft from each end of pipe (i.e., above Sections 1 and 3, see Figure 3.14)

Figure 3.15 presents photos showing various stages of the field test. Table 3.4 presents results of nuclear density gauge tests for all 4 lifts. Figure 3.16 shows the downward earth pressure versus time recorded by the embedded pressure cells. Figure 3.17 shows the strains along pipe versus time recorded by the mounted strain gages.

Table 3.4 Results of nuclear density gauge tests for Test SC-3 (reinforced concrete pipe)

Lifts	Location 1 (Above Section #1)		Location 2 (Above Section #3)	
	Relative Density	Moisture Content	Relative Density	Moisture Content
1 (Bottom)	100.1%	4.9%	99.9%	7.2%
2	103.1%	6.4%	102.8%	6.8%
3	102.3%	5.8%	101.1%	6.0%
4 (Top)	100.5%	3.5%	103.9%	6.1%

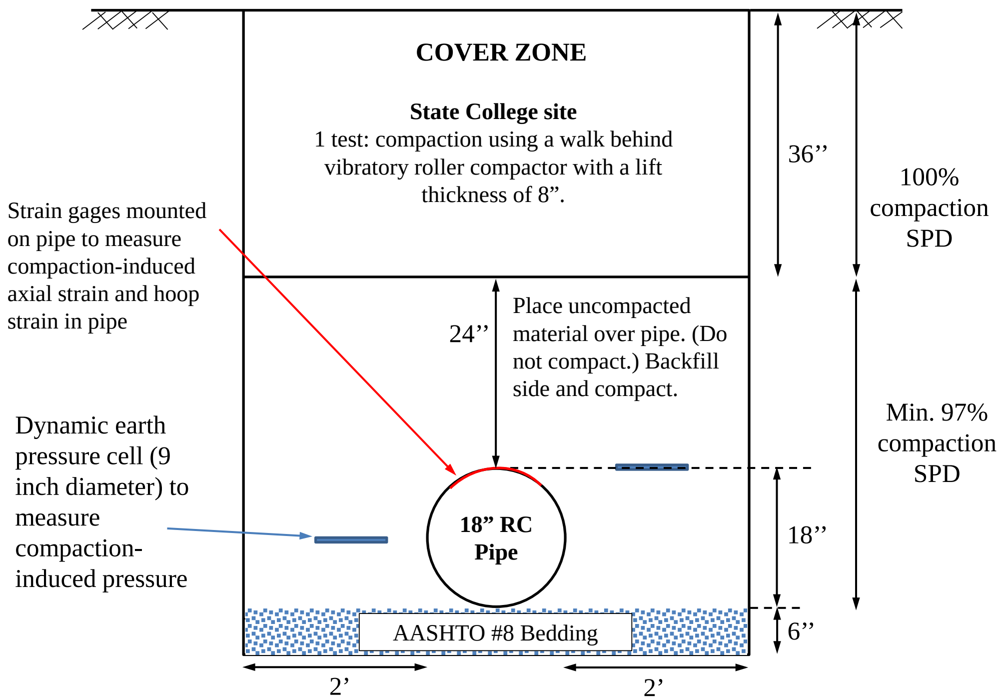

Figure 3.13 Cross-sectional view of trench and instrumentation for 18-inch diameter reinforced concrete pipe (not to scale)

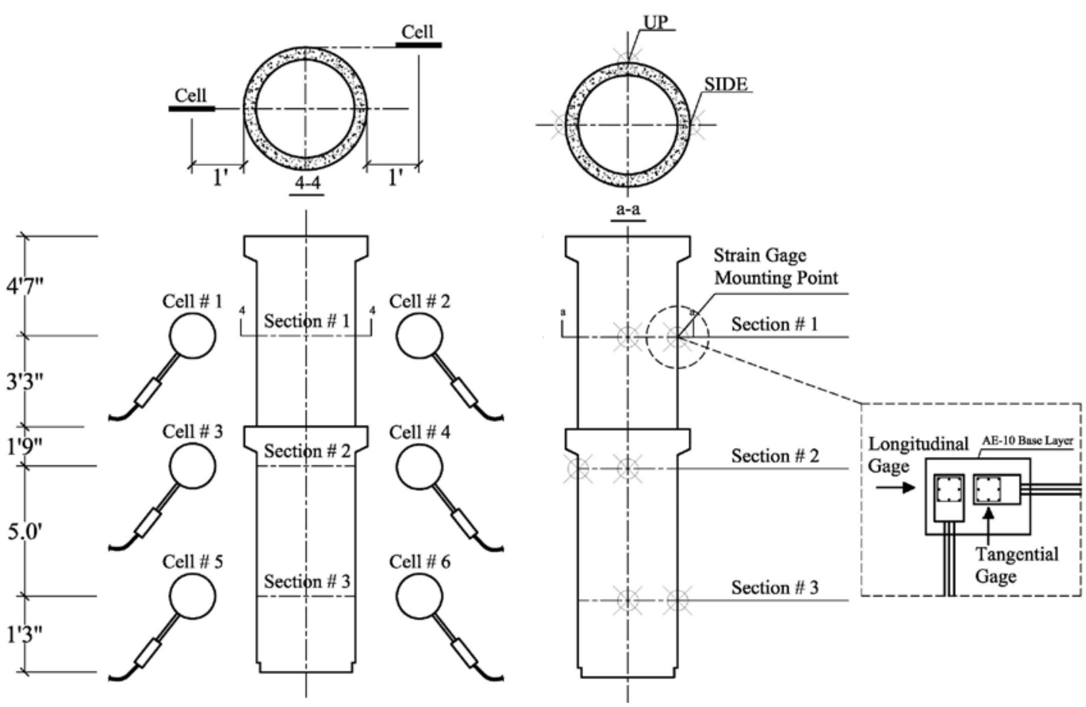

Figure 3.14 Detailed view of instrumentation for 18-inch diameter reinforced concrete pipe (not to scale)

Figure 3.15 Photos showing various stages of field test: a) measuring AASHTO #8 bedding; b) compaction using a small tamper on side of pipe; c) placement of pressure cells on side along top of pipe; d) compaction using a walk-behind vibratory roller compactor in cover zone; e) compaction after last lift and data acquisition system with wires

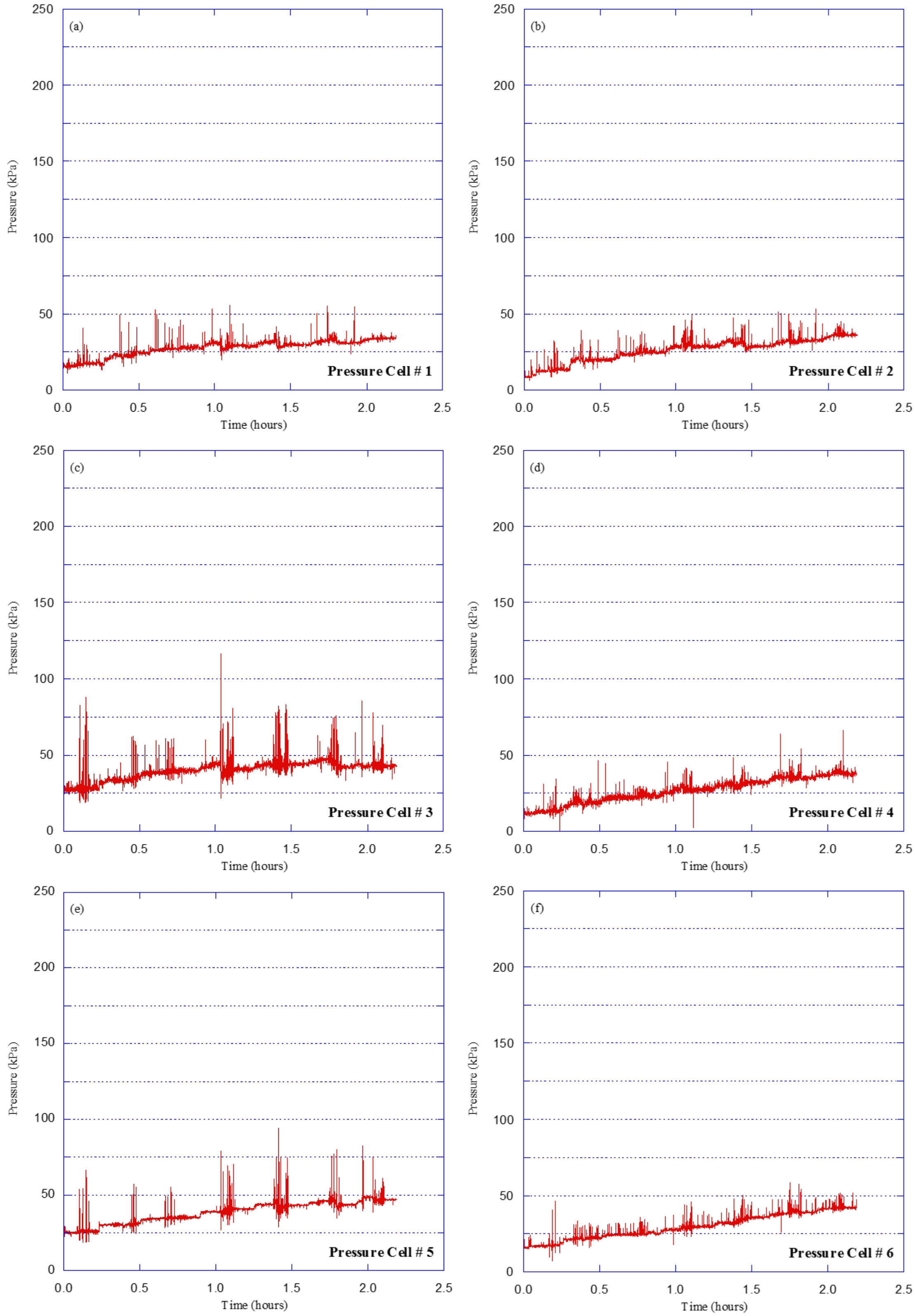

Figure 3.16 Downward earth pressures versus time for Test SC-3 (reinforced concrete pipe)

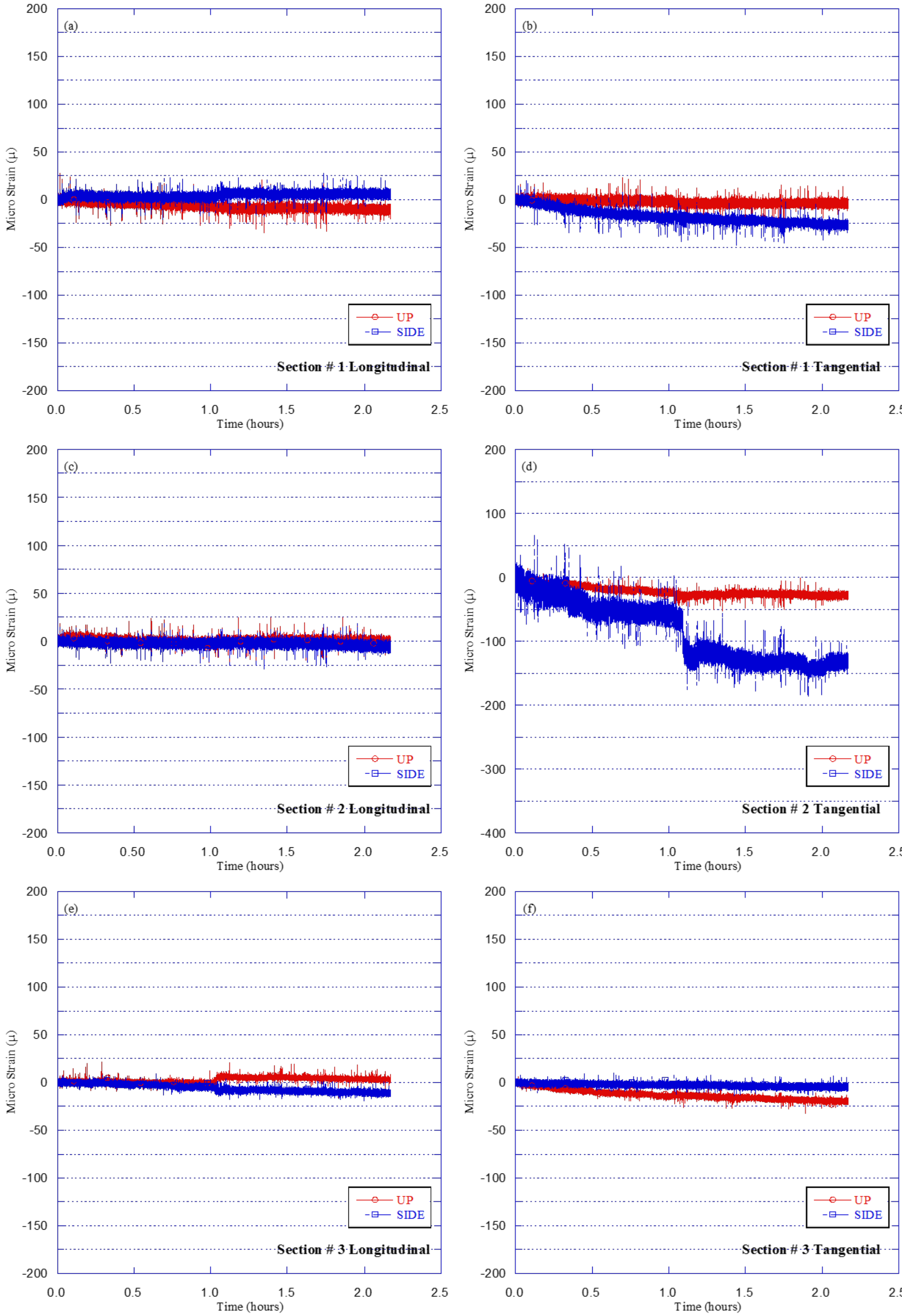

Figure 3.17 Strains along pipe versus time for Test SC-3 (reinforced concrete pipe)

3.4 Test SC-4: 18-inch Diameter HDPE Drainage Pipe

Figure 3.18 shows the cross-sectional view of trench and instrumentation for the 18-inch diameter HDPE drainage pipe. Figure 3.19 shows a detailed view of instrumentation, including the pressure cells and strain gages. Backfill procedures for the backfill zone and cover zone are summarized below.

Backfill Zone:
1) Set 6 inch 2A bedding, compact using a small tamper
2) Lay pipe
3) Add 9 inch 2A aggregates on both sides of pipe, compact using a small tamper, lay three pressure cells on side of pipe, conduct nuclear density gage test at two locations approximately 4 ft from each end of pipe (relative density 99.5%, moisture content 6.7%; relative density 98.7%, moisture content 7.0%)
4) Add 9 inch 2A aggregates to pipe crest, compact using a small tamper, no density measurement
5) Add 6 inch 2A aggregates, compact using a small tamper, lay three pressure cells on top of pipe, conduct nuclear density gage test at two locations approximately 4 ft from each end of pipe (relative density 97.7%, moisture content 6.4%; relative density 95.6%, moisture content 6.2%)
6) Add 6 inch 2A aggregates, compact using a small tamper, conduct nuclear density gage test at two locations approximately 4 ft from each end of pipe (relative density 96.3%, moisture content 7.1%; relative density 95.4%, moisture content 6.1%)

Cover Zone:
7) 8 inches/lift, 6 lifts total
8) Nuclear density gauge testing after compaction of each lift, two density measurements per lift at approximately 4 ft from each end of pipe (i.e., above Sections 1 and 3, see Figure 3.19)

Figure 3.20 presents photos showing various stages of the field test. Table 3.5 presents results of nuclear density gauge tests for all six lifts. Figure 3.21 shows the downward earth pressure versus time recorded by the embedded pressure cells. Figure 3.22 shows the strains along pipe versus time recorded by the mounted strain gages.

Table 3.5 Results of nuclear density gauge tests for Test SC-4 (HDPE drainage pipe)

Lifts	Location 1 (Above Section #1)		Location 2 (Above Section #3)	
	Relative Density	Moisture Content	Relative Density	Moisture Content
1 (Bottom)	100.0%	5.6%	103.8%	6.5%
2	104.1%	6.1%	100.4%	6.3%
3	99.9%	6.2%	101.3%	7.1%
4	101.0%	5.8%	103.1%	5.8%
5	102.9%	6.7%	100.9%	5.0%
6 (Top)	100.3%	4.4%	102.7%	5.6%

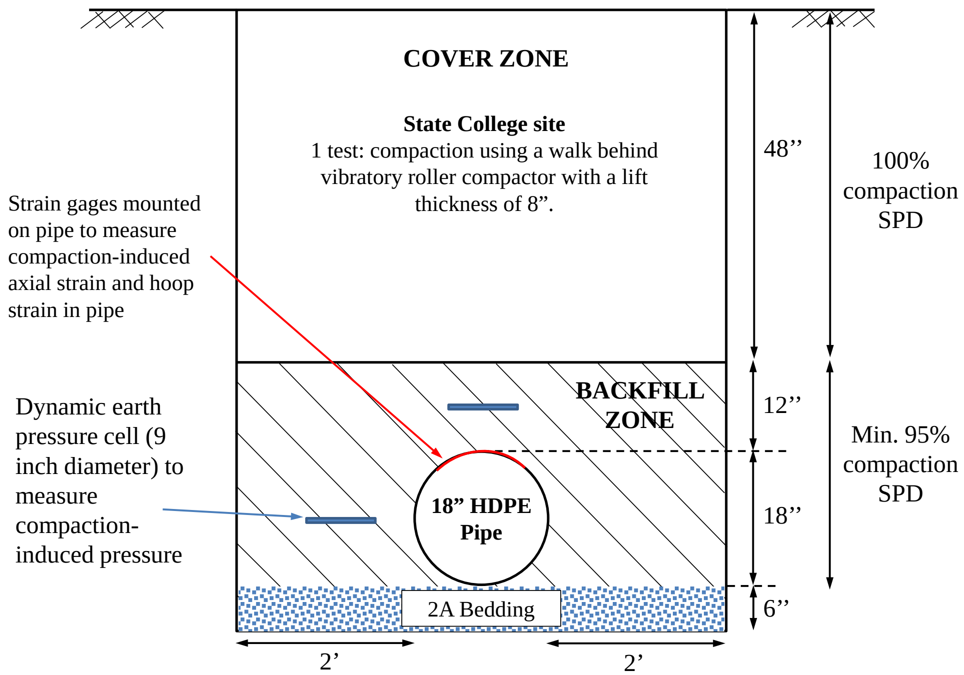

Figure 3.18 Cross-sectional view of trench and instrumentation for 18-inch diameter HDPE drainage pipe (not to scale)

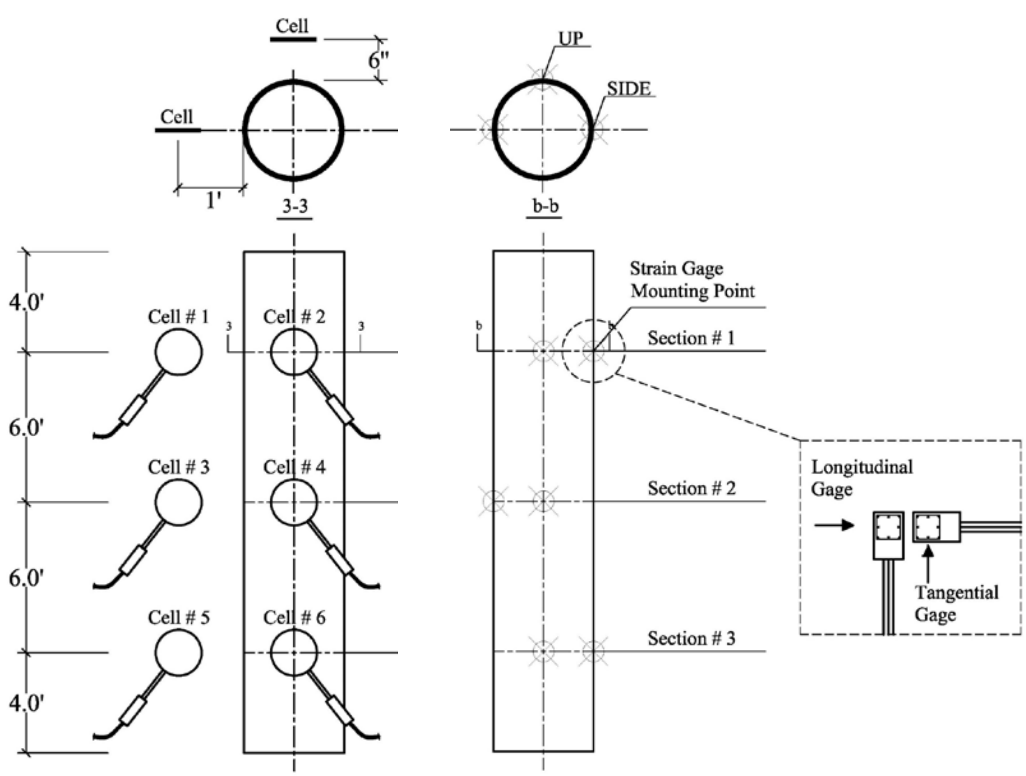

Figure 3.19 Detailed view of instrumentation for 18-inch diameter HDPE drainage pipe (not to scale)

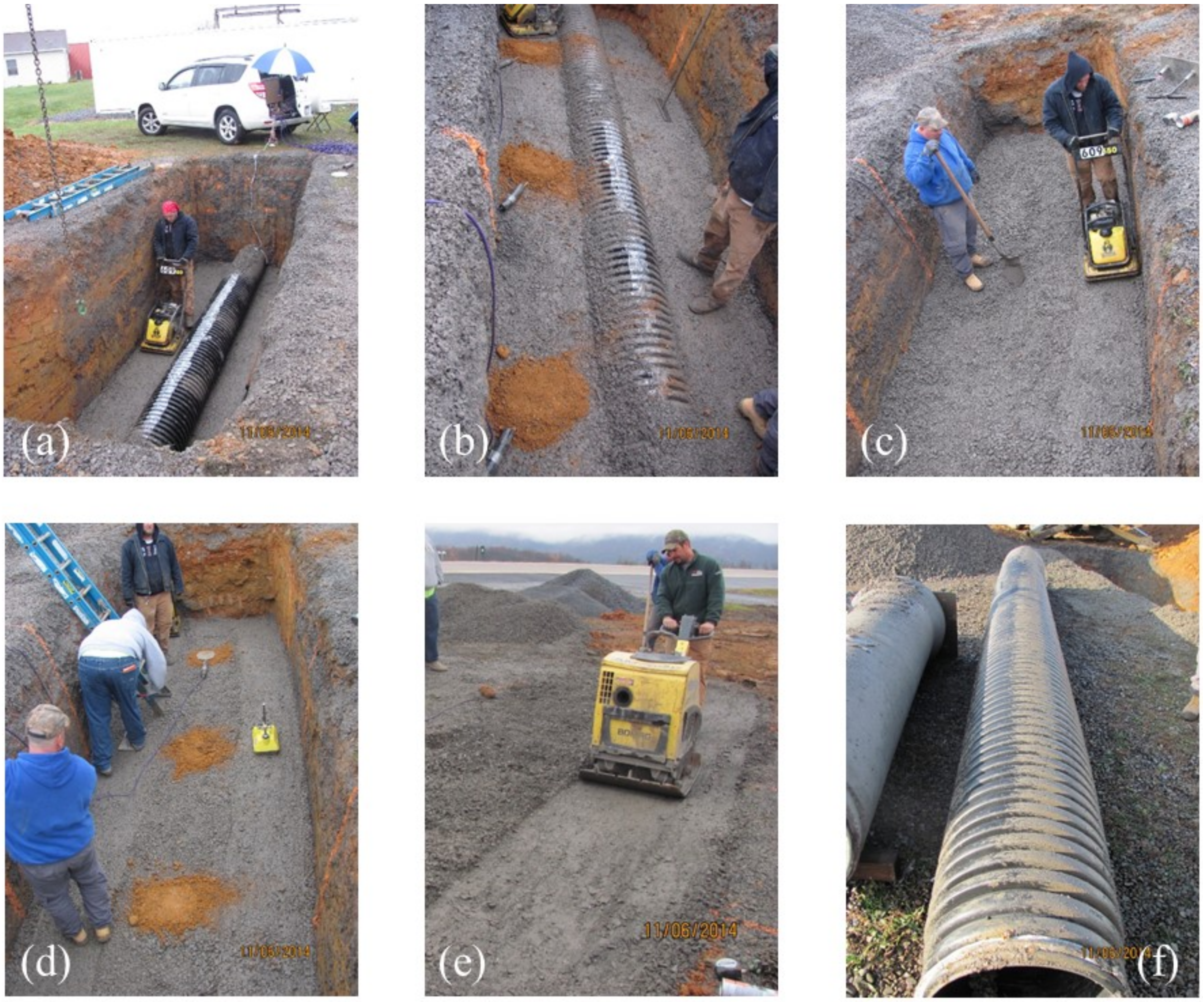

Figure 3.20 Photos showing various stages of field test: a) compaction using a small tamper on side of pipe; b) placement of pressure cells on side along mid elevation of pipe; c) compaction using a small tamper on top of backfill zone; d) placement of pressure cells on top of pipe and nuclear density gauge testing; e) compaction using a walk-behind vibratory roller compactor after last lift; f) retrieved pipe after test

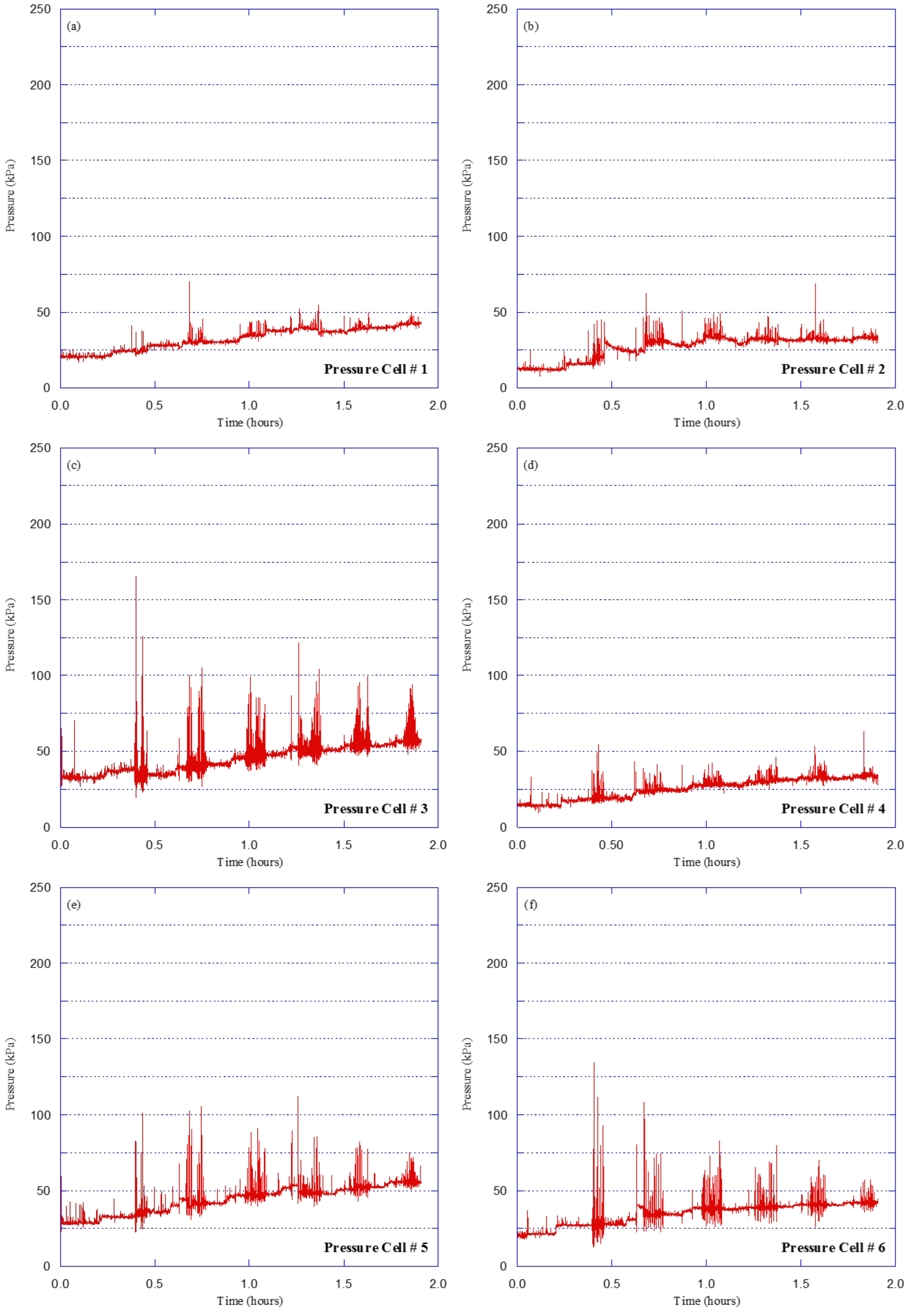

Figure 3.21 Downward earth pressures versus time for Test SC-4 (HDPE drainage pipe)

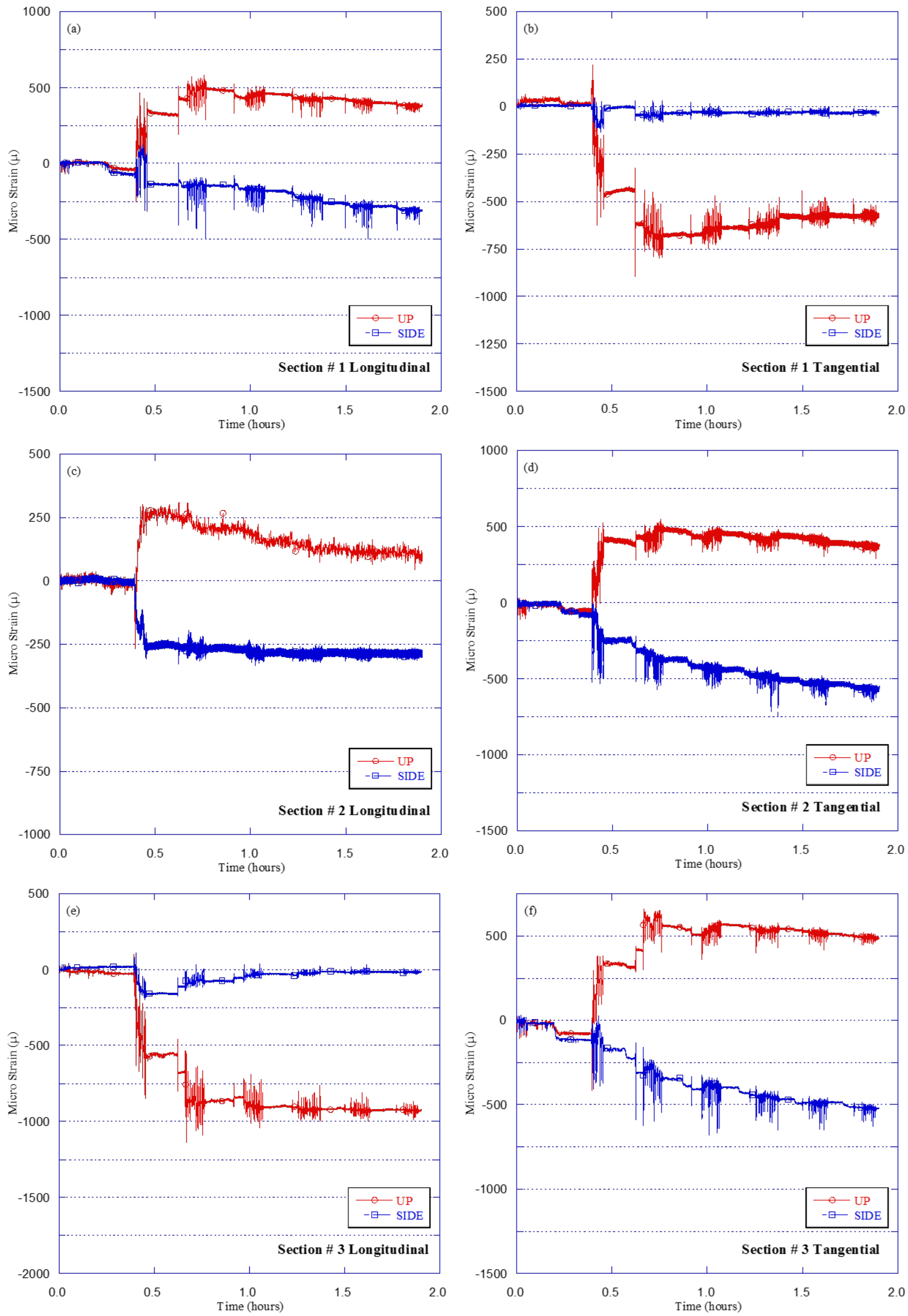

Figure 3.22 Strains along pipe versus time for Test SC-4 (HDPE drainage pipe)

3.5 Discussions

This section presents analyses of data collected from the backfill compaction tests with regard to compacted dry mass density and compaction-induced downward earth pressure and strains in pipe.

3.5.1 Compacted Dry Mass Density

Tables 3.2, 3.3, 3.4, and 3.5 indicate that relative densities of above 100% of the Standard Proctor Density were consistently achieved by using the walk-behind vibratory roller compactor and a lift thickness of 8 inches for all four tests conducted.

3.5.2 Compaction-Induced Downward Earth Pressure

Figures 3.6, 3.11, 3.16, and 3.21 indicate that the recorded earth pressure versus time has two components: 1) a static earth pressure that increases with time and backfill thickness, and 2) a dynamic component that fluctuates rapidly during compaction. The static earth pressure is due to a combination of the self-weight of compacted fill on top of the pressure cell and the residual compaction-induced stress locked in due to particle rearrangement. The dynamic earth pressure is due to the vibration of the vibratory roller compactor. For a given test, the recorded dynamic earth pressures are generally much larger than the static earth pressures. For example, the peak dynamic and static earth pressures recorded for Test SC-1 are approximately 220 kPa and 60 kPa, respectively, as shown in Figure 3.6(f).

Similar dynamic and static earth pressures are observed in Figure 3.6 and Figure 3.11, which suggests that embedding the SDR-35 pipe in the 2B stone or 2A aggregates didn't make a significant difference in compaction-induced downward earth pressures in the backfill zone in these tests. A comparison among Figures 3.6, 3.11, 3.16, and 3.21 indicates that the dynamic earth pressures were the smallest for the reinforced concrete pipe (i.e., Test SC-3). This is due to the high-energy-dissipation characteristics of loose 2A aggregates directly above the pipe. Compaction-induced stress waves were largely absorbed by the loose 2A aggregates; hence smaller dynamic earth pressures were recorded by the pressure cells. The static earth pressures were similar among the four tests, which is due to the generally consistent backfill thickness and compaction energy among these tests.

3.5.3 Compaction-Induced Strains in Pipe

In Figures 3.7, 3.12, 3.17, and 3.22, strains are positive in tension and negative in compression. The signs of longitudinal strains along a pipe indicate whether a section was under compression or tension during the test. For example, the generally positive longitudinal strains in Sections #2 and #3 for Test SC-1, as shown in Figures 3.7(c) and 3.7(e), suggest that these sections were under tension. On the other hand, the generally negative longitudinal strains in Section #3 for Test SC-4, as shown in Figure 3.22(e), suggest that this section was under compression.

The deformation mode of a cross section can be inferred from the tangential strains along the cross section. Two basic modes of deformation are illustrated in Figure 3.23. In the vertical compression mode, the cross section experiences compression (i.e., negative tangential strain) at the top and tension (i.e., positive tangential strain) on the side; whereas in the horizontal compression mode, the cross section experiences tension at the top and compression on the side. For example, Figures 3.7(b), 3.7(d), and 3.7(f) suggest that the SDR-35 pipe in 2B stone experienced vertical compression in Sections #1, #2, and #3 during Test SC-1; whereas, Figures 3.22(d) and 3.22(f) suggest that the HDPE drainage pipe experienced horizontal compression in Sections #2 and #3 during Test SC-4.

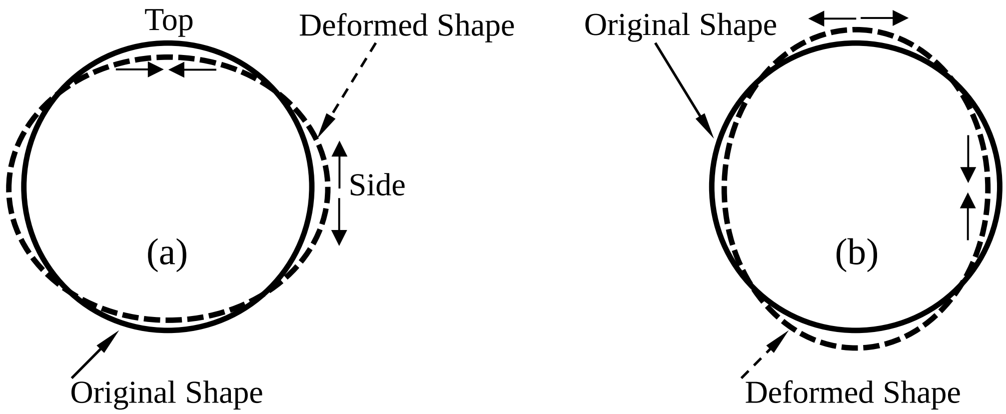

Figure 3.23 Mode of deformation and strains along cross section: (a) vertical compression; (b) horizontal compression

A comparison between Figures 3.7 and 3.12 reveals that the longitudinal strains along the SDR-35 pipe were similar between Test SC-1 and Test SC-2; however, the tangential strains in Test SC-2 were twice as high as those in Test SC-1. This suggests that embedding the SDR-35 pipe in the 2A aggregates may potentially result in more deformation of the pipe cross section. A comparison among Figures 3.7, 3.12, 3.17, and 3.22 indicates that the recorded longitudinal and tangential strains along the reinforced concrete pipe were the smallest (i.e., Test SC-3) due to the high stiffness of the pipe material.

4 TRENCH BACKFILL COMPACTION TESTS AT HARRISBURG

Sixteen trench backfill compaction tests were conducted utilizing an Allied Model 1000B hydraulic plate compactor at Harrisburg between November 19, 2014 and November 21, 2014. These tests are listed in Table 4.1. The compaction tests were instrumented with dynamic earth pressure cells and strain gages to measure compaction-induced downward earth pressure in backfill and strains in pipe, respectively. Ms. Robyn Myers from Troxler Electronic Laboratories, Inc. observed and provided guidance on nuclear density gauge testing on November 19, 2014. For subsequent nuclear density gauge testing, procedures recommended by Ms. Myers were followed. Mr. David Gassert, P.E., from Navarro & Wright Consulting Engineers, Inc. observed the field testing on all three days. This chapter documents the test procedures and data collected. Analyses of the test data are also provided.

Table 4.1 Sixteen compaction tests at Harrisburg

Test	Pipe	Lift Thickness (inch)	Test Date
HB-1	6 inch diameter SDR-35 pipe in 2B stone	24	November 19, 2014
HB-2	6 inch diameter SDR-35 pipe in 2B stone	18	November 19, 2014
HB-3	6 inch diameter SDR-35 pipe in 2B stone	12	November 19, 2014
HB-4	6 inch diameter SDR-35 pipe in 2B stone	8	November 19, 2014
HB-5	6 inch diameter SDR-35 pipe in 2A aggregates	24	November 20, 2014
HB-6	6 inch diameter SDR-35 pipe in 2A aggregates	18	November 20, 2014
HB-7	6 inch diameter SDR-35 pipe in 2A aggregates	12	November 20, 2014
HB-8	6 inch diameter SDR-35 pipe in 2A aggregates	8	November 20, 2014
HB-9	18 inch diameter reinforced concrete pipe	24	November 21, 2014
HB-10	18 inch diameter reinforced concrete pipe	18	November 21, 2014
HB-11	18 inch diameter reinforced concrete pipe	12	November 21, 2014
HB-12	18 inch diameter reinforced concrete pipe	8	November 21, 2014
HB-13	18 inch diameter HDPE drainage pipe	24	November 21, 2014
HB-14	18 inch diameter HDPE drainage pipe	18	November 21, 2014
HB-15	18 inch diameter HDPE drainage pipe	12	November 21, 2014
HB-16	18 inch diameter HDPE drainage pipe	8	November 21, 2014

4.1 Tests HB-1 to HB-4: 6-inch Diameter SDR-35 Pipe in 2B Stone

Figure 4.1 shows a cross-sectional view of trench and instrumentation for the 6-inch diameter SDR-35 pipe in 2B stone. Figure 4.2 shows a detailed view of instrumentation including the pressure cells and strain gages. The instrumentation plan is generally consistent with Test SC-1 in State College (see Chapter 3). Backfill procedures for the backfill zone and cover zone are summarized below.

Backfill Zone:
1) Set 6 inch 2B stone bedding, no compaction
2) Lay pipe
3) Add 3 inch 2B stone, no compaction, lay three pressure cells on side of pipe
4) Add 9 inch 2B stone, no compaction, lay three pressure cells on top of pipe

5) Add 6 inch 2B stone (reach top of backfill zone), compact using a jumping jack (no density measurement)

Cover Zone:

6) Test HB-1: 24 inches/lift, 2 lifts total
7) Nuclear density gauge testing after compaction of each lift:
   Two density measurements (penetration depth of nuclear gauge: 12 inches) on top of compacted surface at approximately 4 ft from each end of pipe (i.e., above Sections 1 and 3, see Figure 4.2)
   Centered around the density measurement locations, scrape 12 inches off the compacted surface and create a flat area that extends at least 12 inches away (in all directions) from previous density measurement location
   Two density measurements (penetration depth of nuclear gauge: 12 inches) at previous density measurement locations on the flattened surface

   Note[1]: To create a smooth surface for nuclear density gauge testing, onsite fine materials (e.g., sand) were used, as needed, to fill in small holes and voids. This procedure was followed throughout the testing program.

   Note[2]: Backfill the scraped area, lightly compact with hydraulic plate compactor before placement of next lift. This procedure was followed throughout the testing program.

8) Excavate compacted fill out of cover zone

9) Test HB-2: 3 lifts total (first two lifts: 18 inches/lift; last lift: 12 inches/lift)
10) Nuclear density gauge testing after compaction of each lift:
   Two density measurements (penetration depth of nuclear gauge: 12 inches) on top of compacted surface at approximately 4 ft from each end of pipe
   Centered around the density measurement locations, scrape 6 inches off the compacted surface and create a flat area that extends at least 12 inches away (in all directions) from previous density measurement location (for the first two lifts only)
   Two density measurements (penetration depth of nuclear gauge: 12 inches) at previous density measurement locations on the flattened surface (for the first two lifts only)

   Note[3]: Excavated backfill materials, if contaminated with onsite soil, cannot be reused. This procedure was followed throughout the testing program.

11) Excavate compacted fill out of cover zone

12) Test HB-3: 12 inches/lift, 4 lifts total
13) Nuclear density gauge testing (penetration depth of nuclear gauge: 12 inches) after compaction of each lift, two density measurements per lift at approximately 4 ft from each end of pipe

14) Excavate compacted fill out of cover zone

15) Test HB-4: 8 inches/lift, 6 lifts total
16) Nuclear density gauge testing (penetration depth of nuclear gauge: 8 inches) after compaction of each lift, two density measurements per lift at approximately 4 ft from each end of pipe

Figure 4.3 presents photos showing various stages of the field test. Table 4.2 presents results of nuclear density gauge tests for all four tests. Figure 4.4 shows the downward earth pressure versus time recorded by the embedded pressure cells for Test HB-1. Figure 4.5 shows the strains along pipe versus time recorded by the mounted strain gages for Test HB-1. Figures 4.6, 4.7, 4.8, 4.9, 4.10, and 4.11 show the corresponding plots for Tests HB-2, HB-3, and HB-4.

Table 4.2 Results of nuclear density gauge tests for Tests HB-1 to HB-4 (SDR-35 pipe in 2B stone)

Test	Lifts (Surface)	Location 1 (Above Section #1)		Location 2 (Above Section #3)	
		Relative Density	Moisture Content	Relative Density	Moisture Content
HB-1	1 (Top)	98.5%	4.2%	100.3%	4.5%
	1 (Scraped)	81.6%*	3.4%	81.0%*	3.6%
	2 (Top)	103.7%	3.1%	103.0%	8.1%
	2 (Scraped)	95.4%	4.2%	94.2%	7.7%
HB-2	1 (Top)	96.3%	4.3%	104.5%	4.5%
	1 (Scraped)	92.7%	3.8%	100.1%	5.1%
	2 (Top)	103.1%	4.3%	101.5%	3.9%
	2 (Scraped)	97.2%	4.3%	94.1%	4.4%
	3	108.1%	5.0%	104.3%	3.8%
HB-3	1	102.5%	4.7%	102.7%	4.1%
	2	107.9%	4.4%	105.5%	4.7%
	3	107.8%	4.1%	107.8%	4.6%
	4	104.9%	3.7%	105.0%	5.8%
HB-4	1	104.9%	4.1%	100.7%	4.1%
	2	102.2%	4.9%	100.8%	3.9%
	3	103.5%	4.0%	102.4%	4.7%
	4	104.4%	4.2%	102.8%	5.2%
	5	104.2%	4.4%	103.7%	5.1%
	6	102.5%	4.3%	104.8%	4.4%

*: Rod of nuclear gauge penetrated into uncompacted 2B stone.

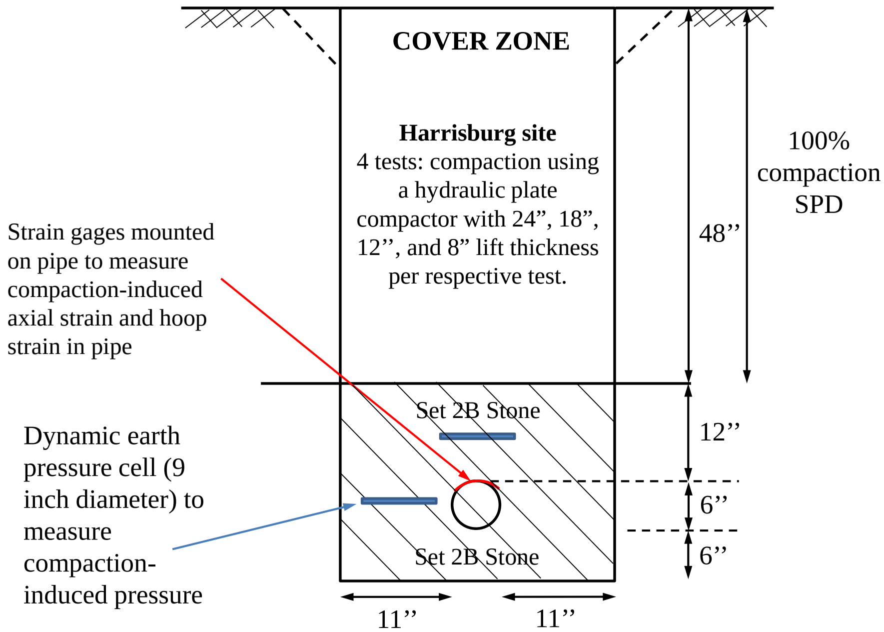

Figure 4.1 Cross-sectional view of trench and instrumentation for 6-inch diameter SDR-35 pipe in 2B stone (not to scale)

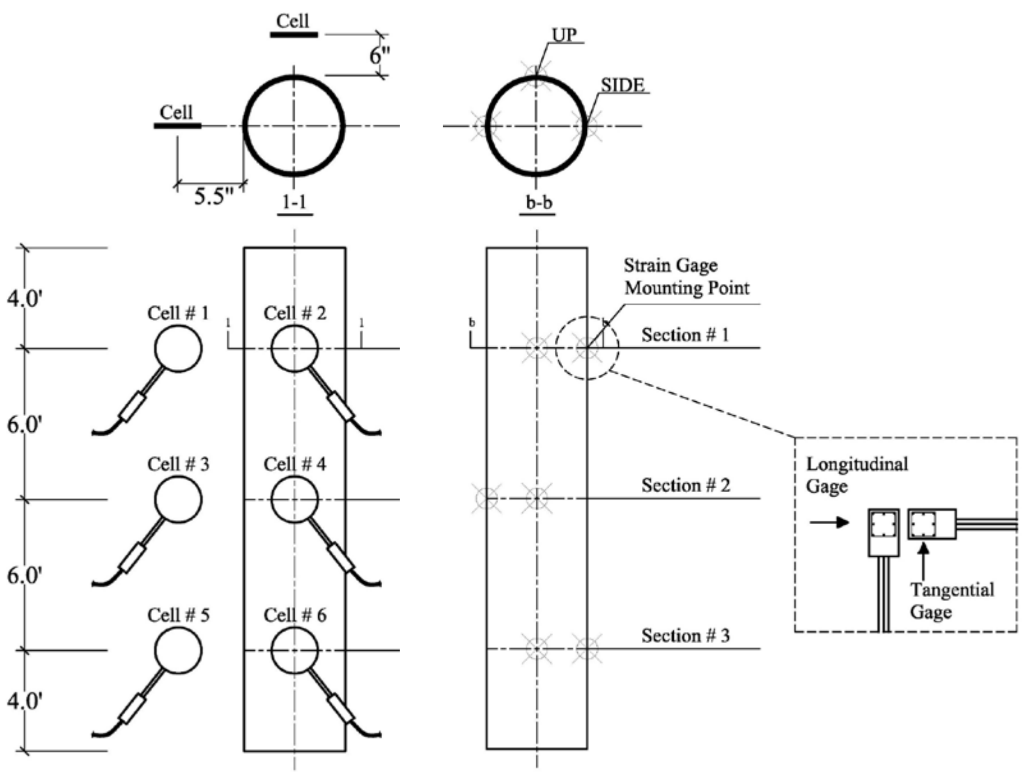

Figure 4.2 Detailed view of instrumentation for 6-inch diameter SDR-35 pipe in 2B stone (not to scale)

Figure 4.3. Photos showing various stages of field test: a) 2B stone, pipe, and seating materials for placement of pressure cells; b) placement of a pressure cell on side along mid elevation of pipe; c) compaction using a hydraulic plate compactor; d) Ms. Robyn Myers giving instructions on nuclear density gauge testing; e) retrieved pipe after test

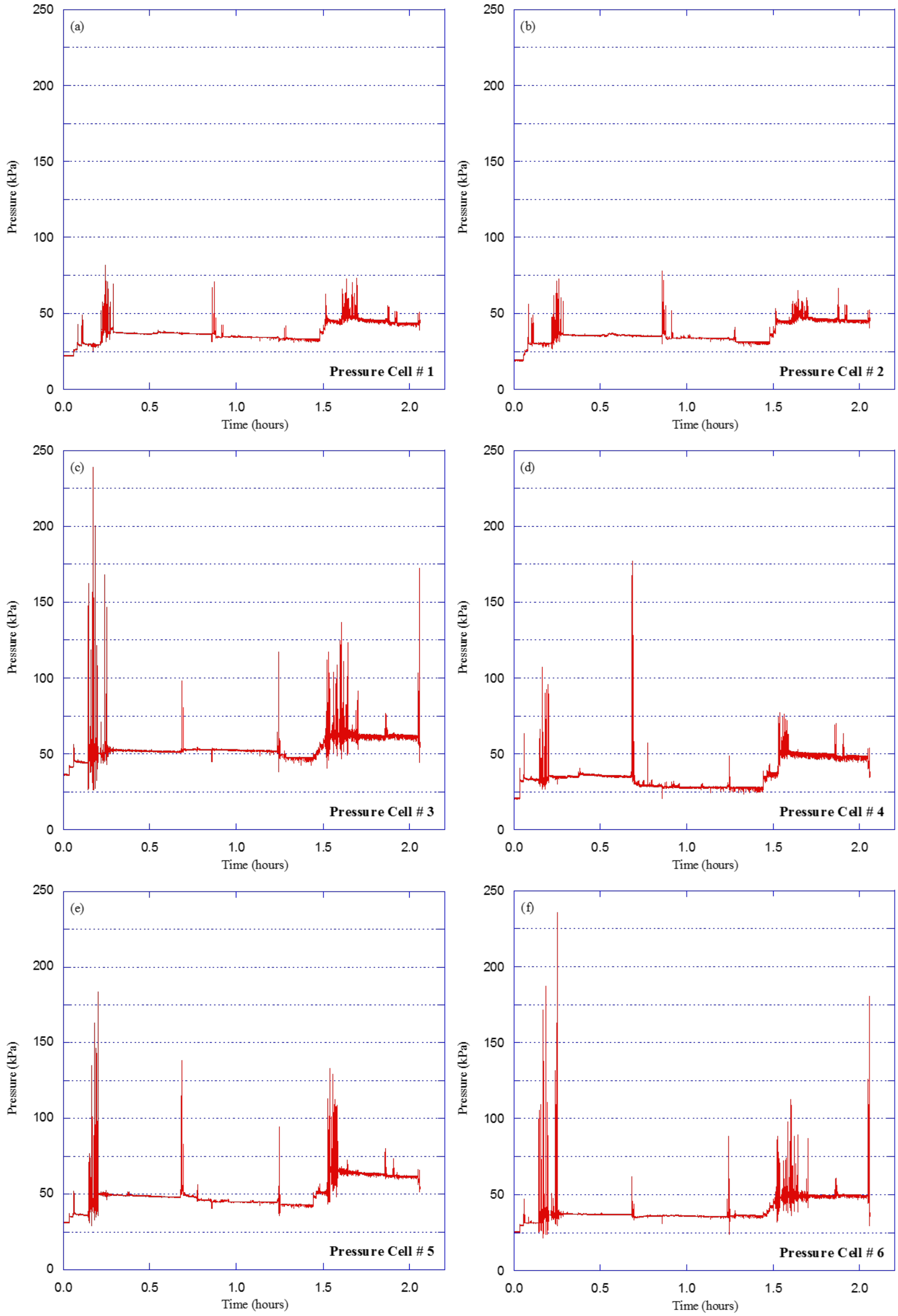

Figure 4.4 Downward earth pressures versus time for Test HB-1 (SDR-35 pipe in 2B stone)

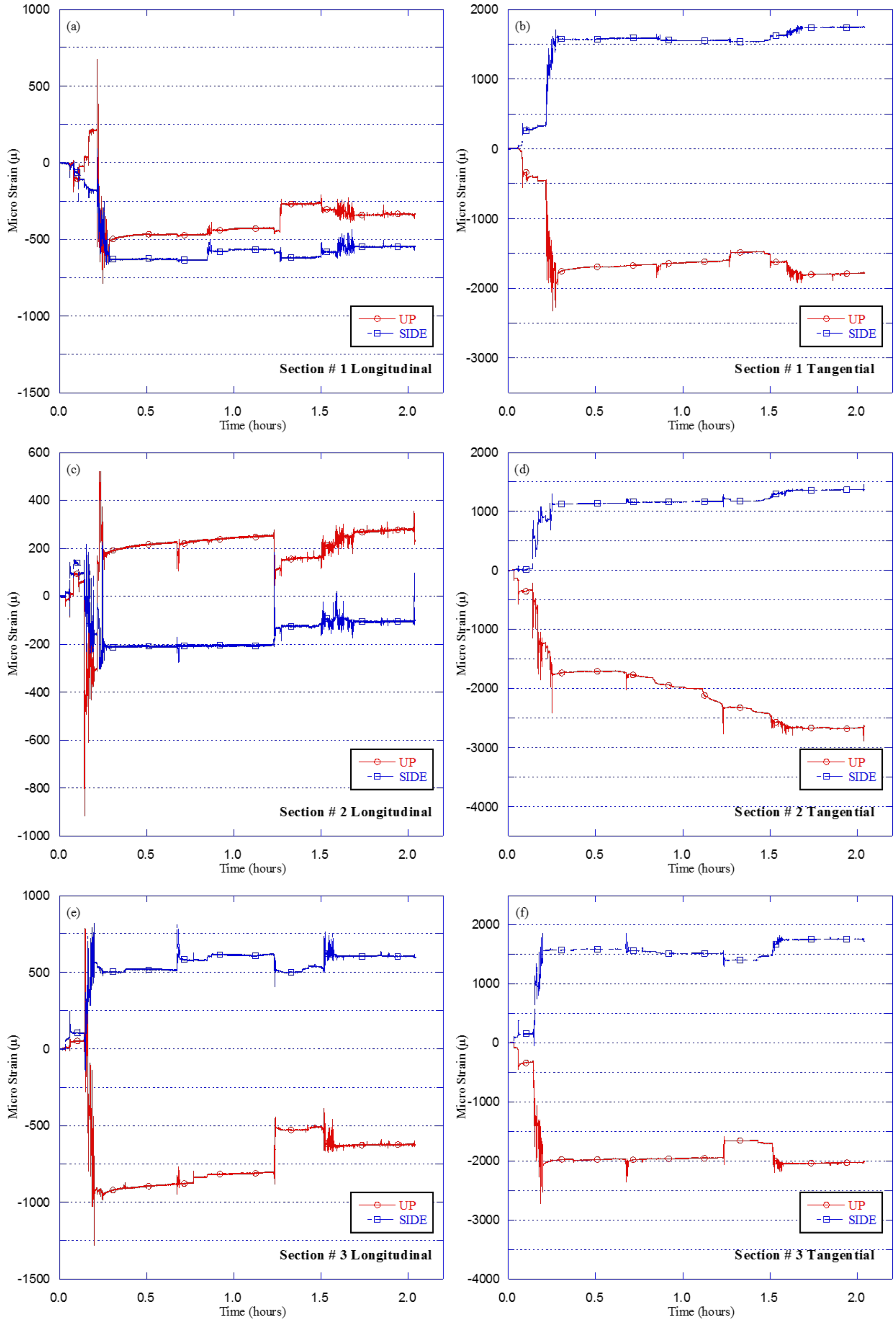

Figure 4.5 Strains along pipe versus time for Test HB-1 (SDR-35 pipe in 2B stone)

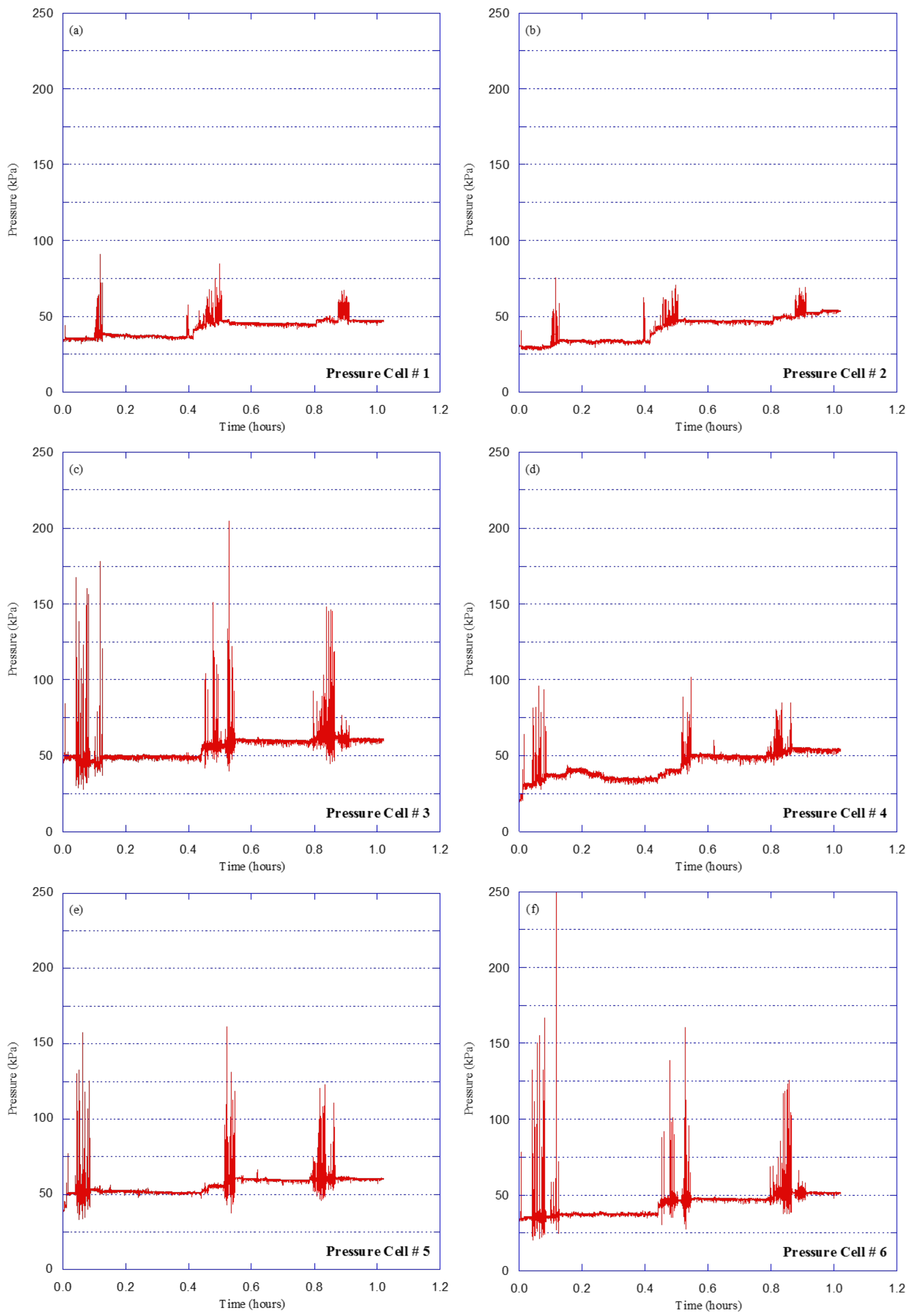

Figure 4.6 Downward earth pressures versus time for Test HB-2 (SDR-35 pipe in 2B stone)

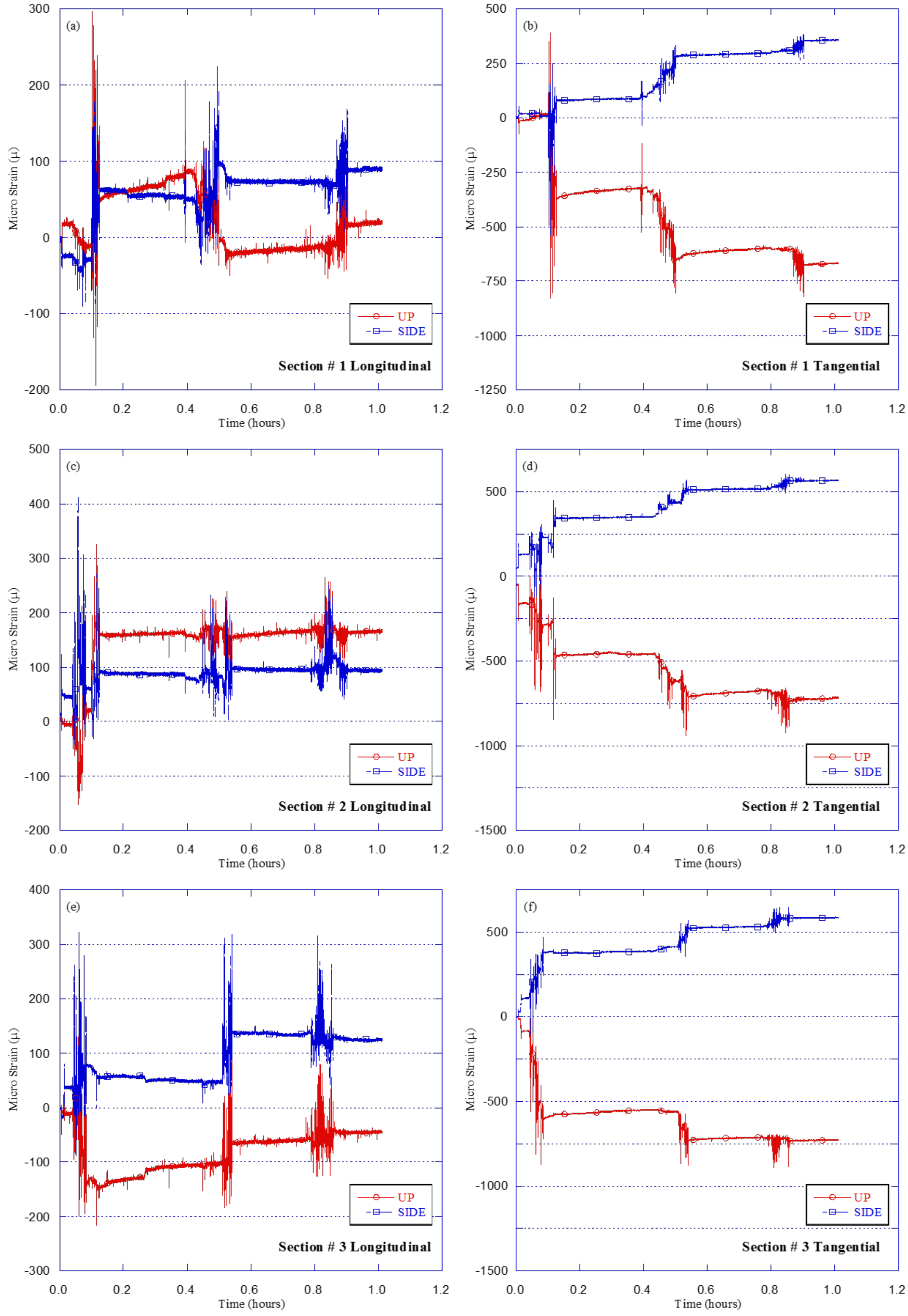

Figure 4.7 Strains along pipe versus time for Test HB-2 (SDR-35 pipe in 2B stone)

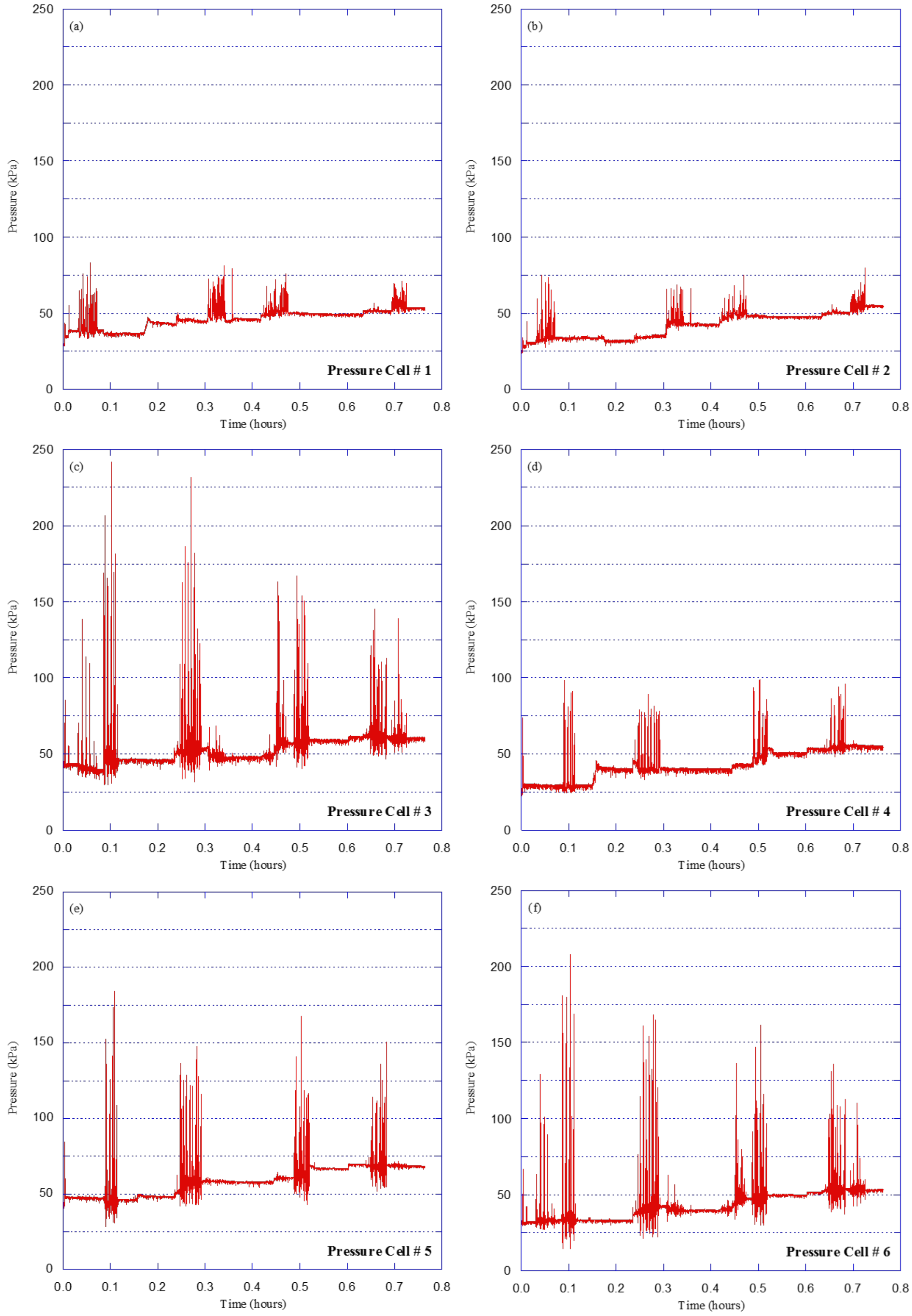

Figure 4.8 Downward earth pressures versus time for Test HB-3 (SDR-35 pipe in 2B stone)

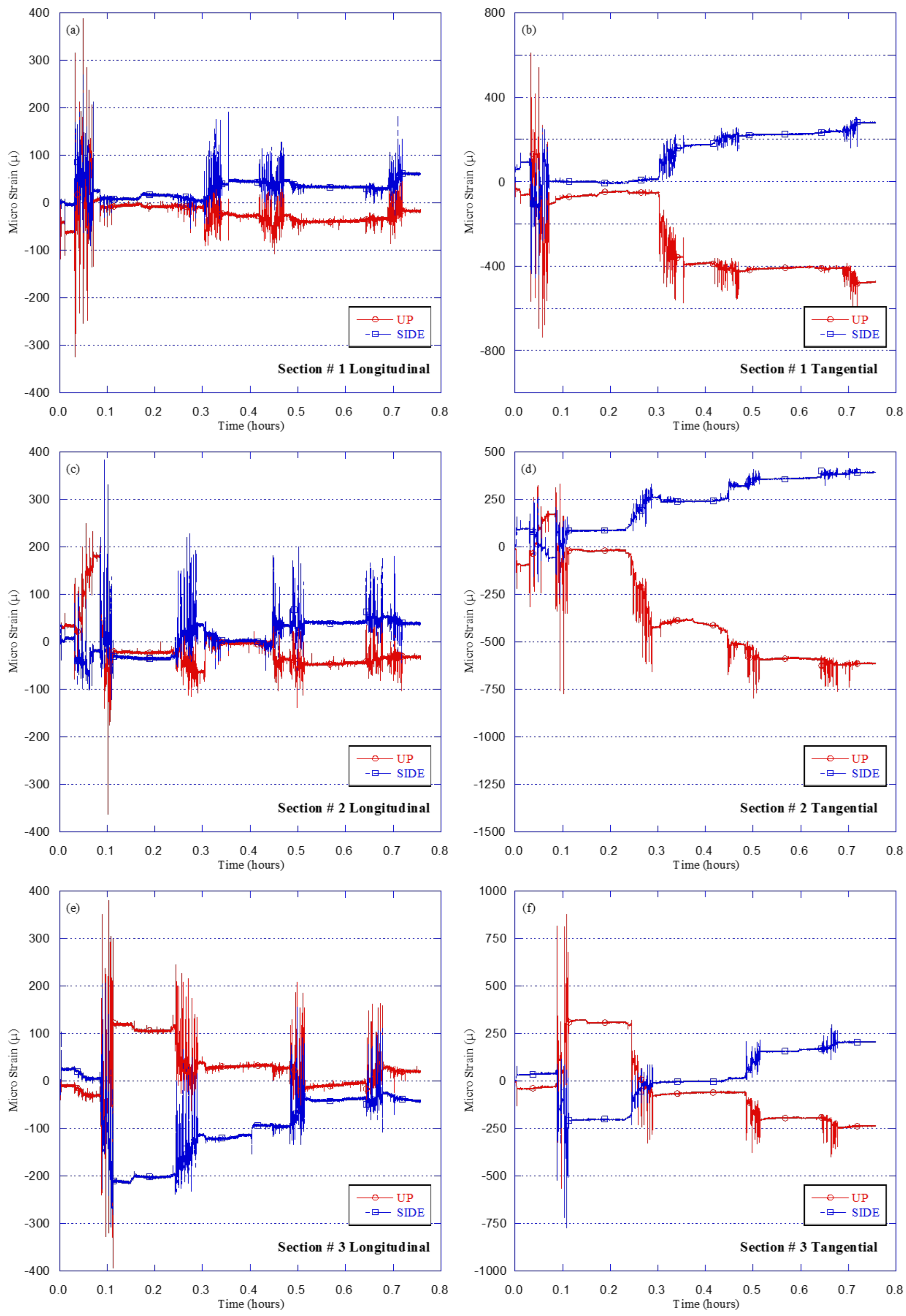

Figure 4.9 Strains along pipe versus time for Test HB-3 (SDR-35 pipe in 2B stone)

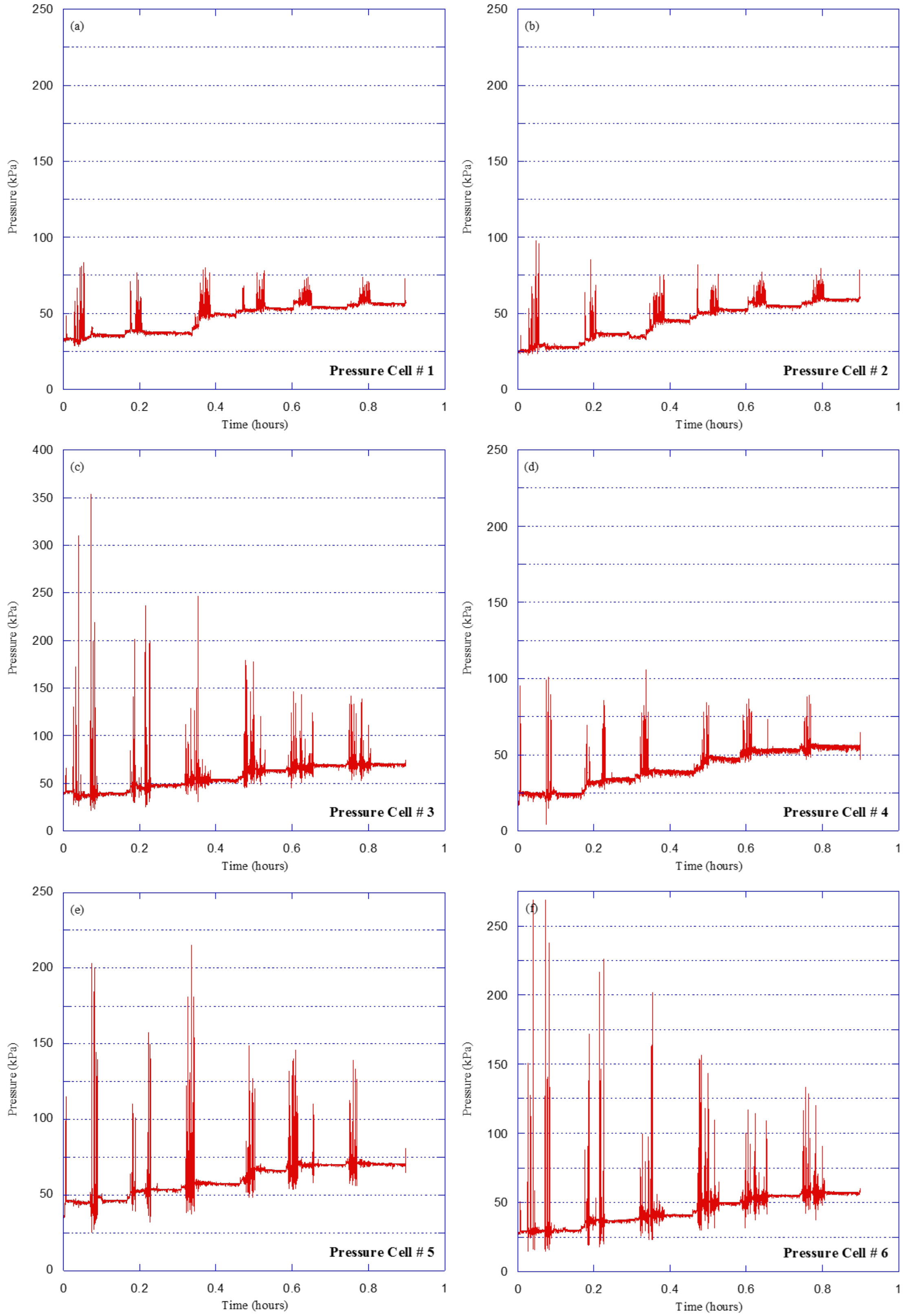

Figure 4.10 Downward earth pressures versus time for Test HB-4 (SDR-35 pipe in 2B stone)

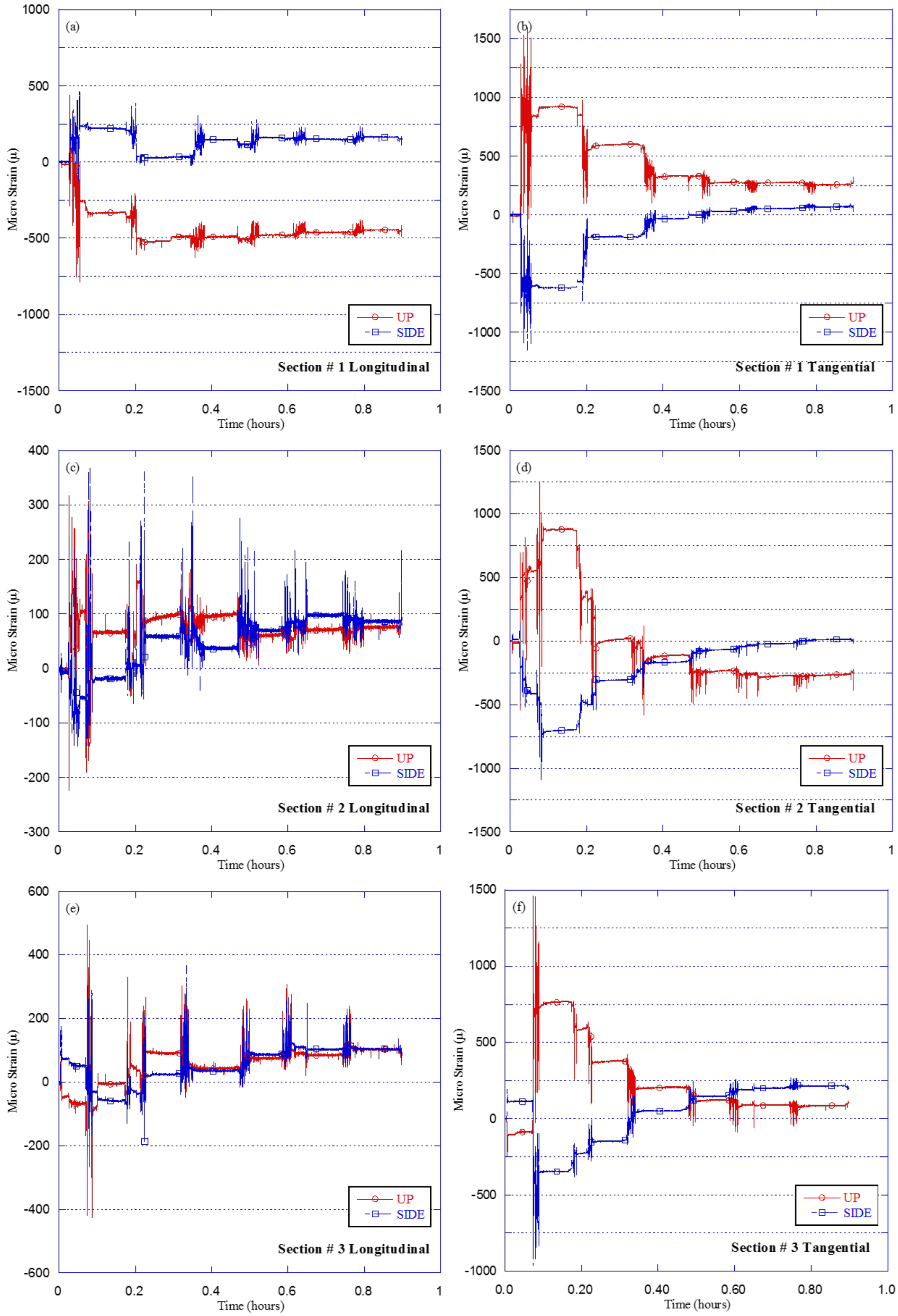

Figure 4.11 Strains along pipe versus time for Test HB-4 (SDR-35 pipe in 2B stone)

4.2 Tests HB-5 to HB-8: 6-inch Diameter SDR-35 Pipe in 2A Aggregates

Figure 4.12 shows the cross-sectional view of trench and instrumentation for the 6-inch diameter SDR-35 pipe in 2A aggregates. Figure 4.13 shows a detailed view of instrumentation including the pressure cells and strain gages. The instrumentation plan is generally consistent with Test SC-2 in State College (see Chapter 3). Backfill procedures for the backfill zone and cover zone are summarized below.

Backfill Zone:

1) Set 6 inch 2B stone bedding, no compaction
2) Lay pipe
3) Add 3 inch 2A aggregates, no compaction, lay three pressure cells on side of pipe
4) Add 9 inch 2A aggregates, compact using a jumping jack, lay three pressure cells on top of pipe, conduct nuclear density gage test at middle section of trench away from pipe (relative density 95.0%, moisture content 7.1%)
5) Add 6 inch 2A aggregates (reach top of backfill zone), compact using a jumping jack, conduct nuclear density gage test at middle section of trench away from pipe (relative density 96.5%, moisture content 4.8%)

Cover Zone:

6) Test HB-5: 24 inches/lift, 2 lifts total
7) Nuclear density gauge testing after compaction of each lift:
   Two density measurements (penetration depth of nuclear gauge: 12 inches) on top of compacted surface at approximately 4 ft from each end of pipe (i.e., above Sections 1 and 3, see Figure 4.2)
   Centered around the density measurement locations, scrape 12 inches off the compacted surface and create a flat area that extends at least 12 inches away (in all directions) from previous density measurement location
   Two density measurements (penetration depth of nuclear gauge: 12 inches) at previous density measurement locations on the flattened surface

8) Excavate compacted fill out of cover zone

9) Test HB-6: 3 lifts total (first two lifts: 18 inches/lift; last lift: 12 inches/lift)
10) Nuclear density gauge testing after compaction of each lift:
    Two density measurements (penetration depth of nuclear gauge: 12 inches) on top of compacted surface at approximately 4 ft from each end of pipe
    Centered around the density measurement locations, scrape 6 inches off the compacted surface and create a flat area that extends at least 12 inches away (in all directions) from previous density measurement location (for the first two lifts only)
    Two density measurements (penetration depth of nuclear gauge: 12 inches) at previous density measurement locations on the flattened surface (for the first two lifts only)

11) Excavate compacted fill out of cover zone

12) Test HB-7: 12 inches/lift, 4 lifts total
13) Nuclear density gauge testing (penetration depth of nuclear gauge: 12 inches) after compaction of each lift, two density measurements per lift at approximately 4 ft from each end of pipe

14) Excavate compacted fill out of cover zone

15) Test HB-8: 8 inches/lift, 6 lifts total
16) Nuclear density gauge testing (penetration depth of nuclear gauge: 8 inches) after compaction of each lift, two density measurements per lift at approximately 4 ft from each end of pipe

Figure 4.14 presents photos showing various stages of the field test. Table 4.3 presents results of nuclear density gauge tests for all four tests. Figure 4.15 shows the downward earth pressure versus time recorded by the embedded pressure cells for Test HB-5. Figure 4.16 shows the strains along pipe versus time recorded by the mounted strain gages for Test HB-5. Figures 4.17, 4.18, 4.19, 4.20, 4.21, and 4.22 show the corresponding plots for Test HB-6, HB-7, and HB-8.

Table 4.3 Results of nuclear density gauge tests for Tests HB-5 to HB-8 (SDR-35 pipe in 2A aggregates)

Test	Lifts (Surface)	Location 1 (Above Section #1)		Location 2 (Above Section #3)	
		Relative Density	Moisture Content	Relative Density	Moisture Content
HB-5	1 (Top)	104.4%	4.5%	105.2%	4.4%
	1 (Scraped)	93.5%	4.5%	100.0%	4.5%
	2 (Top)	99.4%	2.8%	100.4%	2.7%
	2 (Scraped)	90.0%	3.0%	97.2%	3.3%
HB-6	1 (Top)	101.3%	5.1%	106.3%	4.3%
	1 (Scraped)	95.6%	5.0%	100.9%	5.2%
	2 (Top)	101.2%	4.5%	101.5%	5.1%
	2 (Scraped)	95.5%	4.3%	93.7%	4.8%
	3	102.5%	3.9%	102.0%	2.9%
HB-7	1	104.2%	5.1%	103.9%	4.7%
	2	105.5%	3.9%	104.2%	5.3%
	3	103.3%	4.3%	100.1%	3.3%
	4	103.6%	4.1%	107.7%	3.5%
HB-8	1	104.0%	4.7%	108.7%	5.0%
	2	99.8%	4.2%	100.4%	3.6%
	3	106.6%	4.4%	102.4%	4.4%
	4	102.4%	3.3%	106.4%	4.0%
	5	104.5%	3.6%	106.5%	4.3%
	6	102.4%	3.9%	105.4%	3.4%

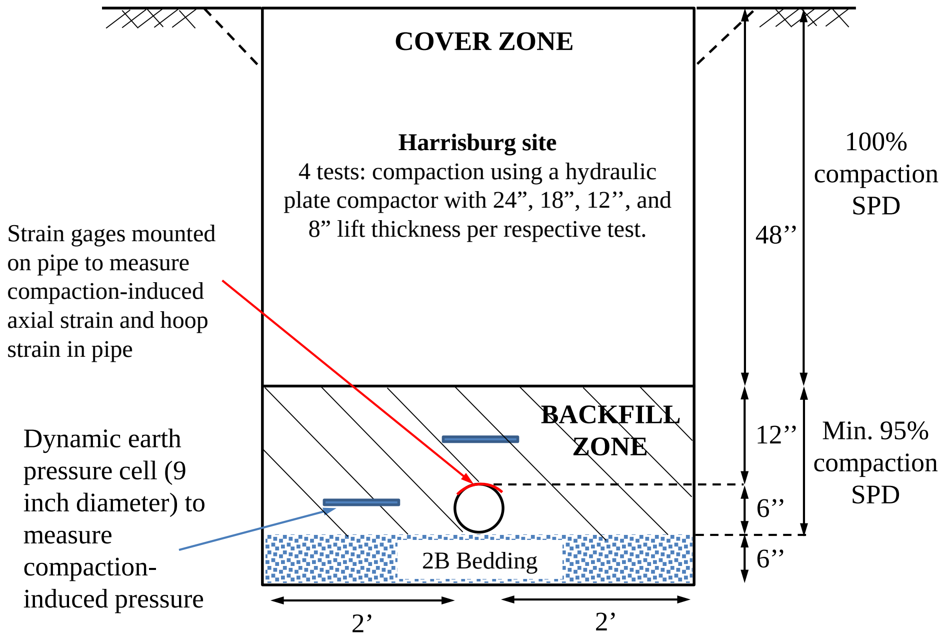

Figure 4.12 Cross-sectional view of trench and instrumentation for 6-inch diameter SDR-35 pipe in 2A aggregates (not to scale)

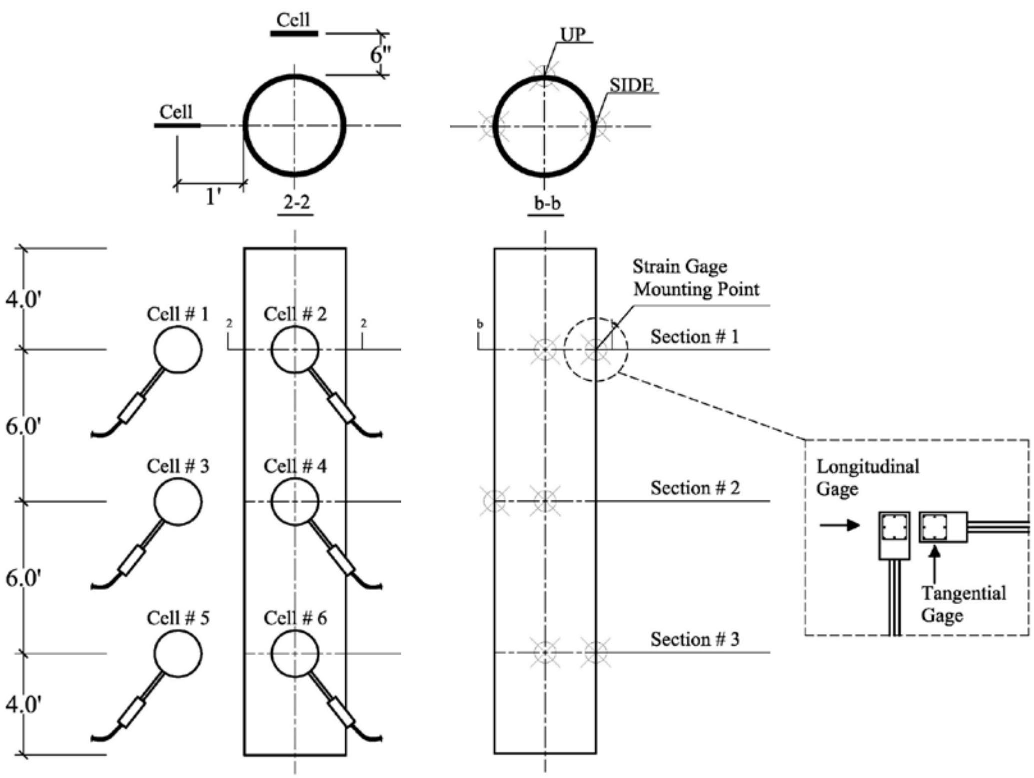

Figure 4.13 Detailed view of instrumentation for 6-inch diameter SDR-35 pipe in 2A aggregates (not to scale)

Figure 4.14 Photos showing various stages of field test: a) placement of pressure cells on side along mid elevation of pipe; b) compaction using a hydraulic plate compactor; c) model of hydraulic plate compactor used: Applied 1000B; d) nuclear density gauge testing on a compacted surface; e) fine material is used to create a smooth surface in a scraped area for nuclear density gauge testing

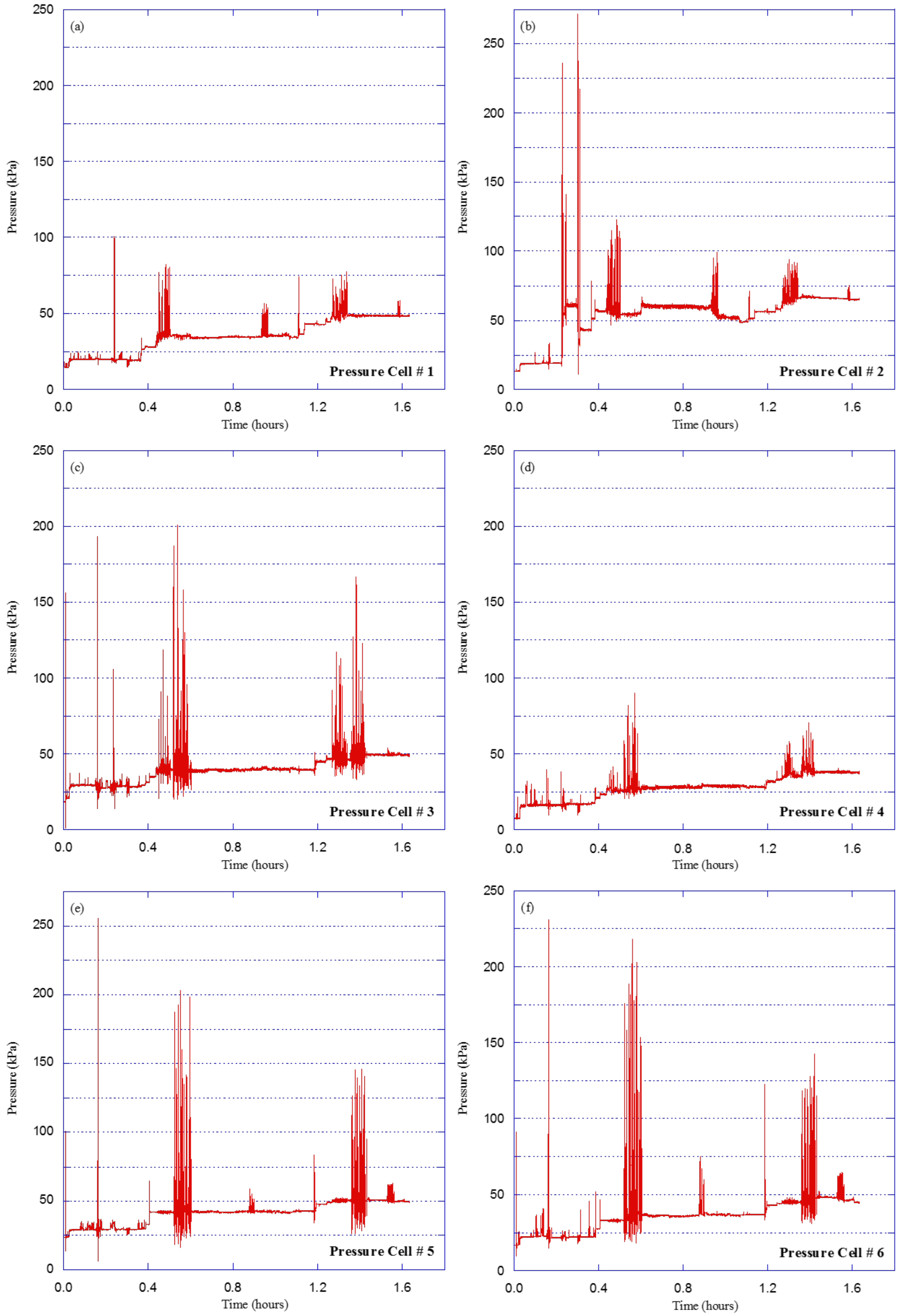

Figure 4.15 Downward earth pressures versus time for Test HB-5 (SDR-35 pipe in 2A aggregates)

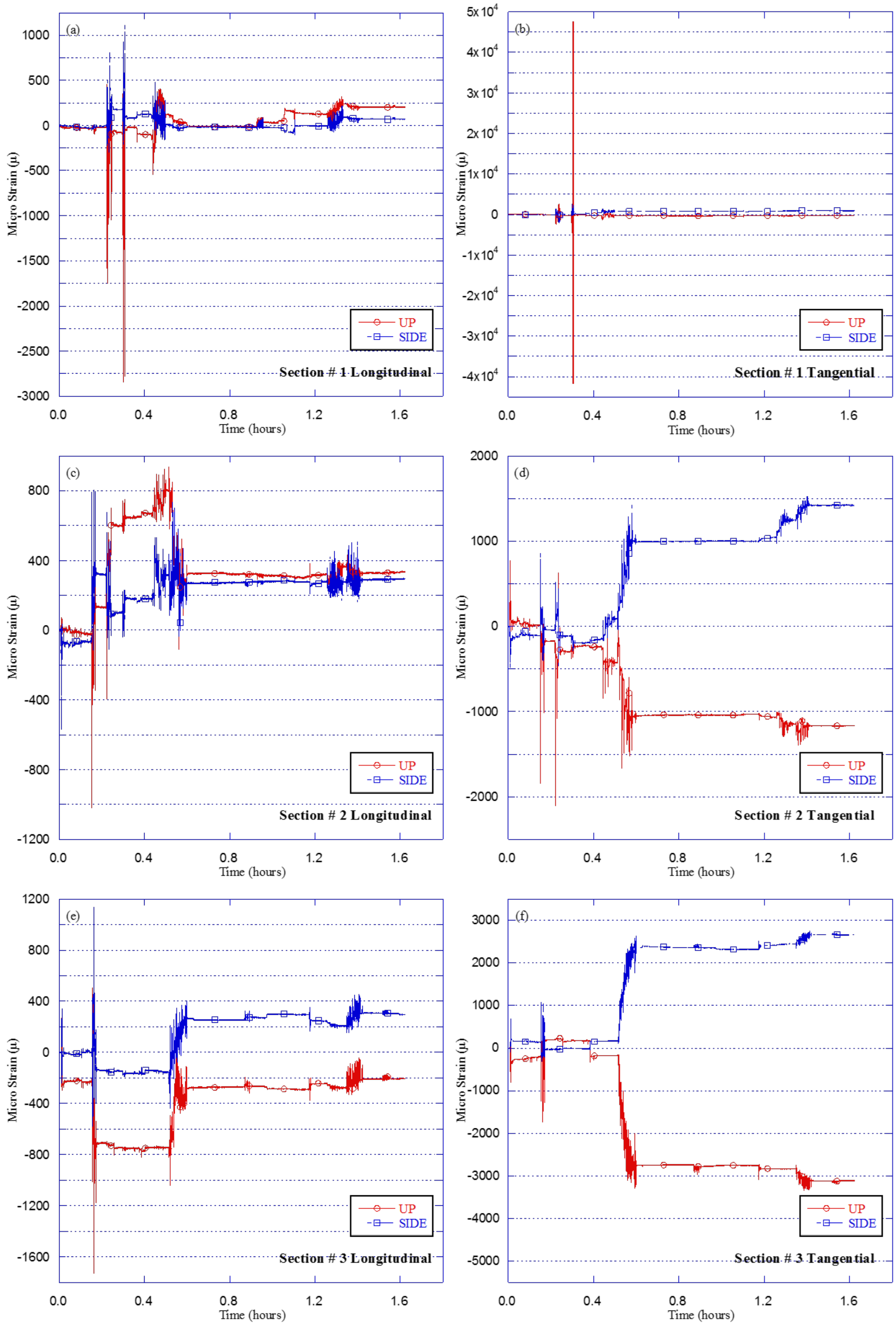

Figure 4.16 Strains along pipe versus time for Test HB-5 (SDR-35 pipe in 2A aggregates)

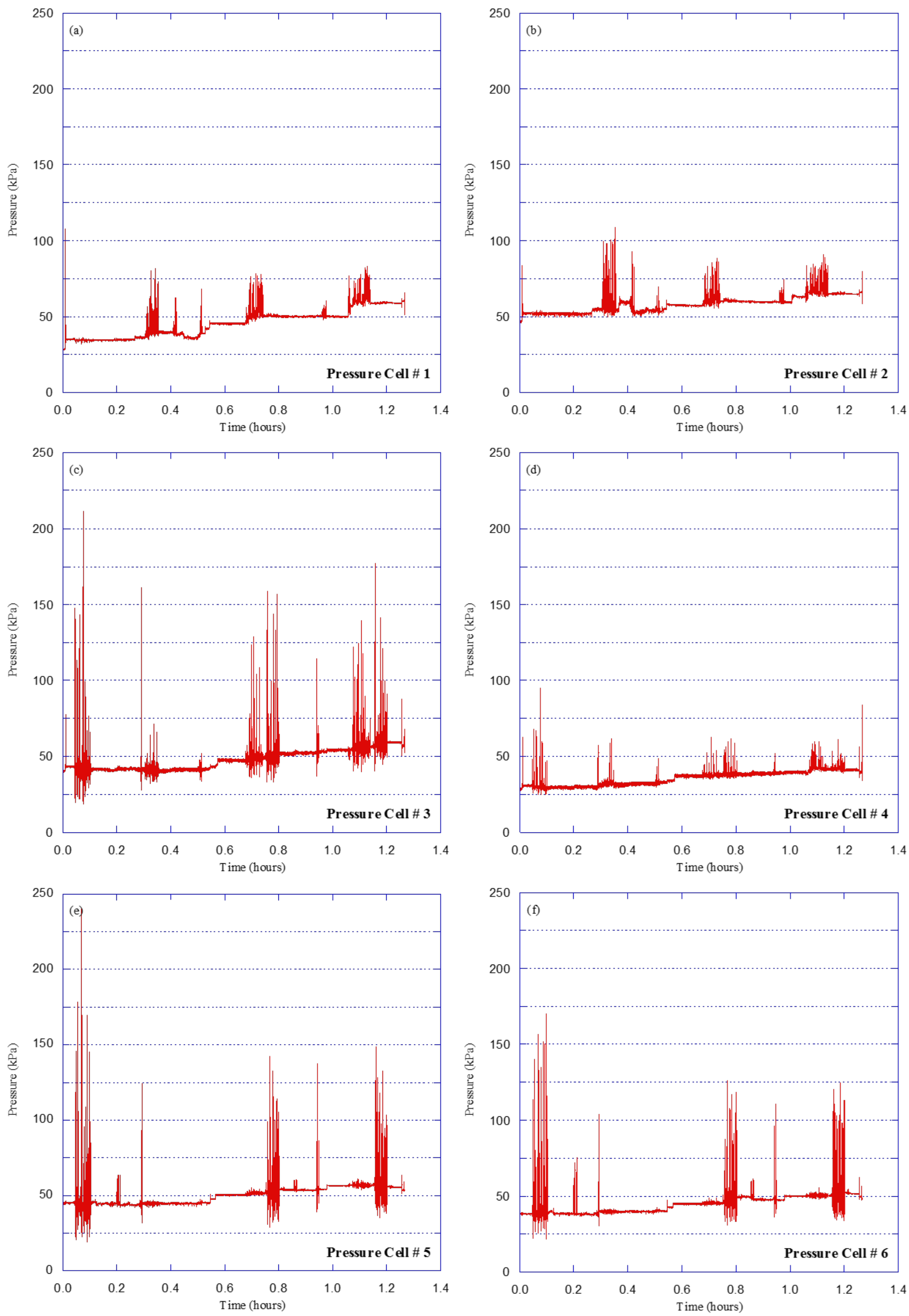

Figure 4.17 Downward earth pressures versus time for Test HB-6 (SDR-35 pipe in 2A aggregates)

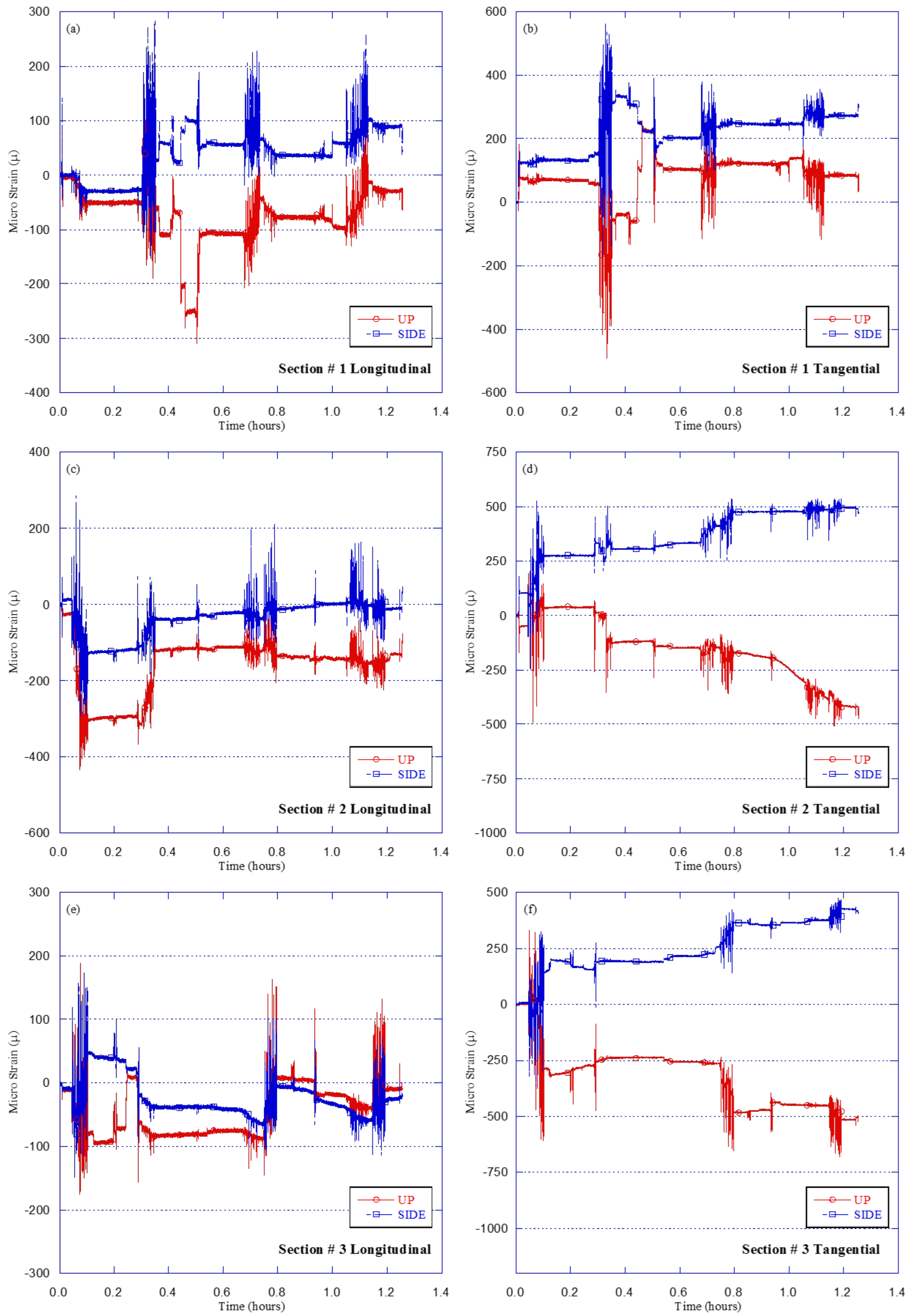

Figure 4.18 Strains along pipe versus time for Test HB-6 (SDR-35 pipe in 2A aggregates)

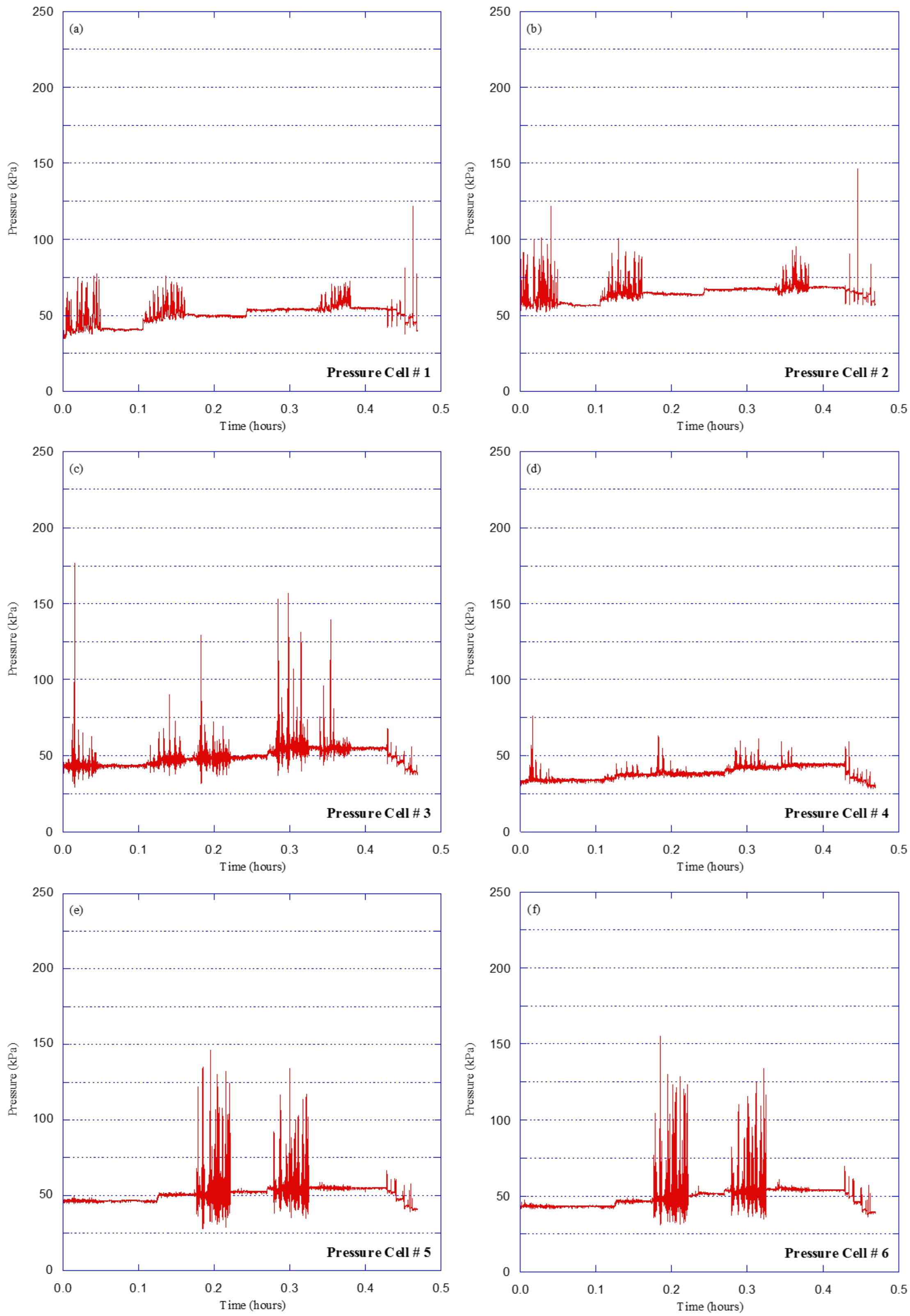

Figure 4.19 Downward earth pressures versus time for Test HB-7 (SDR-35 pipe in 2A aggregates)

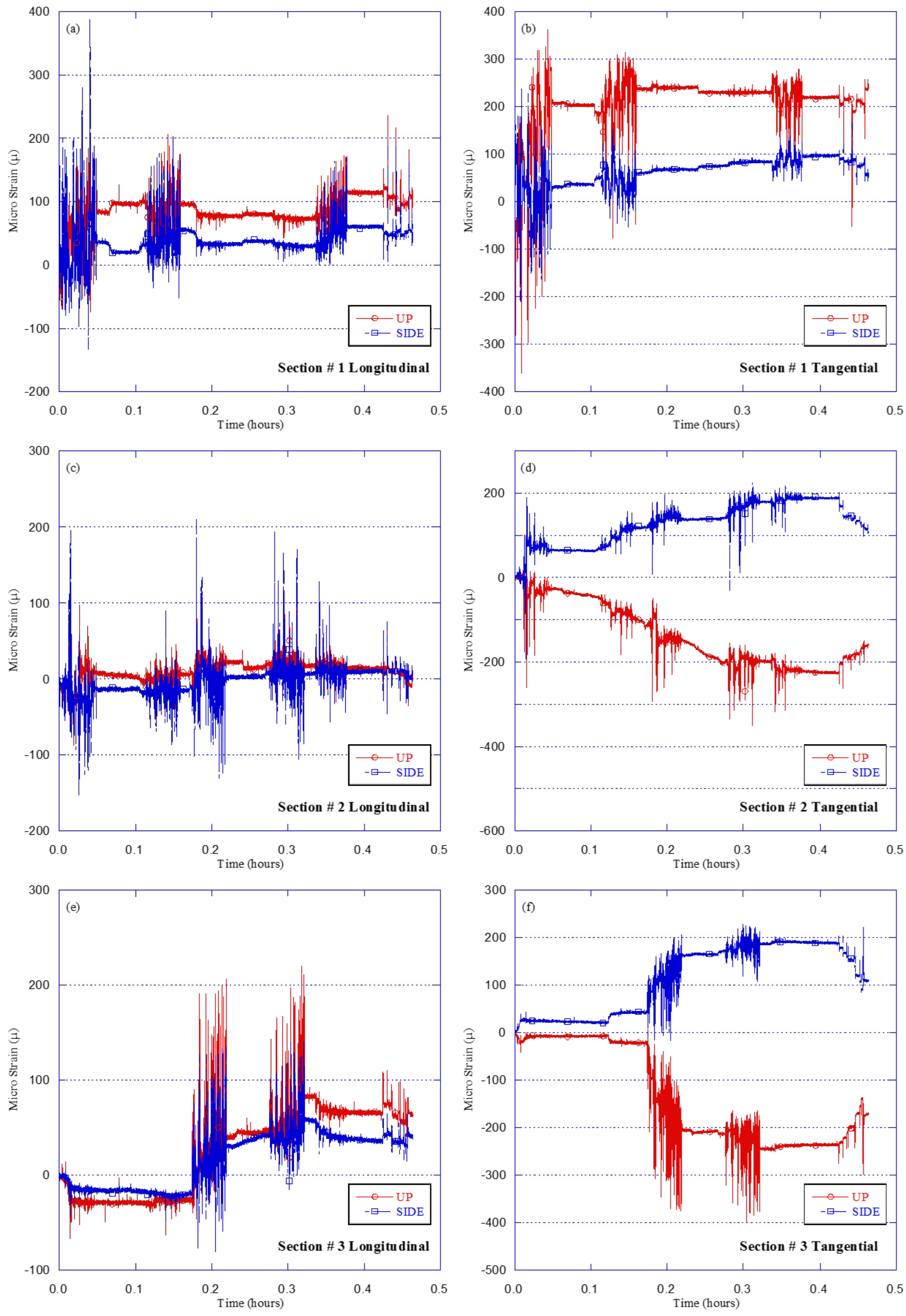

Figure 4.20 Strains along pipe versus time for Test HB-7 (SDR-35 pipe in 2A aggregates)

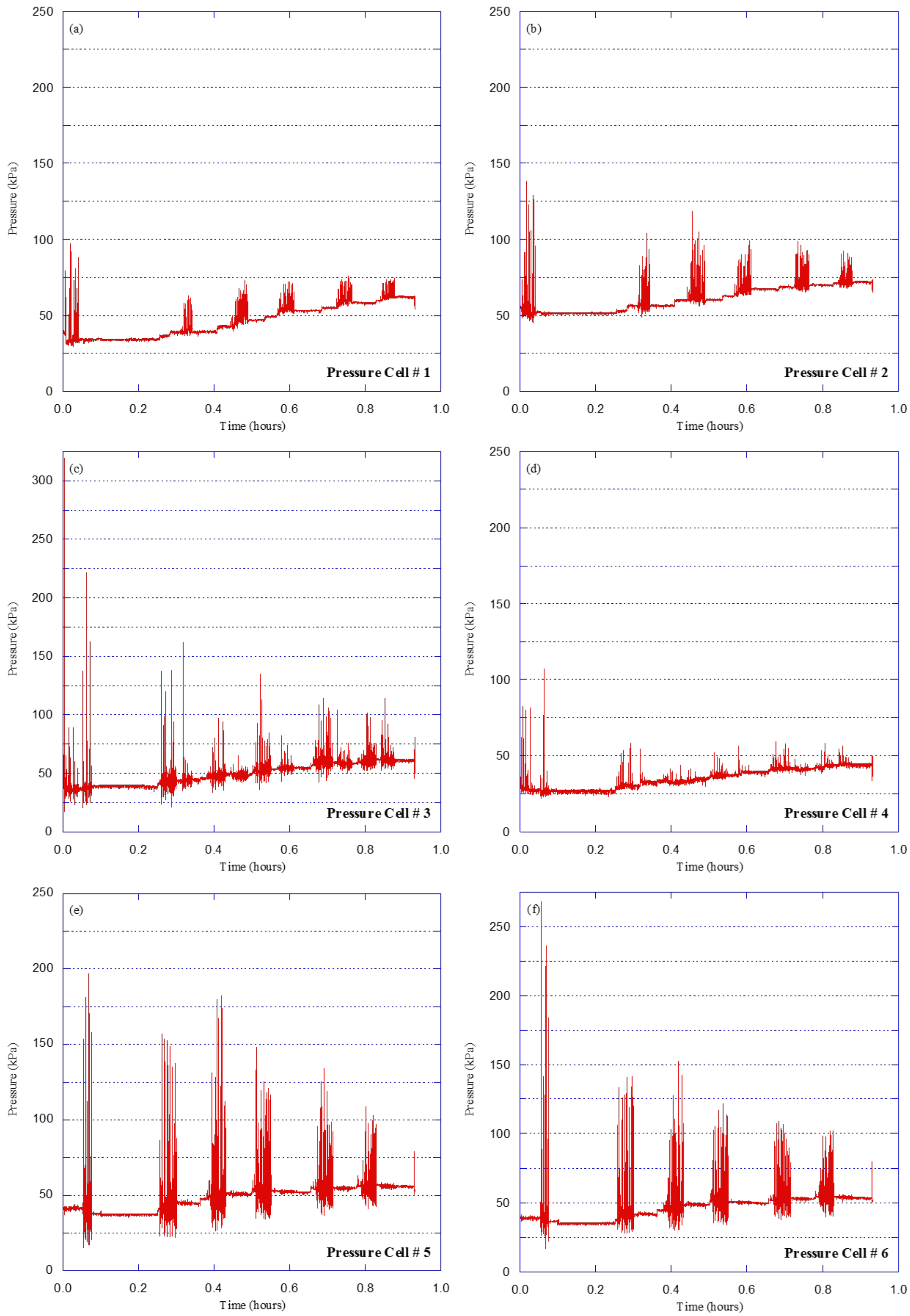

Figure 4.21 Downward earth pressures versus time for Test HB-8 (SDR-35 pipe in 2A aggregates)

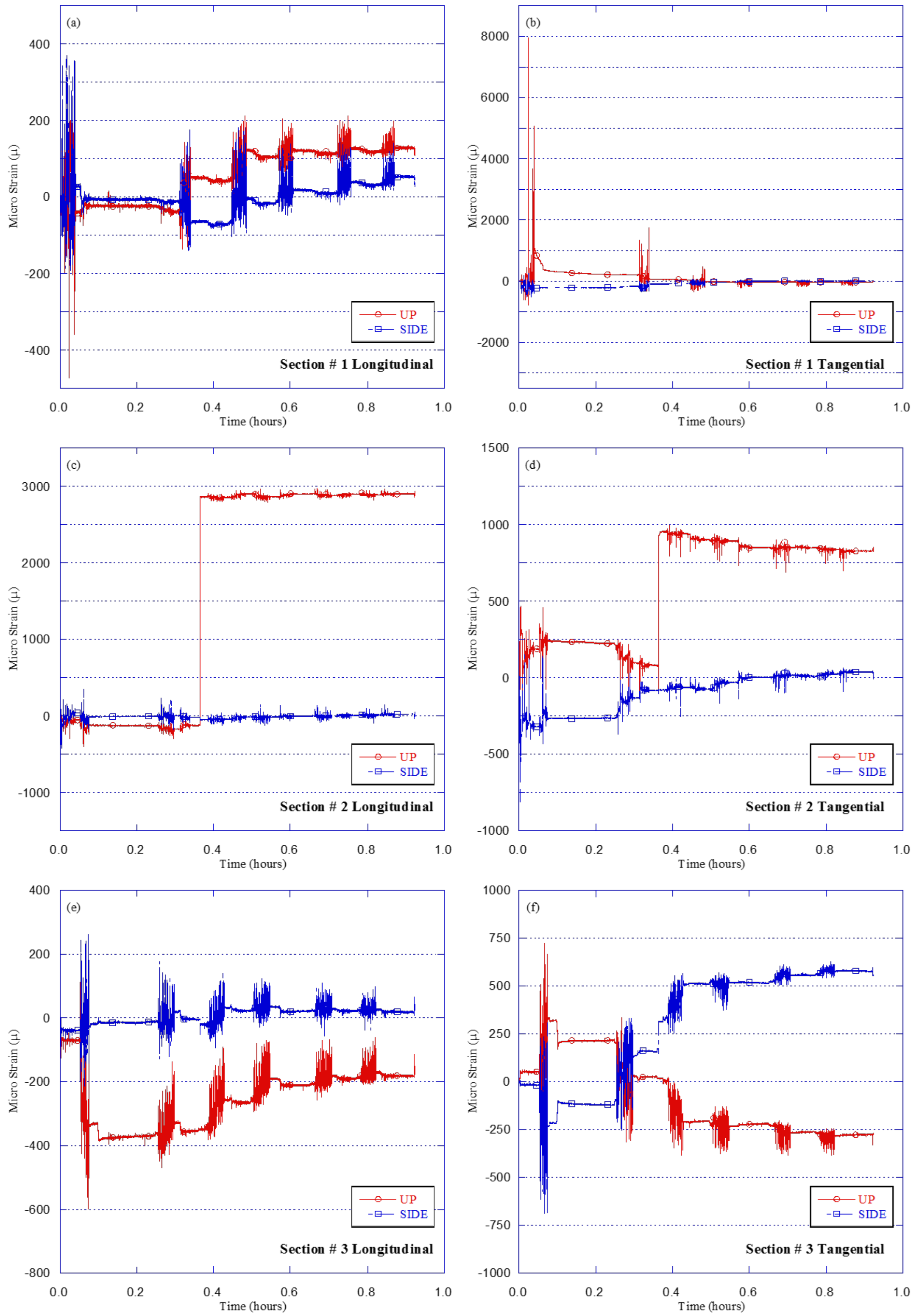

Figure 4.22 Strains along pipe versus time for Test HB-8 (SDR-35 pipe in 2A aggregates)

4.3 Tests HB-9 to HB-12: 18-inch Diameter Reinforced Concrete Pipe

Figure 4.23 shows the cross-sectional view of trench and instrumentation for the 18-inch diameter reinforced concrete pipe. Figure 4.24 shows a detailed view of instrumentation including the pressure cells and strain gages. The instrumentation plan is generally consistent with Test SC-3 in State College (see Chapter 3). Backfill procedures for the backfill zone and cover zone are summarized below.

Backfill Zone:

1) Set 6 inch AASHTO #8 bedding, no compaction
2) Lay pipe: each section of pipe is 8 feet long, two sections are connected in the trench using rubber seal gasket, the pipe was positioned along the centerline of the trench.
3) Add 9 inch 2A aggregates on both sides of pipe, lightly compact (away from pipe) using a hydraulic plate compactor, lay three pressure cells on side of pipe, conduct nuclear density gage test at middle section of trench away from pipe (relative density 95.0%, moisture content 3.9%)
4) Add 9 inch 2A aggregates on both sides of pipe, lightly compact (away from pipe) using a hydraulic plate compactor, lay three pressure cells on opposite side of pipe, conduct nuclear density gage test at middle section of trench away from pipe (relative density 96.1%, moisture content 3.9%)
5) Add 24 inch 2A aggregates at once (reach top of backfill zone), lightly compact using a hydraulic plate compactor (stay away from backfill directly above pipe), conduct nuclear density gage test at middle section of trench away from pipe (relative density 97.3%, moisture content 3.6%)

Cover Zone:

6) Test HB-9: 24 inches/lift, 2 lifts total
7) Nuclear density gauge testing after compaction of each lift:
   Two density measurements (penetration depth of nuclear gauge: 12 inches) on top of compacted surface at approximately 4 feet from each end of pipe (i.e., above Sections 1 and 3, see Figure 4.2)
   Centered around the density measurement locations, scrape 12 inches off the compacted surface and create a flat area that extends at least 12 inches away (in all directions) from previous density measurement location
   Two density measurements (penetration depth of nuclear gauge: 12 inches) at previous density measurement locations on the flattened surface

8) Excavate compacted fill out of cover zone

9) Test HB-10: 18 inches/lift, 2 lifts total
10) Nuclear density gauge testing after compaction of each lift:
    Two density measurements (penetration depth of nuclear gauge: 12 inches) on top of compacted surface at approximately 4 feet from each end of pipe
    Centered around the density measurement locations, scrape 6 inches off the compacted surface and create a flat area that extends at least 12 inches away (in all directions) from previous density measurement location

Two density measurements (penetration depth of nuclear gauge: 12 inches) at previous density measurement locations on the flattened surface

11) Excavate compacted fill out of cover zone

12) Test HB-11: 12 inches/lift, 3 lifts total
13) Nuclear density gauge testing (penetration depth of nuclear gauge: 12 inches) after compaction of each lift, two density measurements per lift at approximately 4 feet from each end of pipe

14) Excavate compacted fill out of cover zone

15) Test HB-12: 8 inches/lift, 5 lifts total
16) Nuclear density gauge testing (penetration depth of nuclear gauge: 8 inches) after compaction of each lift, two density measurements per lift at approximately 4 feet from each end of pipe

Figure 4.25 presents photos showing various stages of the field test. Table 4.4 presents results of nuclear density gauge tests for all four tests. Figure 4.26 shows the downward earth pressure versus time recorded by the embedded pressure cells for Test HB-9. Figure 4.27 shows the strains along pipe versus time recorded by the mounted strain gages for Test HB-9. Figures 4.28, 4.29, 4.30, 4.31, 4.32, and 4.33 show the corresponding plots for Test HB-10, HB-11, and HB-12.

Table 4.4 Results of nuclear density gauge tests for Tests HB-9 to HB-12 (reinforced concrete pipe)

Test	Lifts (Surface)	Location 1 (Above Section #1)		Location 2 (Above Section #3)	
		Relative Density	Moisture Content	Relative Density	Moisture Content
HB-9	1 (Top)	103.5%	4.6%	101.8%	5.1%
	1 (Scraped)	97.4%	6.4%	93.7%	4.6%
	2 (Top)	101.5%	5.3%	103.5%	4.7%
	2 (Scraped)	92.3%	4.9%	91.7%	5.8%
HB-10	1 (Top)	98.7%	4.9%	100.4%	5.2%
	1 (Scraped)	99.0%	5.1%	96.1%	6.3%
	2 (Top)	103.1%	5.6%	101.3%	4.7%
	2 (Scraped)	96.2%	7.3%	94.9%	5.7%
HB-11	1	102.1%	4.6%	103.5%	5.4%
	2	106.9%	5.2%	100.2%	5.1%
	3	100.9%	5.2%	104.1%	4.9%
HB-12	1	102.6%	5.4%	106.5%	5.3%
	2	99.0%	4.7%	104.4%	5.3%
	3	102.6%	5.1%	100.8%	5.3%
	4	102.6%	5.2%	103.4%	4.8%
	5	98.9%	4.3%	98.5%	4.8%

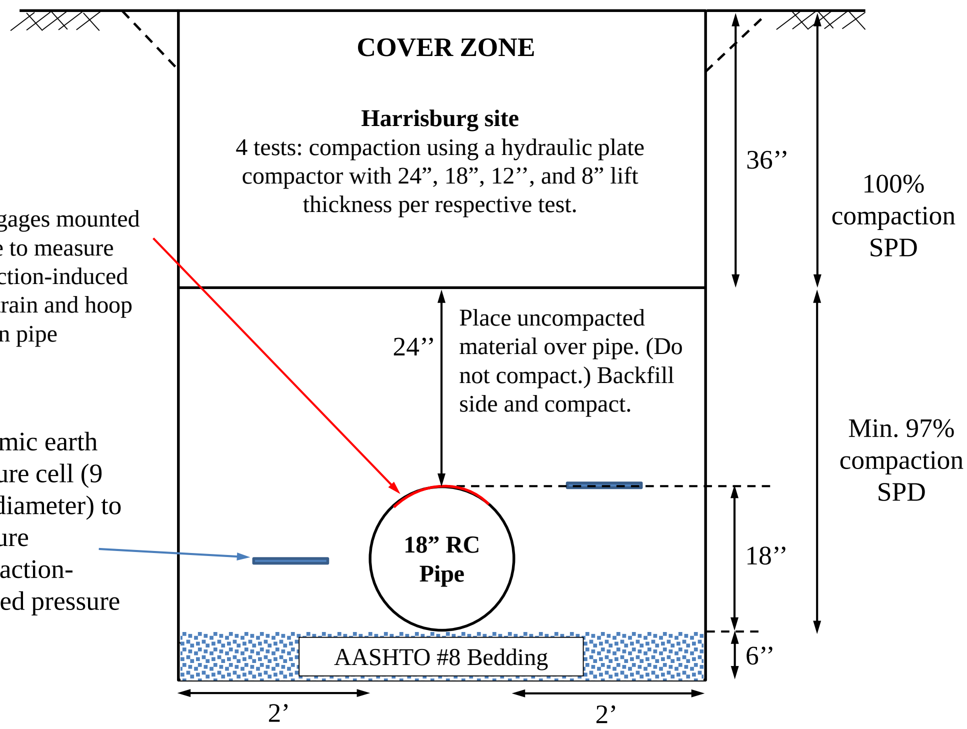

Figure 4.23 Cross-sectional view of trench and instrumentation for 18-inch diameter reinforced concrete pipe (not to scale)

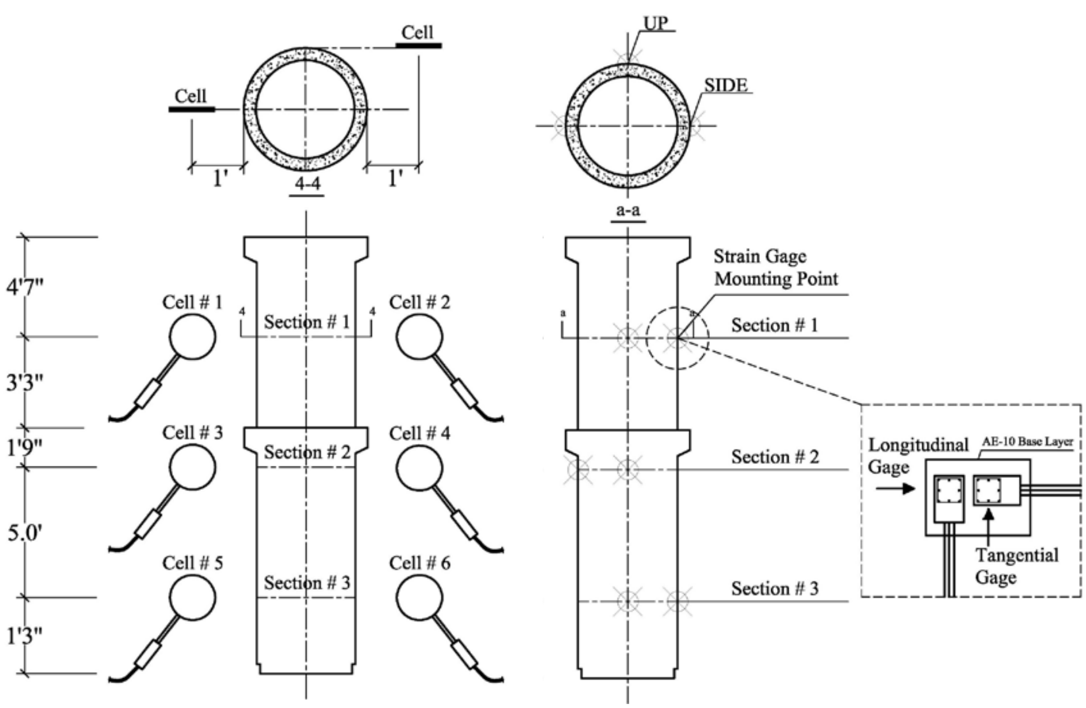

Figure 4.24 Detailed view of instrumentation for 18-inch diameter reinforced concrete pipe (not to scale)

Figure 4.25 Photos showing various stages of field test: a) AASHTO #8 bedding in trench; b) connecting concrete pipes in trench; c) dump fill materials into trench, both ends of concrete pipe covered by wood plate; d) compaction using a hydraulic plate compactor; e) excavating compacted fill materials; f) retrieved pipe after test

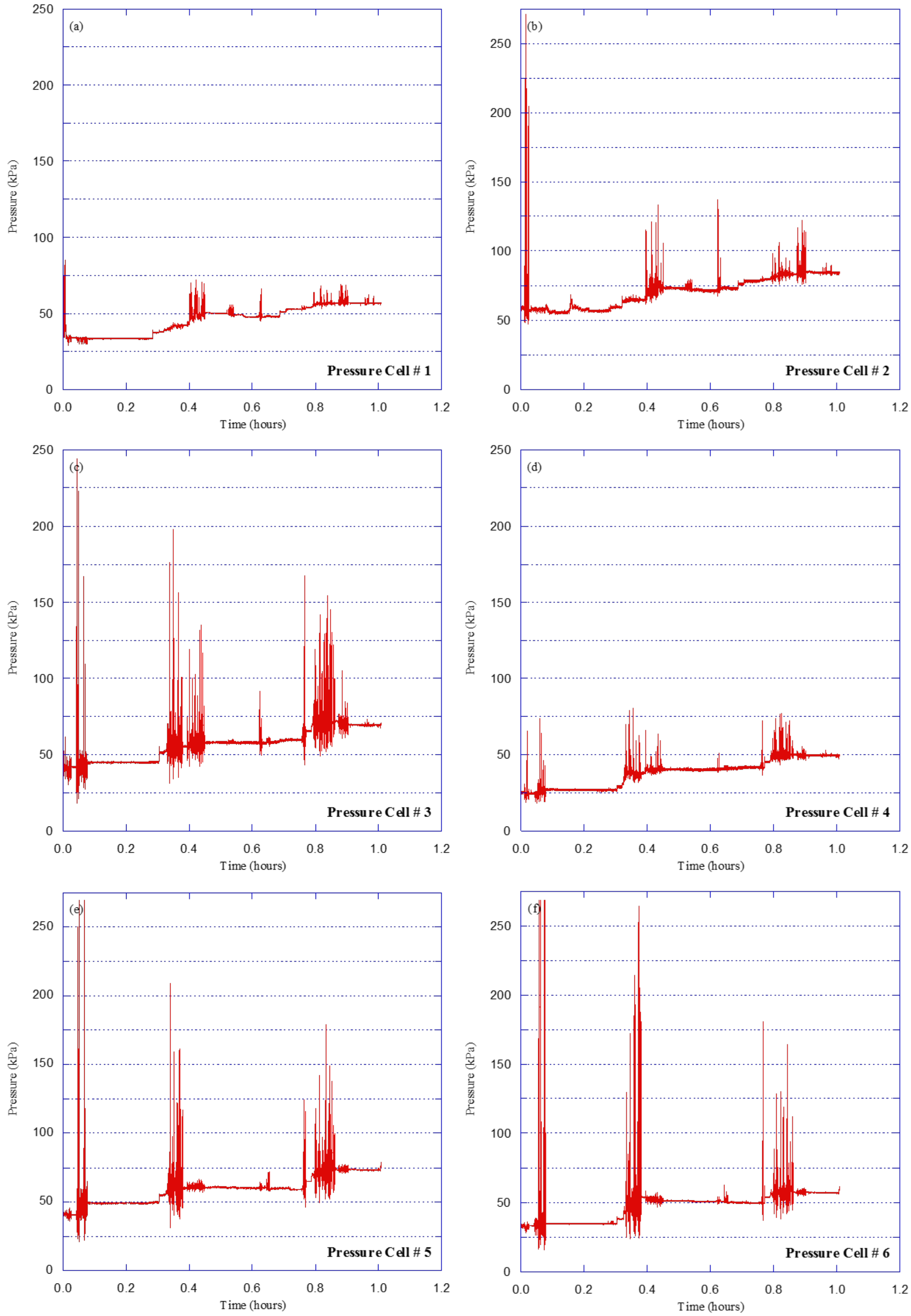

Figure 4.26 Downward earth pressures versus time for Test HB-9 (reinforced concrete pipe)

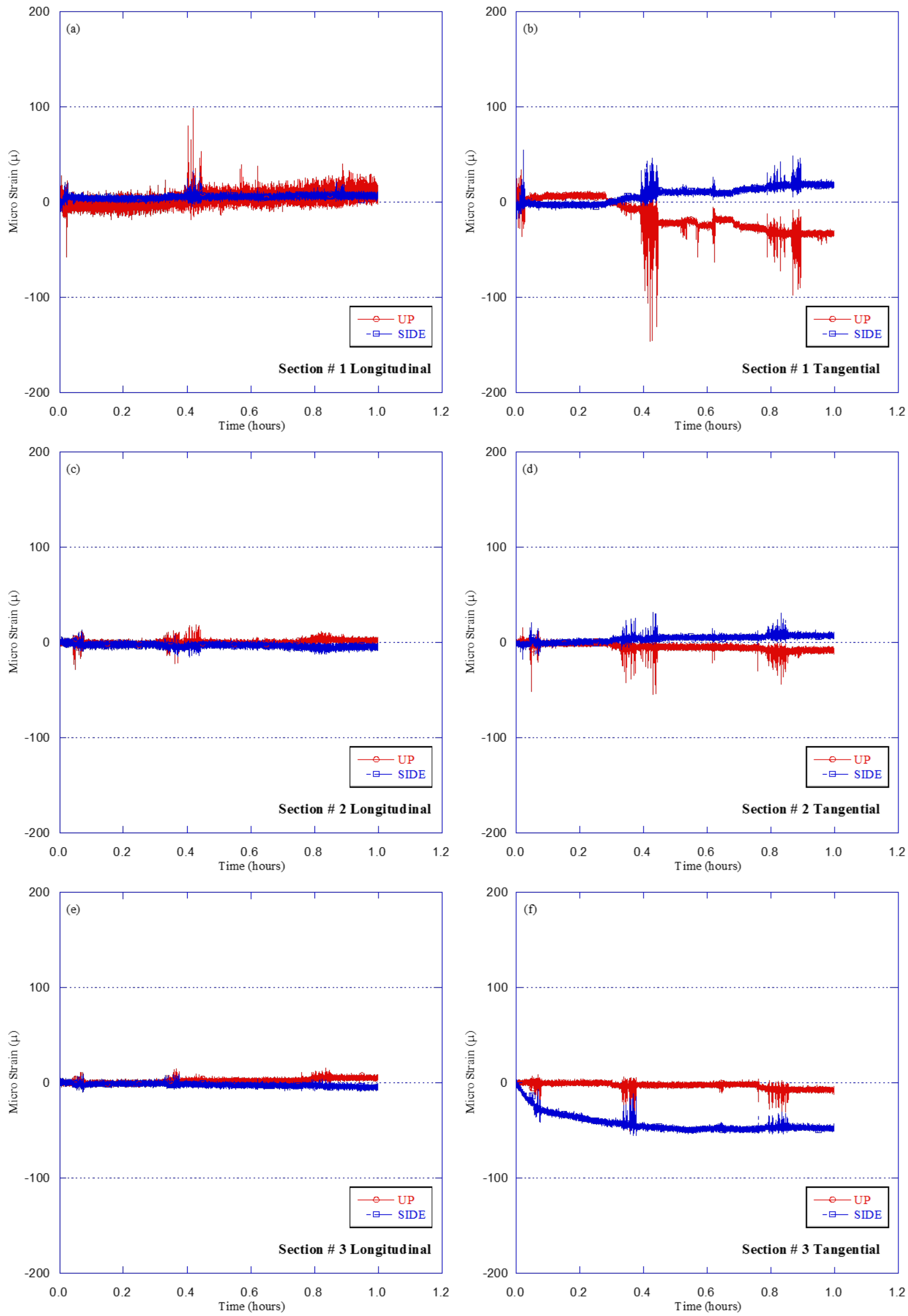

Figure 4.27 Strains along pipe versus time for Test HB-9 (reinforced concrete pipe)

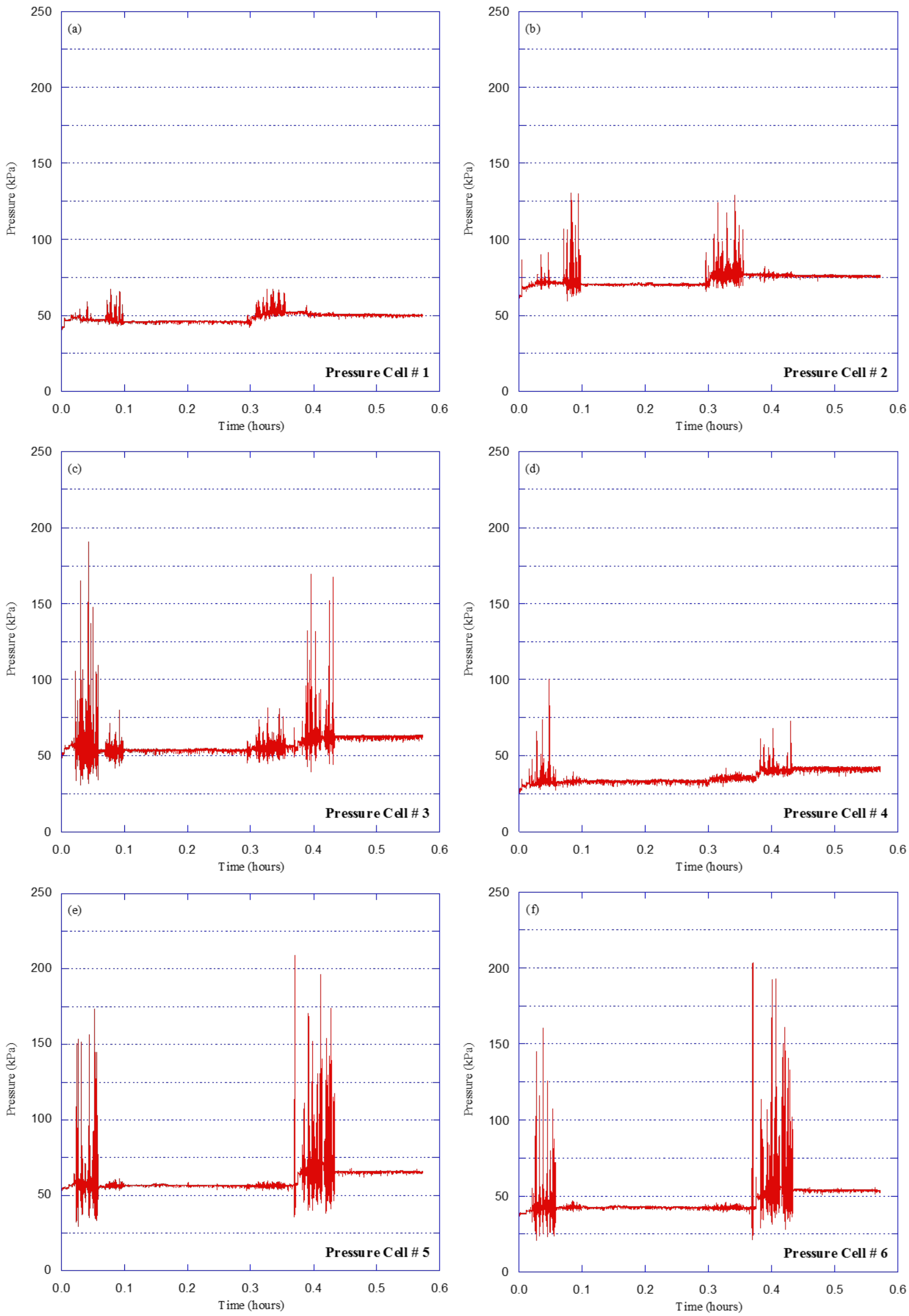

Figure 4.28 Downward earth pressures versus time for Test HB-10 (reinforced concrete pipe)

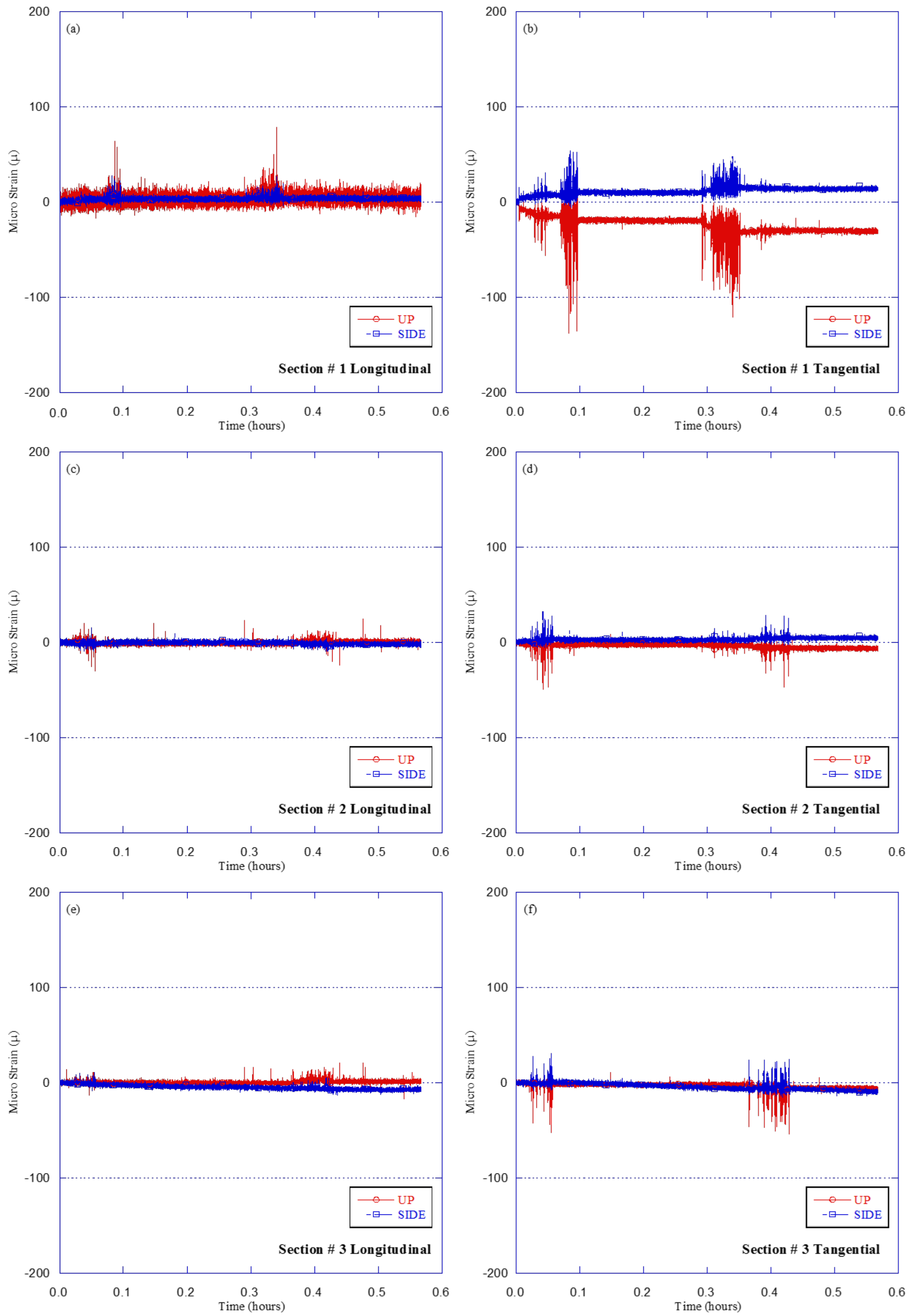

Figure 4.29 Strains along pipe versus time for Test HB-10 (reinforced concrete pipe)

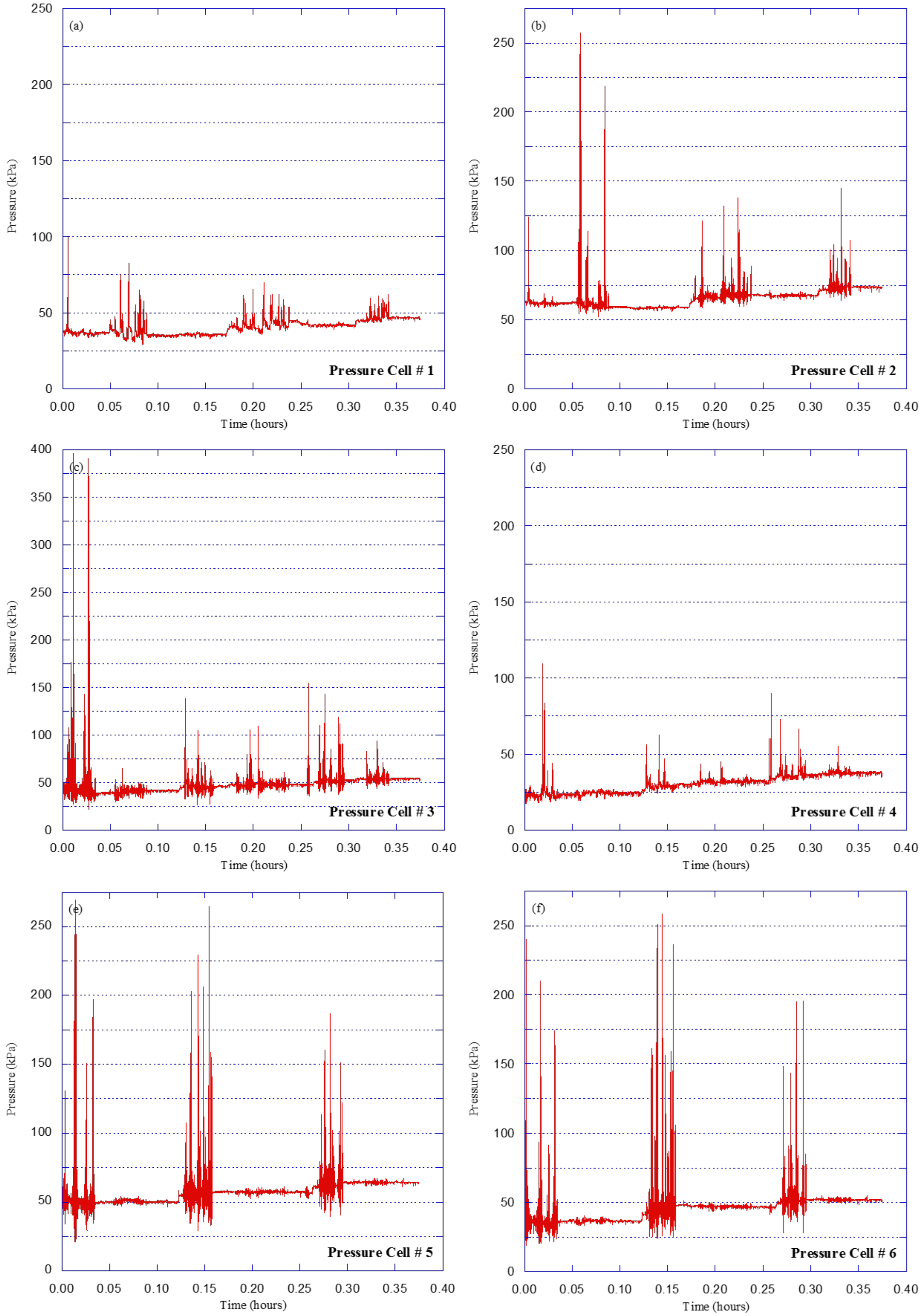

Figure 4.30 Downward earth pressures versus time for Test HB-11 (reinforced concrete pipe)

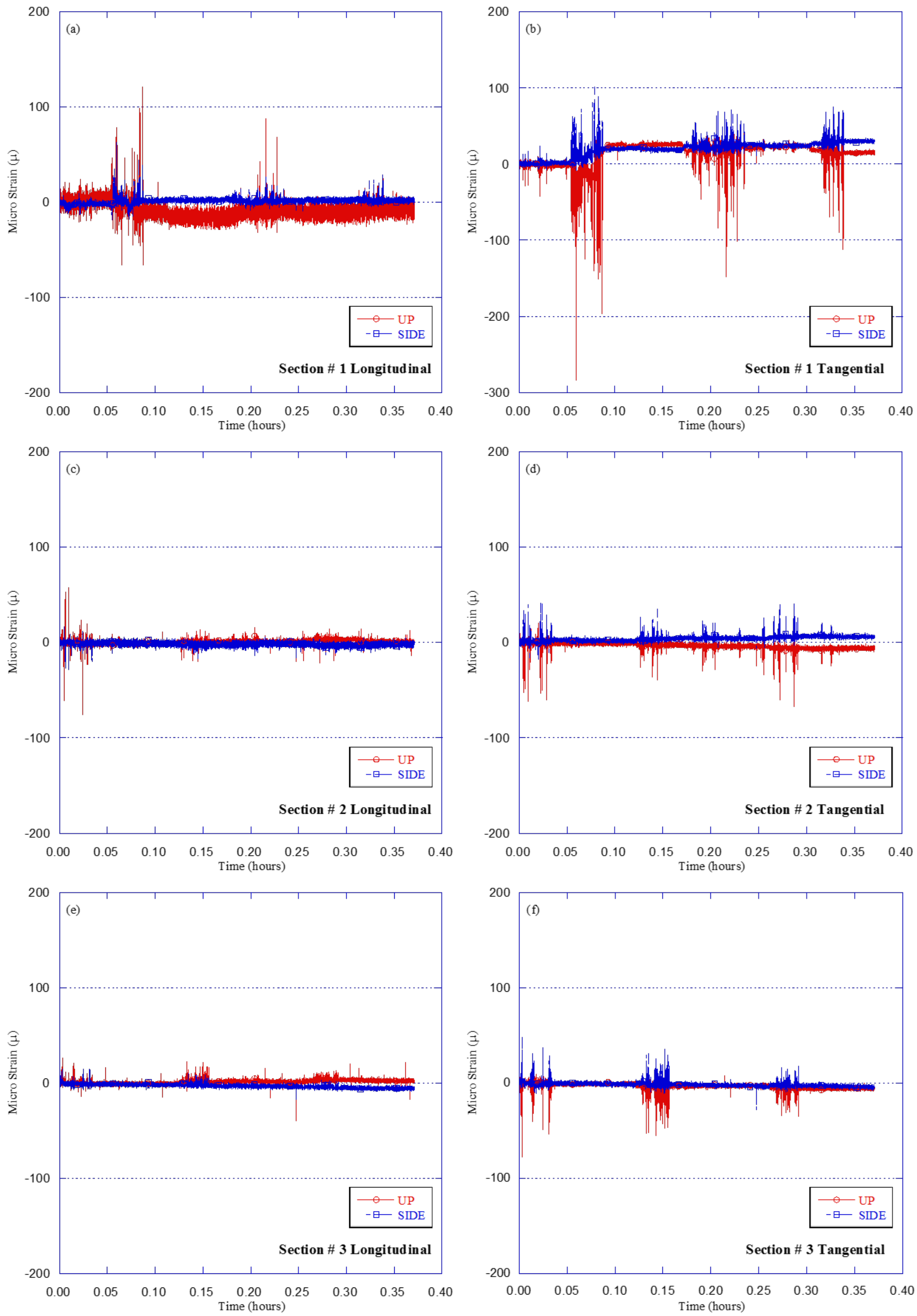

Figure 4.31 Strains along pipe versus time for Test HB-11 (reinforced concrete pipe)

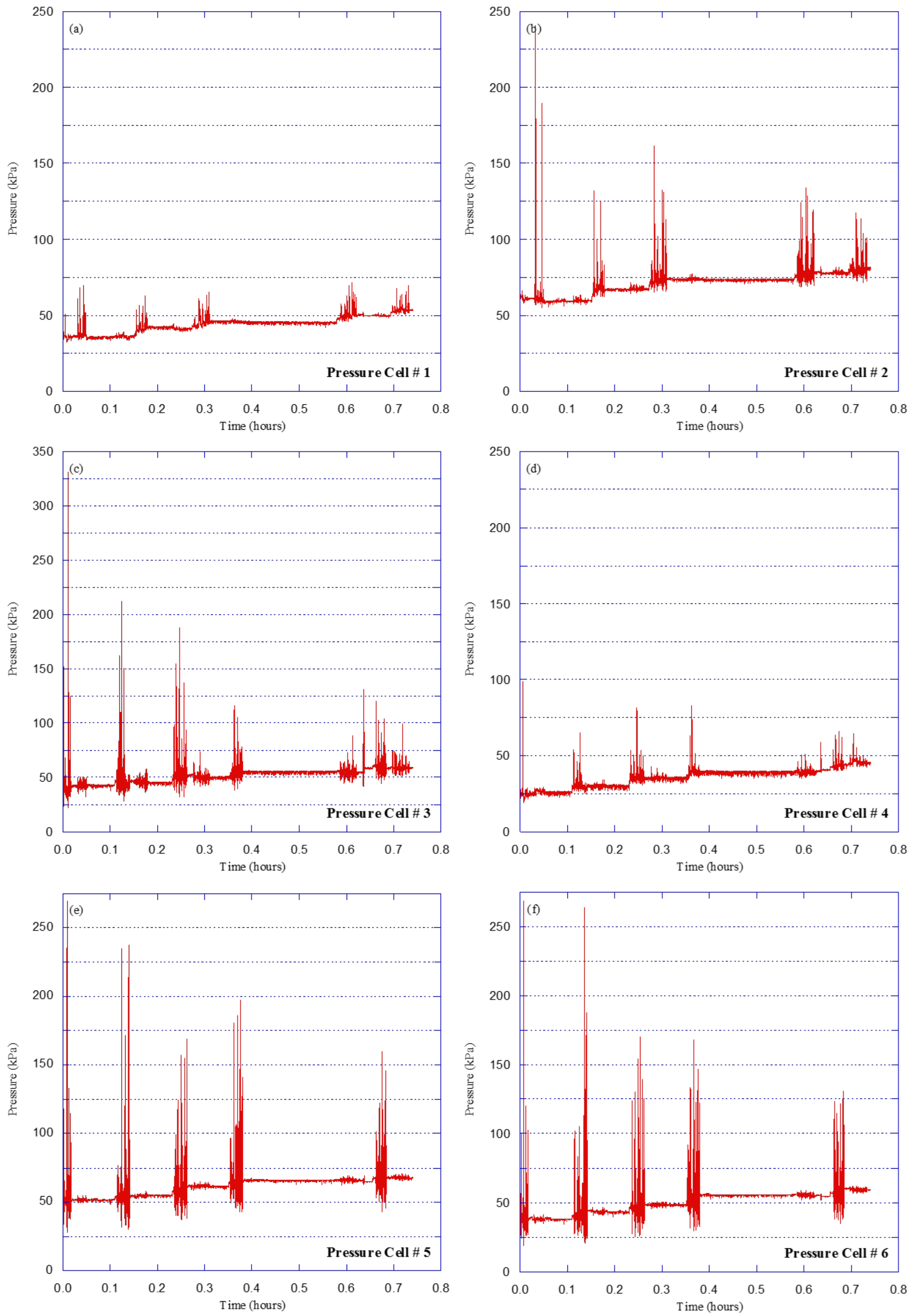

Figure 4.32 Downward earth pressures versus time for Test HB-12 (reinforced concrete pipe)

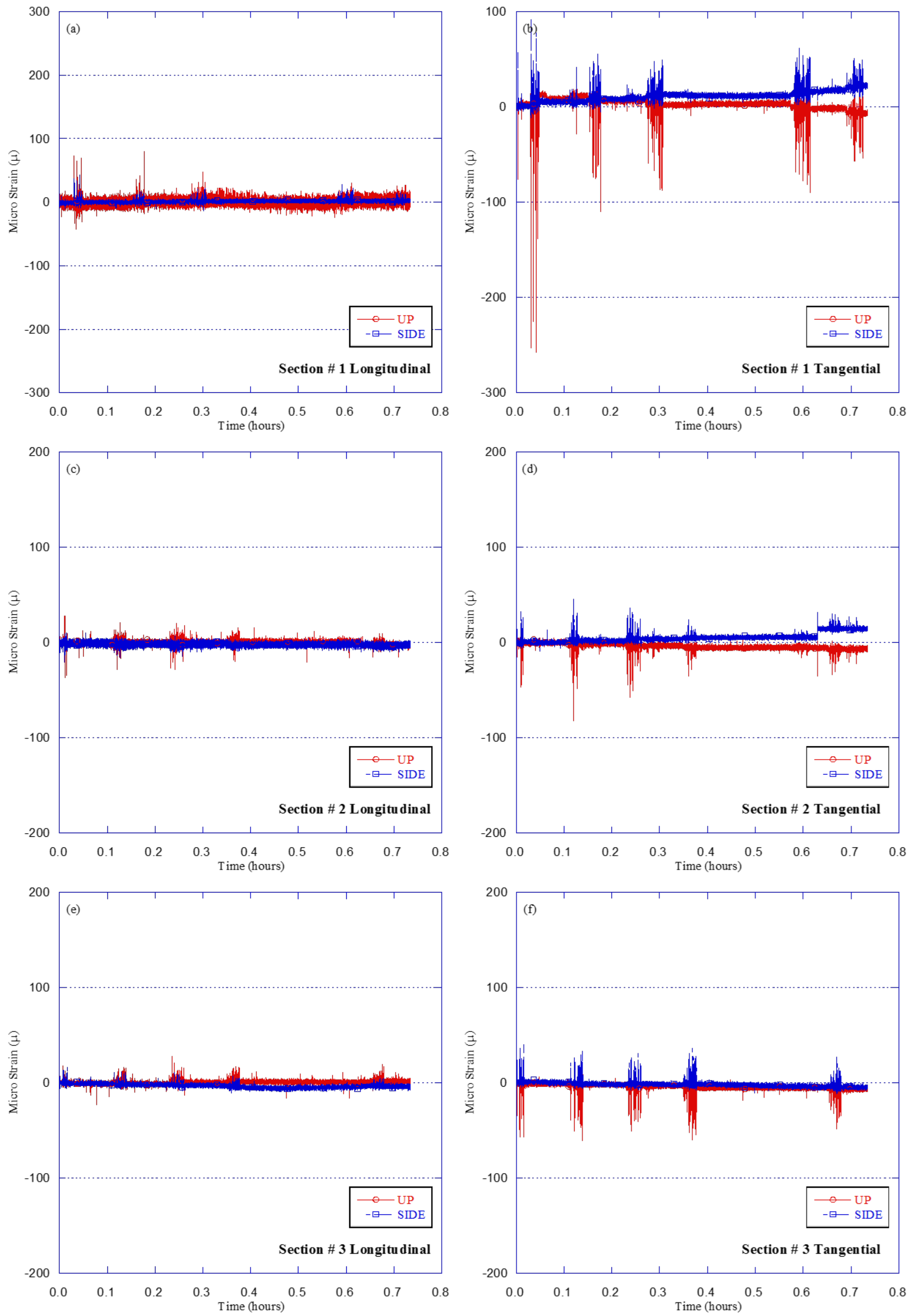

Figure 4.33 Strains along pipe versus time for Test HB-12 (reinforced concrete pipe)

4.4 Tests HB-13 to HB-16: 18-inch Diameter HDPE Drainage Pipe

Figure 4.34 shows the cross-sectional view of trench and instrumentation for the 18-inch diameter HDPE drainage pipe. Figure 4.35 shows a detailed view of instrumentation including the pressure cells and strain gages. The instrumentation plan is generally consistent with Test SC-4 in State College (see Chapter 3). Backfill procedures for the backfill zone and cover zone are summarized below.

Backfill Zone:

1) Set 6 inch 2A bedding, compact using a jumping jack
2) Lay pipe
3) Add 9 inch 2A aggregates on both sides of pipe, lightly compact using a hydraulic plate compactor, lay three pressure cells on side of pipe, conduct nuclear density gage test at middle section of trench away from pipe (relative density 95.9%, moisture content 5.3%)
4) Add 9 inch 2A aggregates to pipe crest, lightly compact using a hydraulic plate compactor, no density measurement
5) Add 6 inch 2A aggregates, lightly compact using a hydraulic plate compactor, lay three pressure cells on top of pipe, conduct nuclear density gage test at middle section of trench away from pipe (relative density 99.3%, moisture content 5.0%)
6) Add 6 inch 2A aggregates, lightly compact using a hydraulic plate compactor, conduct nuclear density gage test at middle section of trench away from pipe (relative density 99.1%, moisture content 5.0%)

Cover Zone:

7) Test HB-13: 24 inches/lift, 2 lifts total
8) Nuclear density gauge testing after compaction of each lift:
   Two density measurements (penetration depth of nuclear gauge: 12 inches) on top of compacted surface at approximately 4 ft from each end of pipe (i.e., above Sections 1 and 3, see Figure 4.2)
   Centered around the density measurement locations, scrape 12 inches off the compacted surface and create a flat area that extends at least 12 inches away (in all directions) from previous density measurement location
   Two density measurements (penetration depth of nuclear gauge: 12 inches) at previous density measurement locations on the flattened surface

9) Excavate compacted fill out of cover zone

10) Test HB-14: 3 lifts total (first two lifts: 18 inches/lift; last lift: 12 inches/lift)
11) Nuclear density gauge testing after compaction of each lift:
   Two density measurements (penetration depth of nuclear gauge: 12 inches) on top of compacted surface at approximately 4 ft from each end of pipe
   Centered around the density measurement locations, scrape 6 inches off the compacted surface and create a flat area that extends at least 12 inches away (in all directions) from previous density measurement location (for the first two lifts only)

Two density measurements (penetration depth of nuclear gauge: 12 inches) at previous density measurement locations on the flattened surface (for the first two lifts only)

12) Excavate compacted fill out of cover zone

13) Test HB-15: 12 inches/lift, 4 lifts total
14) Nuclear density gauge testing (penetration depth of nuclear gauge: 12 inches) after compaction of each lift, two density measurements per lift at approximately 4 feet from each end of pipe

15) Excavate compacted fill out of cover zone

16) Test HB-16: 8 inches/lift, 6 lifts total
17) Nuclear density gauge testing (penetration depth of nuclear gauge: 8 inches) after compaction of each lift, two density measurements per lift at approximately 4 feet from each end of pipe

Figure 4.36 presents photos showing various stages of the field test. Table 4.5 presents results of nuclear density gauge tests for all four tests. Figure 4.37 shows the downward earth pressure versus time recorded by the embedded pressure cells for Test HB-13. Figure 4.38 shows the strains along pipe versus time recorded by the mounted strain gages for Test HB-13. Figures 4.39, 4.40, 4.41, 4.42, 4.43, and 4.44 show the corresponding plots for Test HB-14, HB-15, and HB-16.

Table 4.5 Results of nuclear density gauge tests for Tests HB-13 to HB-16 (HDPE drainage pipe)

Test	Lifts (Surface)	Location 1 (Above Section #1)		Location 2 (Above Section #3)	
		Relative Density	Moisture Content	Relative Density	Moisture Content
HB-13	1 (Top)	100.0%	4.5%	99.6%	5.1%
	1 (Scraped)	99.7%	5.4%	99.1%	5.5%
	2 (Top)	99.2%	6.6%	99.8%	5.6%
	2 (Scraped)	94.0%	8.3%	100.9%	4.7%
HB-14	1 (Top)	101.1%	4.8%	100.8%	4.8%
	1 (Scraped)	97.6%	5.2%	95.1%	5.6%
	2 (Top)	97.3%	4.2%	103.7%	4.1%
	2 (Scraped)	90.3%	4.9%	100.0%	5.1%
	3	101.8%	4.4%	99.1%	3.8%
HB-15	1	98.3%	4.8%	102.5%	4.4%
	2	100.3%	4.4%	102.7%	4.3%
	3	99.2%	3.9%	100.1%	4.6%
	4	101.6%	4.9%	104.4%	4.2%
HB-16	1	100.6%	4.8%	98.7%	5.0%
	2	97.0%	4.4%	100.0%	4.2%
	3	100.3%	4.4%	100.0%	4.4%
	4	106.0%	4.8%	100.0%	4.2%
	5	100.0%	5.7%	100.1%	5.8%
	6	100.0%	4.9%	101.5%	6.7%

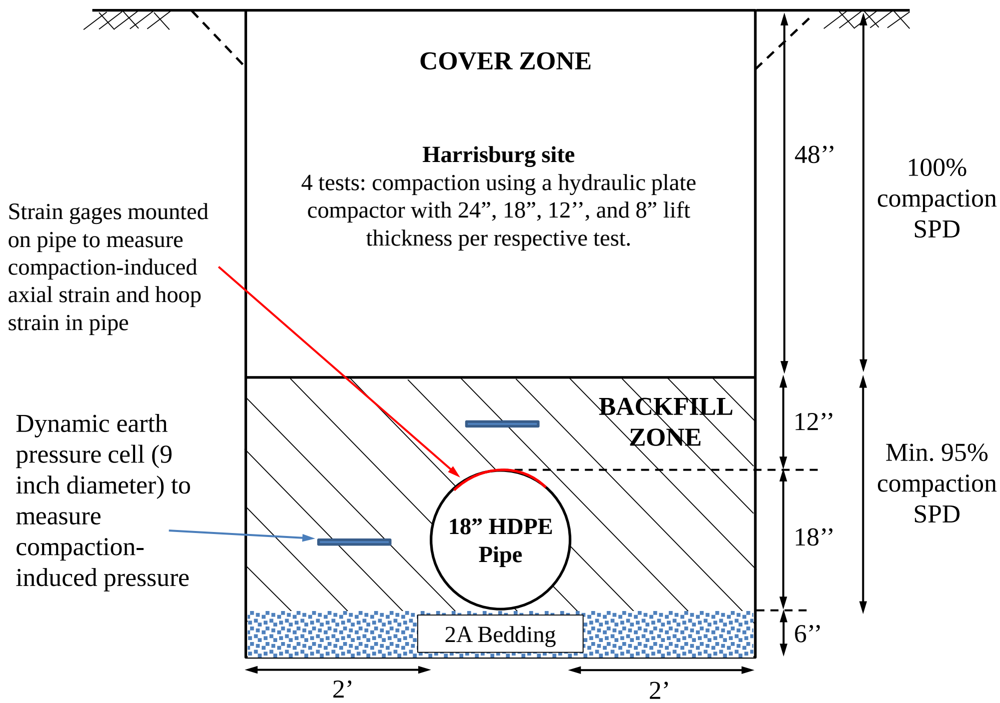

Figure 4.34 Cross-sectional view of trench and instrumentation for 18-inch diameter HDPE drainage pipe (not to scale)

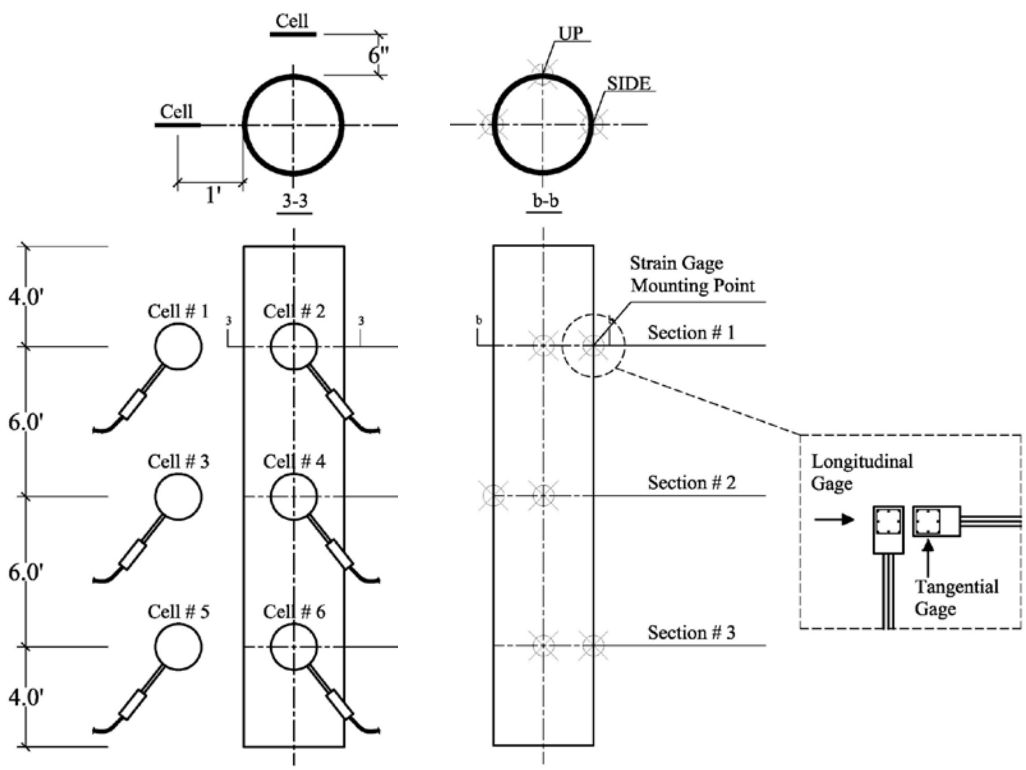

Figure 4.35 Detailed view of instrumentation for 18-inch diameter HDPE drainage pipe (not to scale)

Figure 4.36 Photos showing various stages of field test: a) pipe in trench; b) placement of pressure cells on side along mid elevation of pipe; c) nuclear density gauge testing; d) compaction using a hydraulic plate compactor; e) retrieved pipe after test

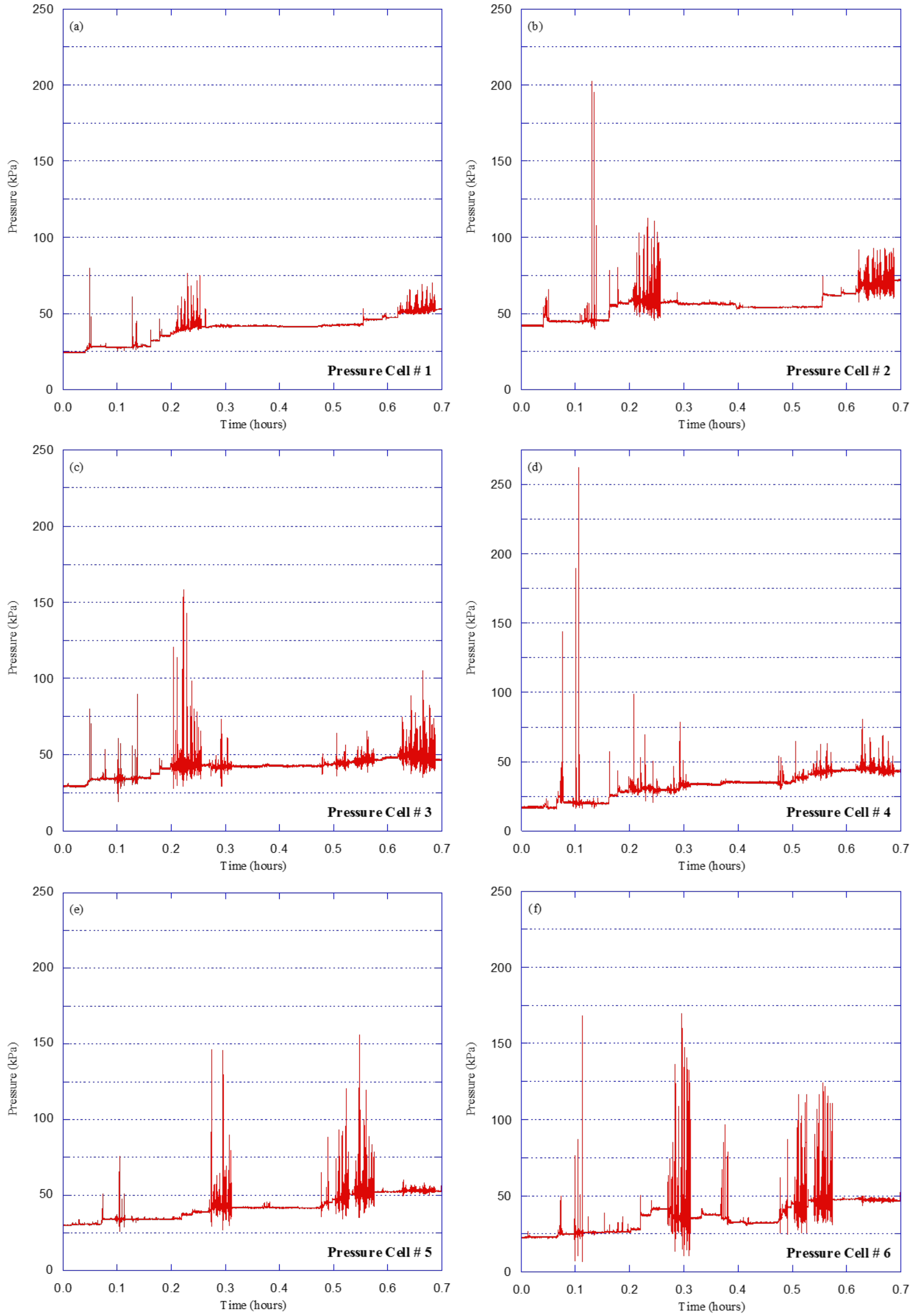

Figure 4.37 Downward earth pressures versus time for Test HB-13 (HDPE drainage pipe)

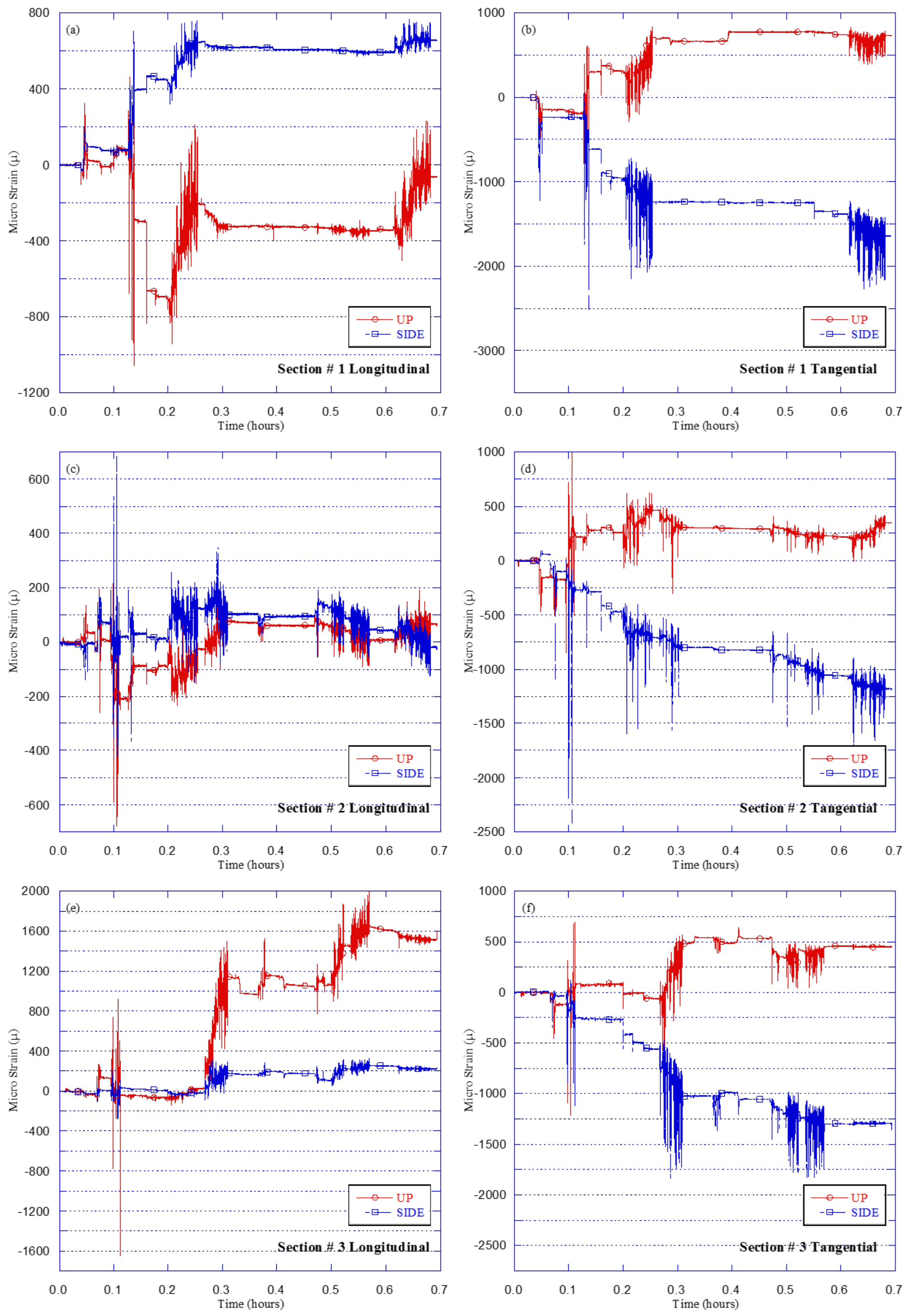

Figure 4.38 Strains along pipe versus time for Test HB-13 (HDPE drainage pipe)

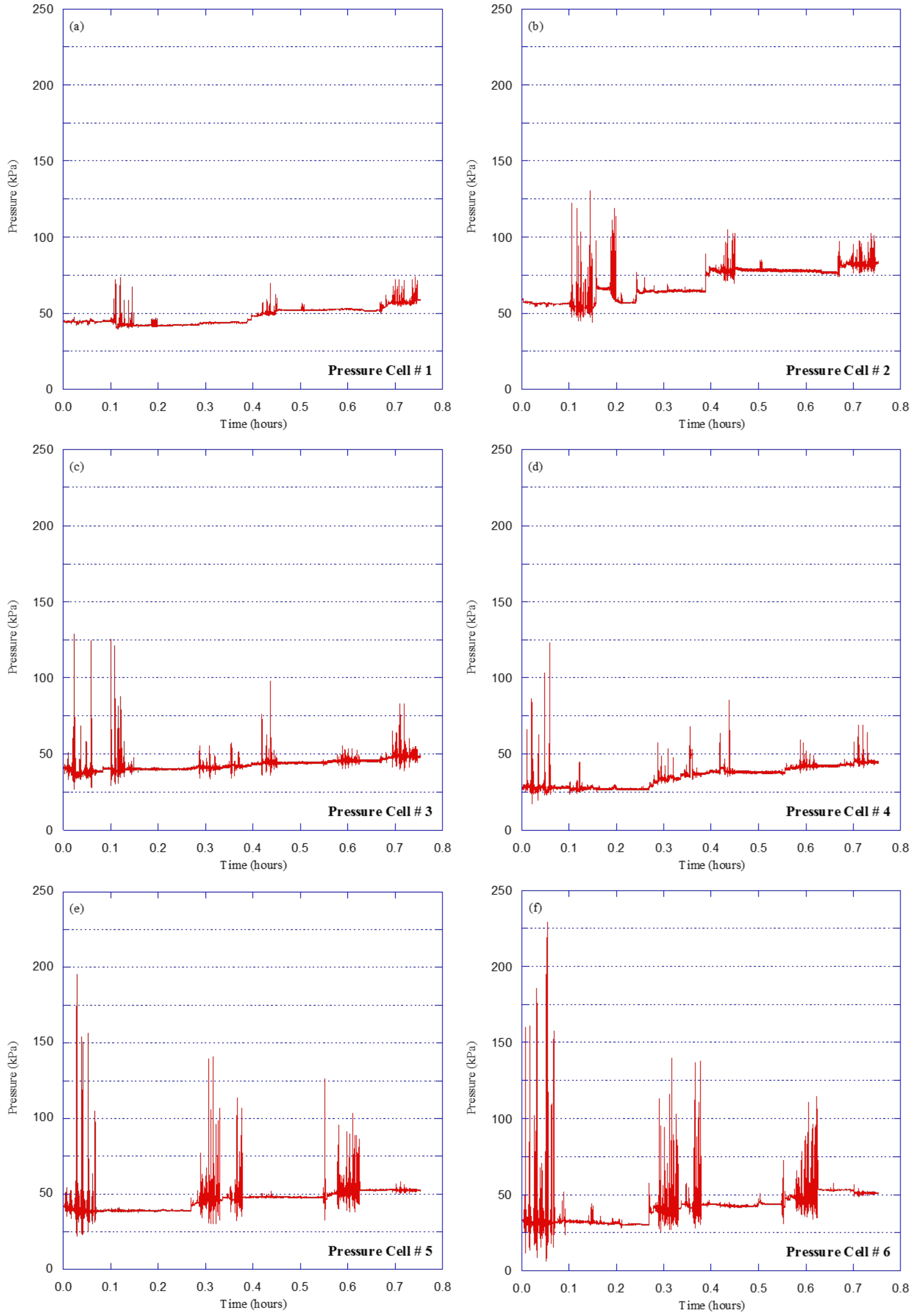

Figure 4.39 Downward earth pressures versus time for Test HB-14 (HDPE drainage pipe)

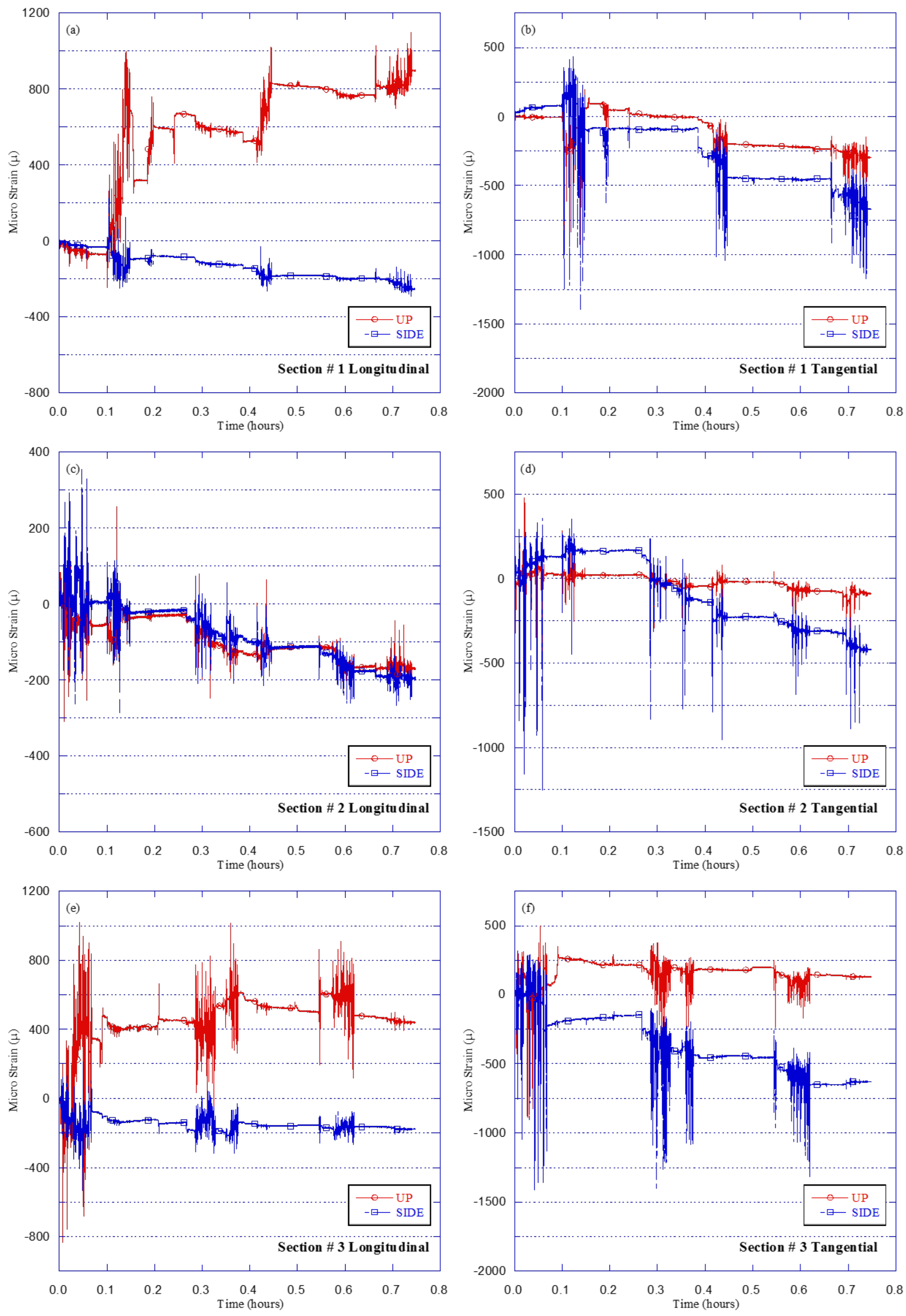

Figure 4.40 Strains along pipe versus time for Test HB-14 (HDPE drainage pipe)

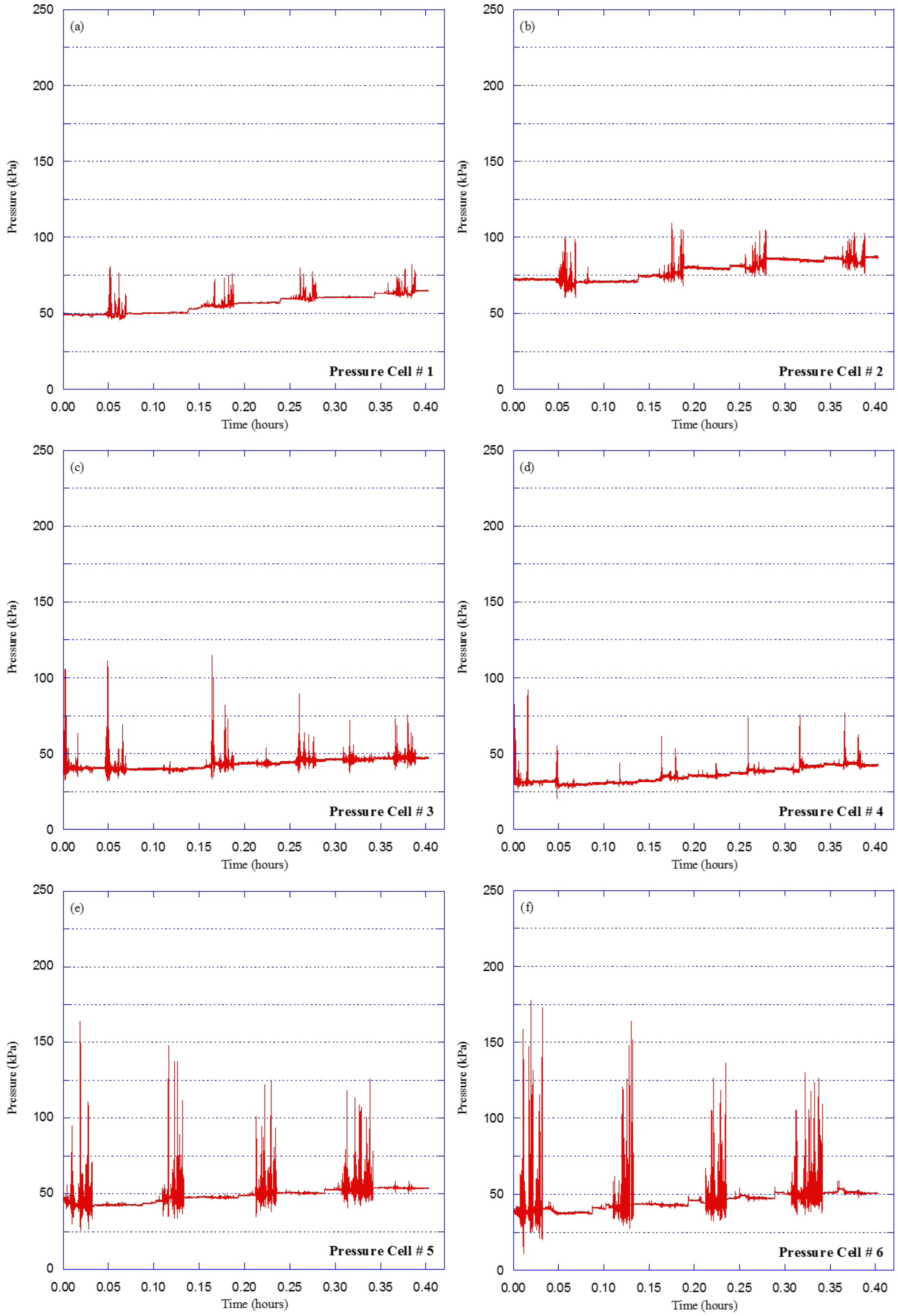

Figure 4.41 Downward earth pressures versus time for Test HB-15 (HDPE drainage pipe)

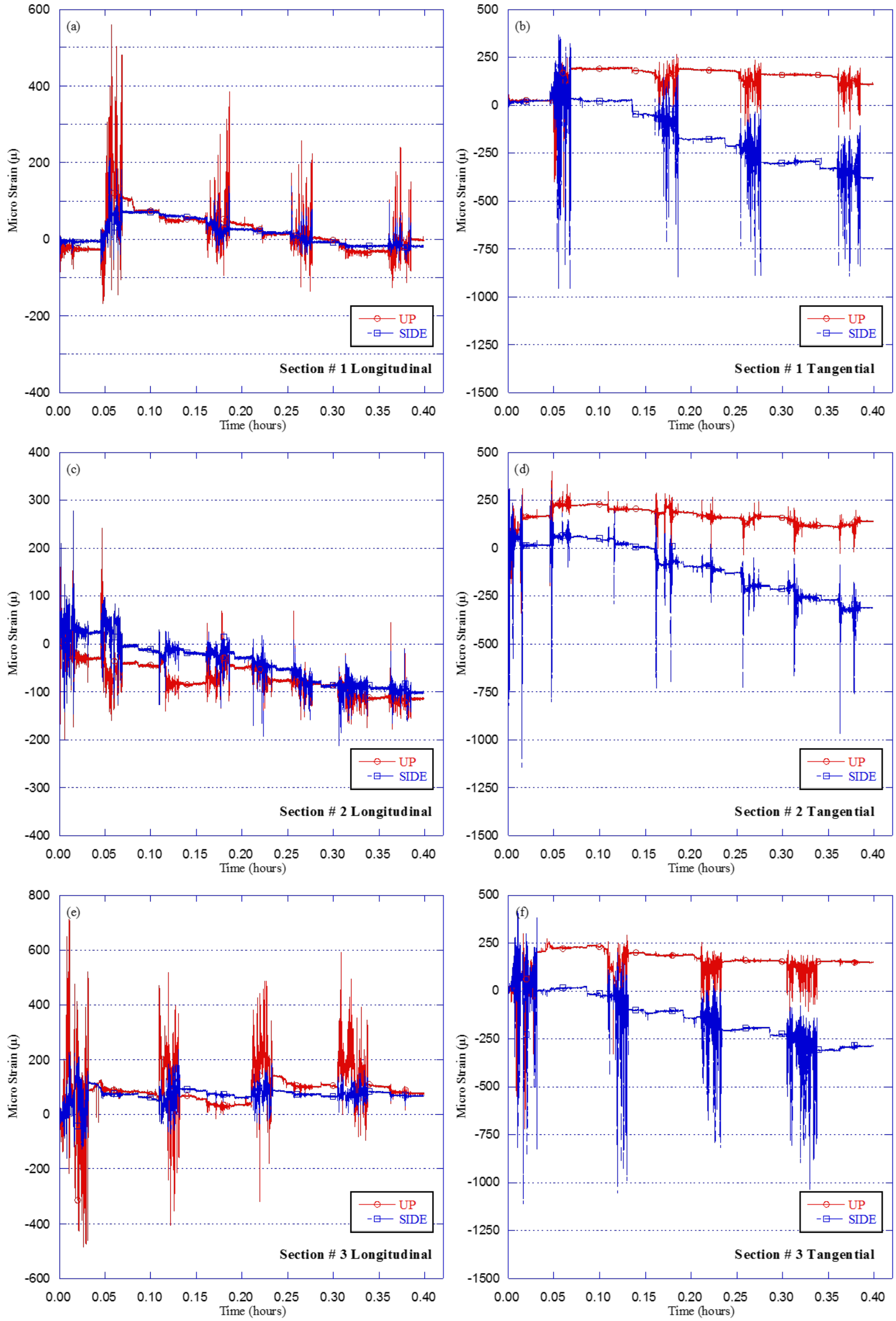

Figure 4.42 Strains along pipe versus time for Test HB-15 (HDPE drainage pipe)

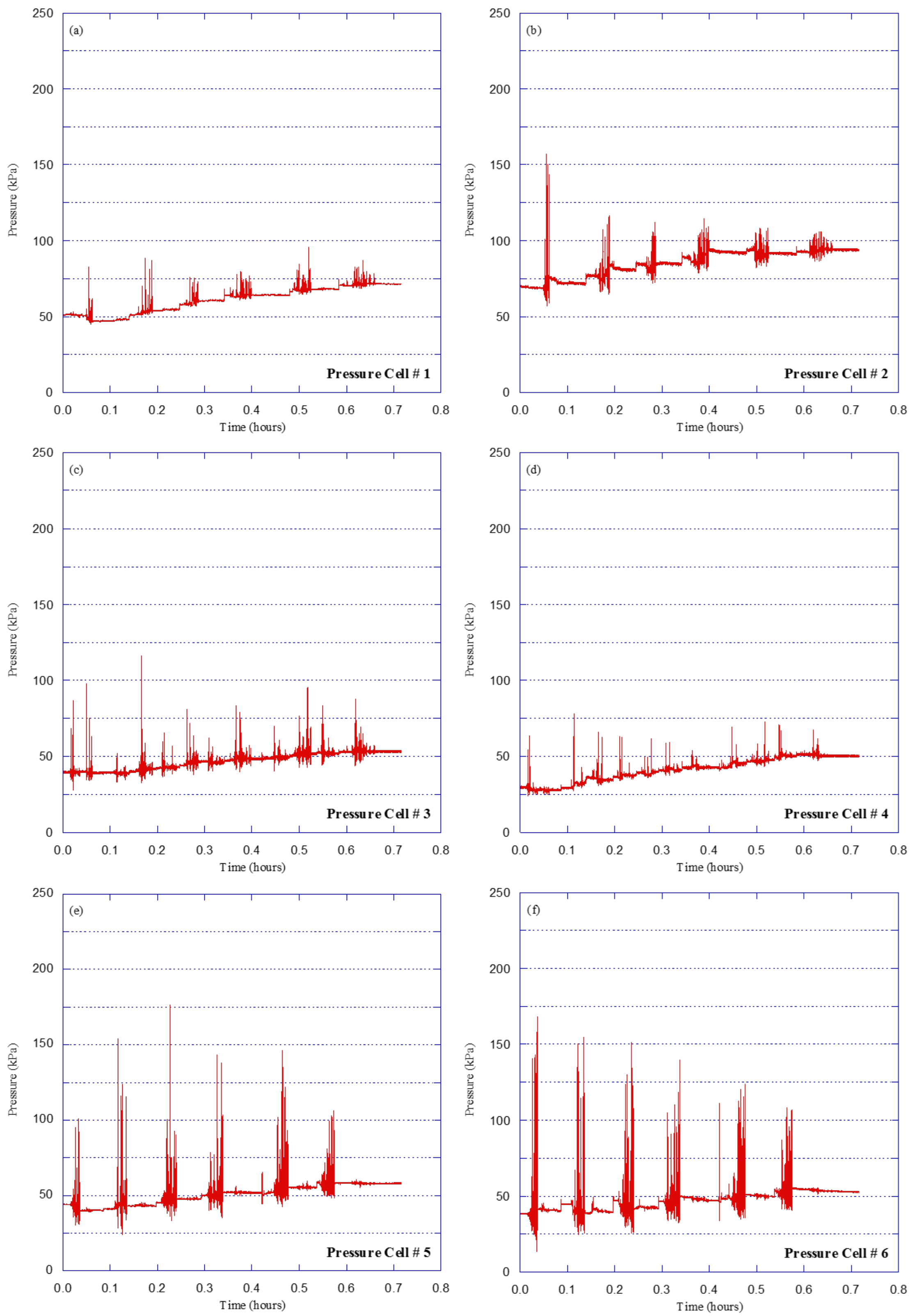

Figure 4.43 Downward earth pressures versus time for Test HB-16 (HDPE drainage pipe)

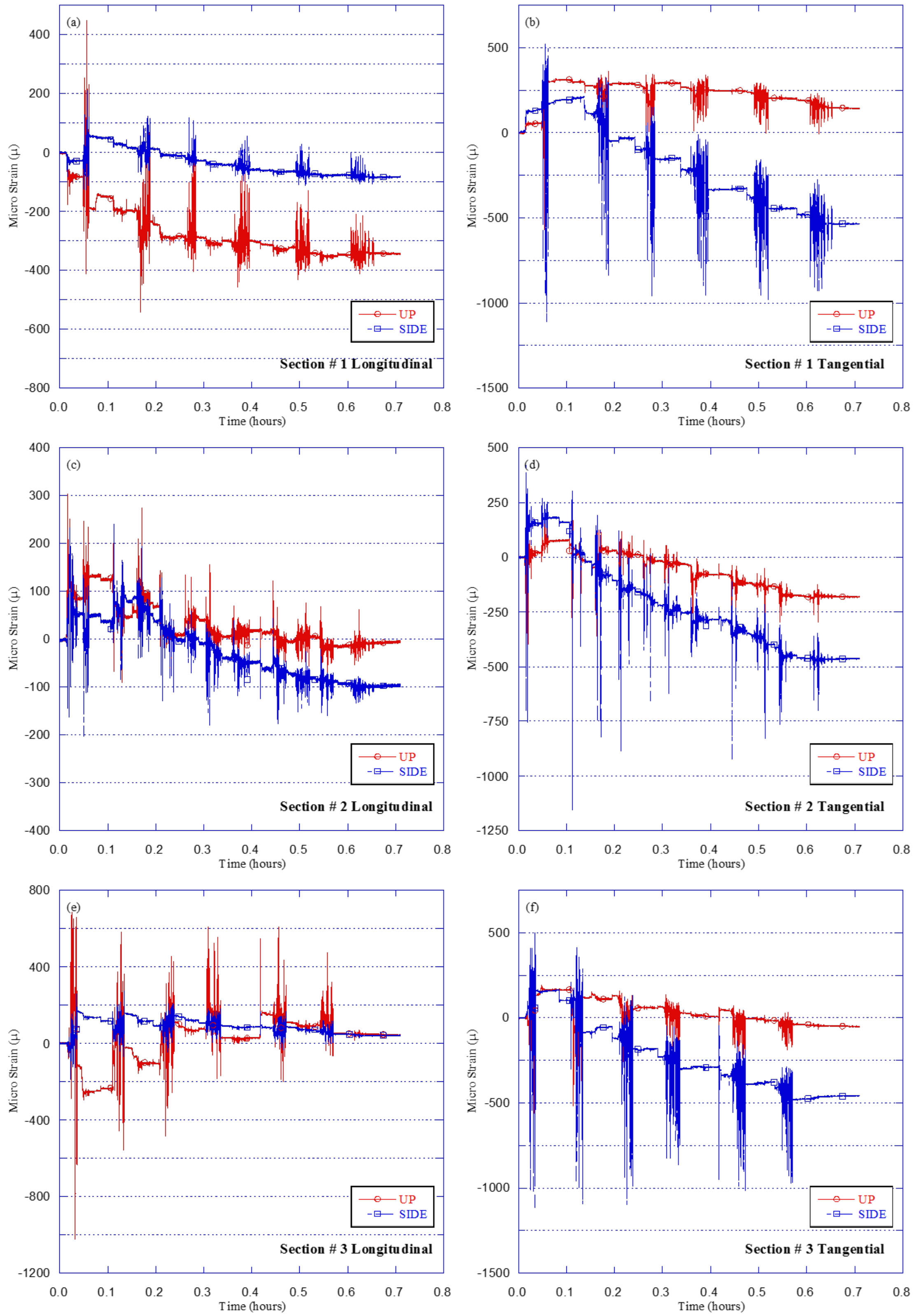

Figure 4.44 Strains along pipe versus time for Test HB-16 (HDPE drainage pipe)

5 EFFECTS OF HYDRAULIC PLATE COMPACTOR AND LIFT THICKNESS ON TRENCH BACKFILL COMPACTION AND RECOMMENDATIONS

The effects of hydraulic plate compactor use and lift thickness on trench backfill compaction are discussed in this chapter by analyzing/comparing the data collected from the field tests in State College and Harrisburg.

5.1 Effect of Hydraulic Plate Compactor

The effect of hydraulic plate compactor use in trench backfill compaction can be demonstrated by comparing the data collected from the tests in State College and those in Harrisburg with a lift thickness of 8 inches (i.e., Tests HB-4, HB-8, HB-12, and HB-16). Comparisons between Tables 3.2 and 4.2, Tables 3.3 and 4.3, Tables 3.4 and 4.4, and Tables 3.5 and 4.5 indicate that, with a lift thickness of 8 inches, the hydraulic plate compactor and walk behind vibratory roller compactor consistently achieved relative densities above 100% of the Standard Proctor Density for all the tests conducted, with the hydraulic plate compactor being able to achieve generally higher relative densities.

Figure 5.1 shows a comparison of downward earth pressure and strains along pipe versus time at Section #2 between Test SC-1 and Test HB-4 for the SDR-35 pipe in 2B stone. Data collected in Sections #1, #2, and #3 are generally consistent for all of the tests conducted; therefore, data collected in Section #2 were selected for comparison purpose due to this section being the middle section. Figures 5.2, 5.3, and 5.4 show the corresponding plots for the SDR-35 pipe in 2A aggregates, reinforced concrete pipe, and HDPE drainage pipe, respectively. Please note that data collected in Section #3 were used for the SDR-35 pipe in 2A aggregates because a strain gage in Section #2 malfunctioned during the test (see Figure 3.12(c)).

Figures. 5.1(a) and 5.1(b) indicate that, with a lift thickness of 8 inches, the hydraulic plate compactor induced approximately twice as much static earth pressure as the vibratory roller compactor did in the backfill zone for the SDR-35 pipe in 2B stone. For the SDR-35 pipe in 2A aggregates, reinforced concrete pipe, and HDPE drainage pipe, the static earth pressures generated by the hydraulic plate compactor and vibratory roller compactor were generally similar in magnitude. Figures 5.1 through 5.4 indicate that the hydraulic plate compactor generally induced significantly higher dynamic earth pressures than the vibratory roller compactor did for the four pipes, with the exception of Cell #3 for the HDPE drainage pipe. While the exact reasons are unknown, this exception is deemed as an abnormality as typical in field-scale geotechnical testing. These observations suggest that the hydraulic plate compactor is likely to induce higher dynamic earth pressures in the backfill zone, but may not induce higher static earth pressures in the backfill zone depending on the pipe.

Figures 5.1 through 5.4 indicate that the strains along pipe induced by the hydraulic plate compactor and vibratory roller compactor were generally similar in magnitude. In some cases, the hydraulic plate compactor induced smaller strains, for instance, the tangential strains in the SDR-35 pipe in 2A aggregates as shown in Figures 5.2(e) and 5.2(f). This could be due to the pipe being locked in a more fixed position by the surrounding fill compacted to higher relative densities under the hydraulic plate compactor.

Figures 5.1 through 5.4 also indicate that, with a lift thickness of 8 inches, the compaction time needed for the hydraulic plate compactor could be less than half of that needed for the vibratory roller compactor. This suggests that the hydraulic plate compactor was more efficient for the tests conducted.

5.2 Effect of Lift Thickness

The effect of lift thickness on trench backfill compaction can be demonstrated by comparing the data collected from the tests in Harrisburg for the same pipe with different lift thicknesses. Tables 4.2, 4.3, 4.4, and 4.5 indicate that the hydraulic plate compactor consistently achieved relative densities over 100% of the Standard Proctor Density for lift thickness values of 8 inches and 12 inches. For lift thickness values of 18 inches and 24 inches, however, the hydraulic plate compactor was not able to consistently achieve relative densities over 100% of the Standard Proctor Density in the fills 12 inches below the compacted surface. These observations suggest that the hydraulic plate compactor used in this study was not able to generate the compaction energy that could penetrate to a sufficient depth to adequately compact the 2A aggregates used in this study for lifts of 18 inches or greater in thickness.

Figure 5.5 shows the effect of lift thickness on downward earth pressure and strains along pipe versus time at Section #2 for the SDR-35 pipe in 2B stone, plotting the data collected from Tests HB-1, HB-2, HB-3, and HB-4. Figures 5.6, 5.7, and 5.8 show the corresponding plots for the SDR-35 pipe in 2A aggregates, reinforced concrete pipe, and HDPE drainage pipe, respectively.

Figures 5.5 through 5.8 show that the static earth pressures for different lift thicknesses were generally similar in magnitude for the tests conducted. However, a consistent trend is not observed regarding the dynamic earth pressures. For example, the peak dynamic earth pressures generally decreased as the lift thickness increased for Cell #3 for the SDR-35 pipe in 2B stone, as shown in Figure 5.5(a), whereas the same cell for the HDPE drainage pipe registered the highest peak dynamic earth pressures for the lift thickness of 24 inches, as shown in Figure 5.8(a). These observations suggest that 1) the static earth pressures were relatively insensitive to lift thickness, and 2) the dynamic earth pressures may decrease as the lift thickness increases depending on the pipe.

Figures 5.5 and 5.6 indicate that, for the SDR-35 pipe in 2B stone or 2A aggregates, Section #2 experienced different deformation modes for the lift thicknesses of 8 inches and 24 inches. For the lift thickness of 8 inches, Section #2 experienced horizontal compression (i.e., positive tangential strains at the top and negative tangential strains on the side), whereas this section experienced vertical compression (i.e., negative tangential strain at the top and positive tangential strains on the side) for the lift thickness of 24 inches. For the lift thicknesses of 12 inches and 18 inches, Section #2 experienced intermediate deformation mode and strains. For the reinforced concrete pipe, Figure 5.7 indicates that the strains along pipe were very small regardless of lift thickness due to the high stiffness of the pipe material. For the HDPE drainage pipe, Figure 5.8 indicates that the strains along pipe were relatively insensitive to lift thickness. These observations suggest that, for the hydraulic plate compactor, the effect of lift thickness on strains along pipe depends on the pipe.

5.3 Conclusions and Recommendations

Based on the field tests conducted and analyses of the data collected, the following conclusions specific to the test conditions (e.g., pipe materials, backfill materials, and model of hydraulic plate compactor) can be drawn:

1. The hydraulic plate compactor used in this study can consistently achieve relative densities above 100% of the Standard Proctor Density for the 2A aggregates with a lift thickness of 8 inches or 12 inches. However, the hydraulic plate compactor is not able to consistently achieve relative densities above 100% of the Standard Proctor Density for the 2A aggregates 12 inches below the compacted surface when the lift thickness is 18 inches or greater.

2. Comparing the performances of the hydraulic plate compactor and vibratory roller compactor used in this study for a lift thickness of 8 inches, the hydraulic plate compactor is more efficient in compacting the 2A aggregates. The hydraulic plate compactor used in this study is likely to induce higher dynamic earth pressures in the backfill zone, but may not induce higher static earth pressures depending on the pipe. The hydraulic plate compactor used in this study generally induces similar strains along pipe as the vibratory roller compactor does.

3. For the hydraulic plate compactor used in this study, the static earth pressures in the backfill zone are relatively insensitive to lift thickness, whereas the dynamic earth pressures may decrease as the lift thickness increases, depending on the pipe. The effect of lift thickness on strains developed along pipe also depends on the pipe.

It is recommended that for trench backfill compaction, a maximum lift thickness of 12 inches be used for hydraulic plate compactors similar to the one used in this study (in terms of impulse force) to consistently achieve 100% compaction of 2A aggregates and other similar backfill materials in accordance with PennDOT RC-30 Standards and Pub 408, Section 206.3.

5.4 Limitations of Current Study

As discussed in Chapter 2, the performance of a hydraulic plate compactor depends on many factors, including the impulse force, downward pressure, baseplate dimensions, and materials being compacted. The current study is based on one model and size of hydraulic plate compactor and one type of backfill material. Therefore, the results and conclusions are specific to these test conditions. Additional research is needed to include a wide range of hydraulic plate compactors and backfill materials.

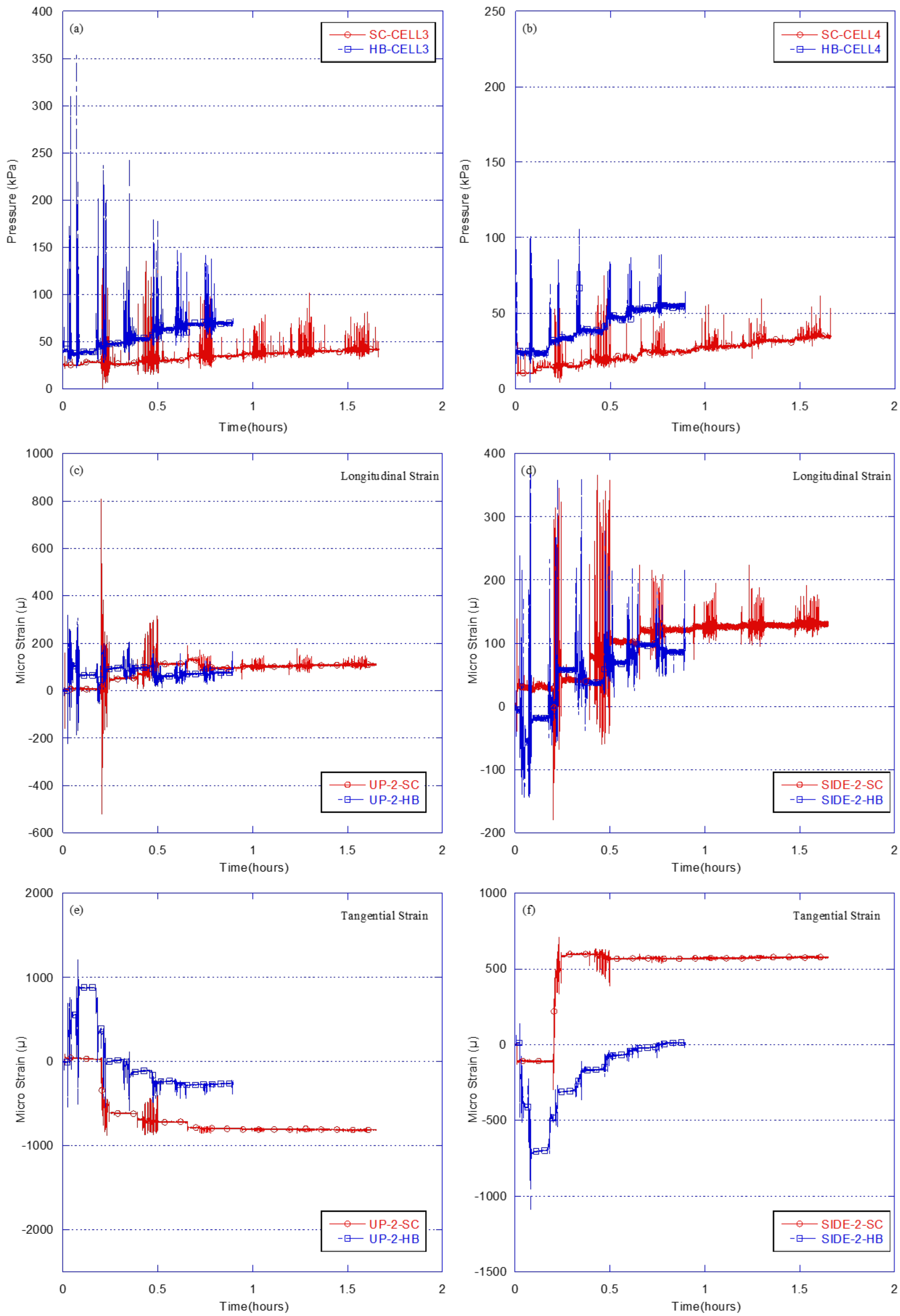

Figure 5.1 Comparison of downward earth pressure and strains along pipe versus time between Test SC-1 and Test HB-4 (SDR-35 pipe in 2B stone)

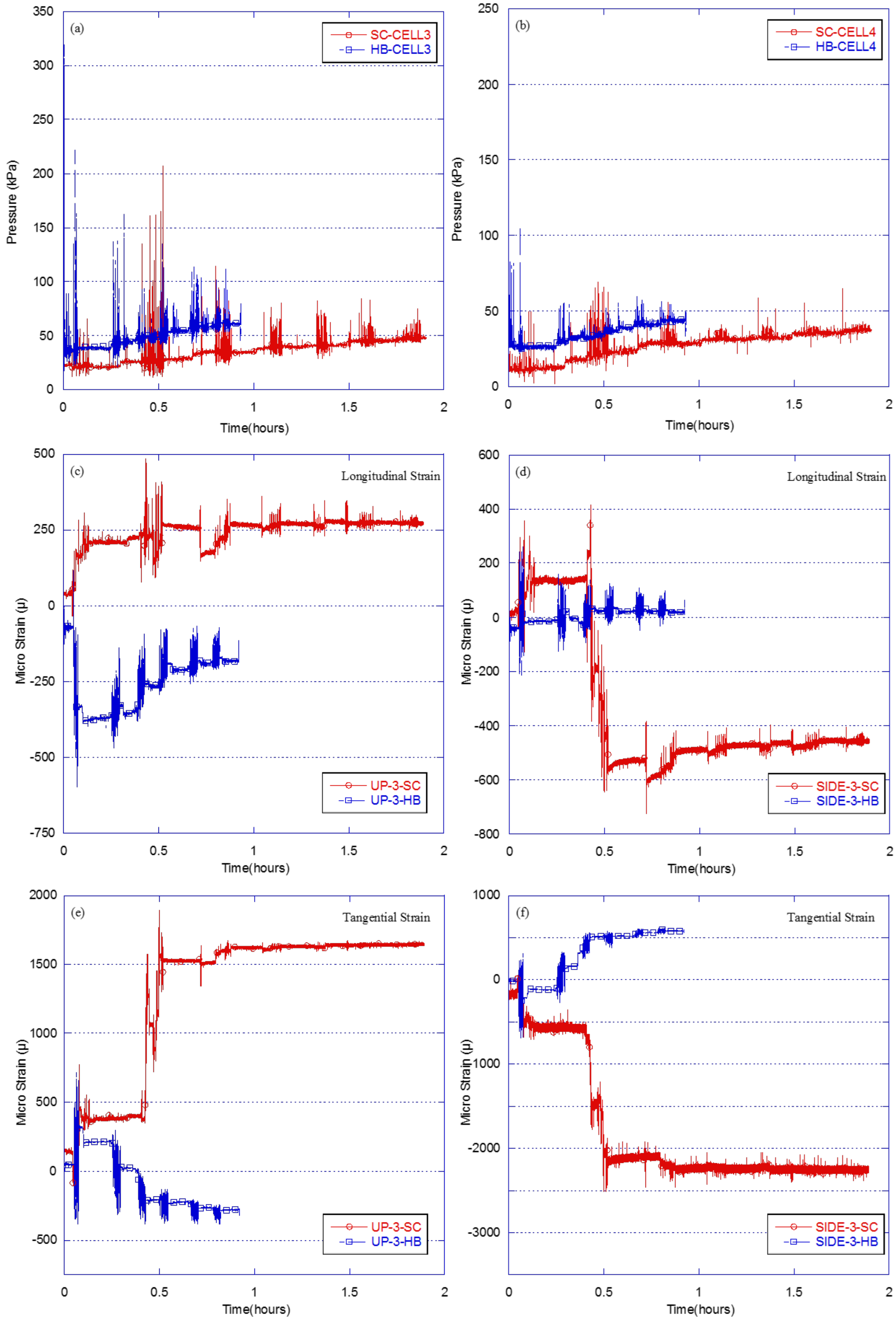

Figure 5.2 Comparison of downward earth pressure and strains along pipe versus time between Test SC-2 and Test HB-8 (SDR-35 pipe in 2A aggregates)

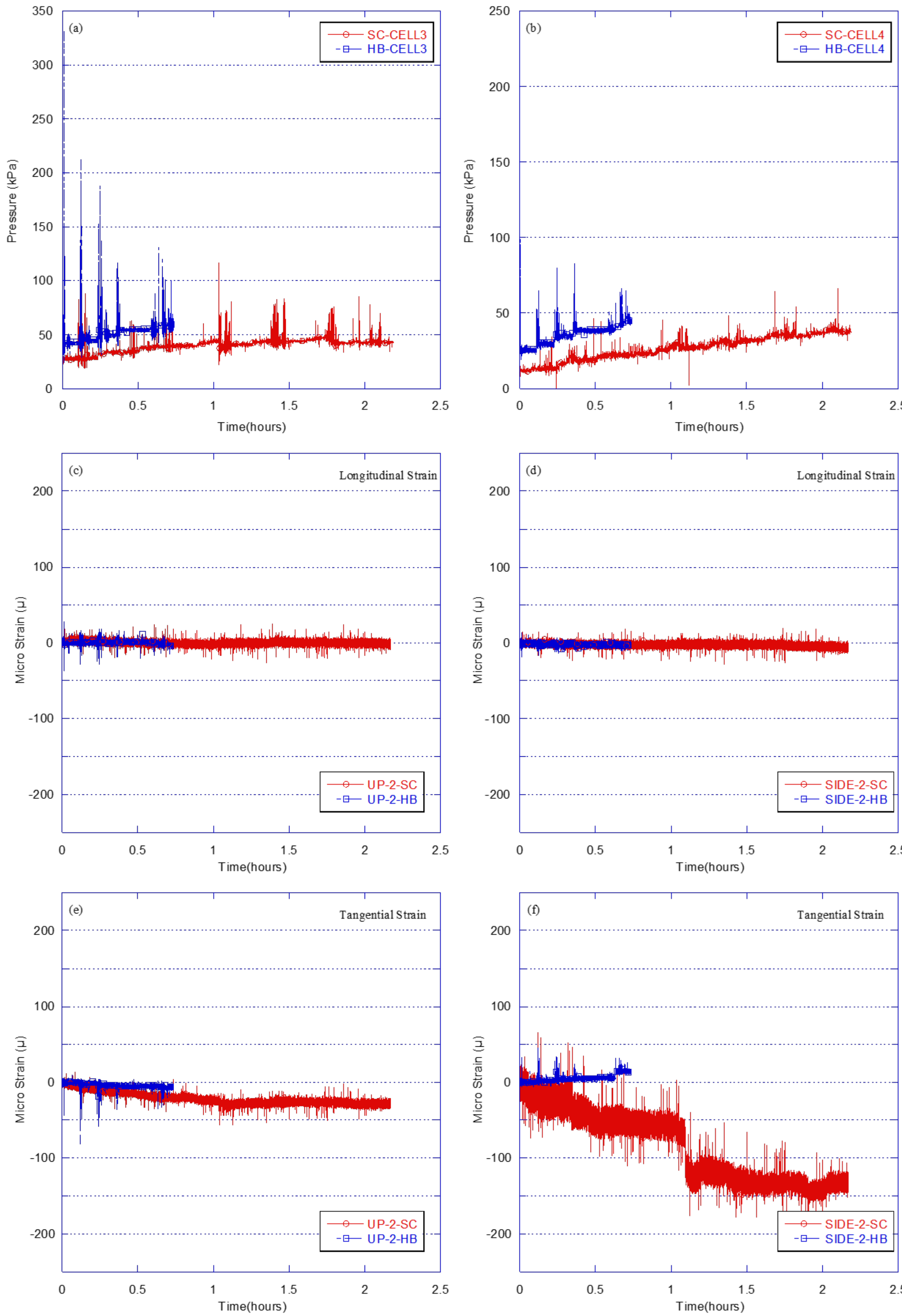

Figure 5.3 Comparison of downward earth pressure and strains along pipe versus time between Test SC-3 and Test HB-12 (reinforced concrete pipe)

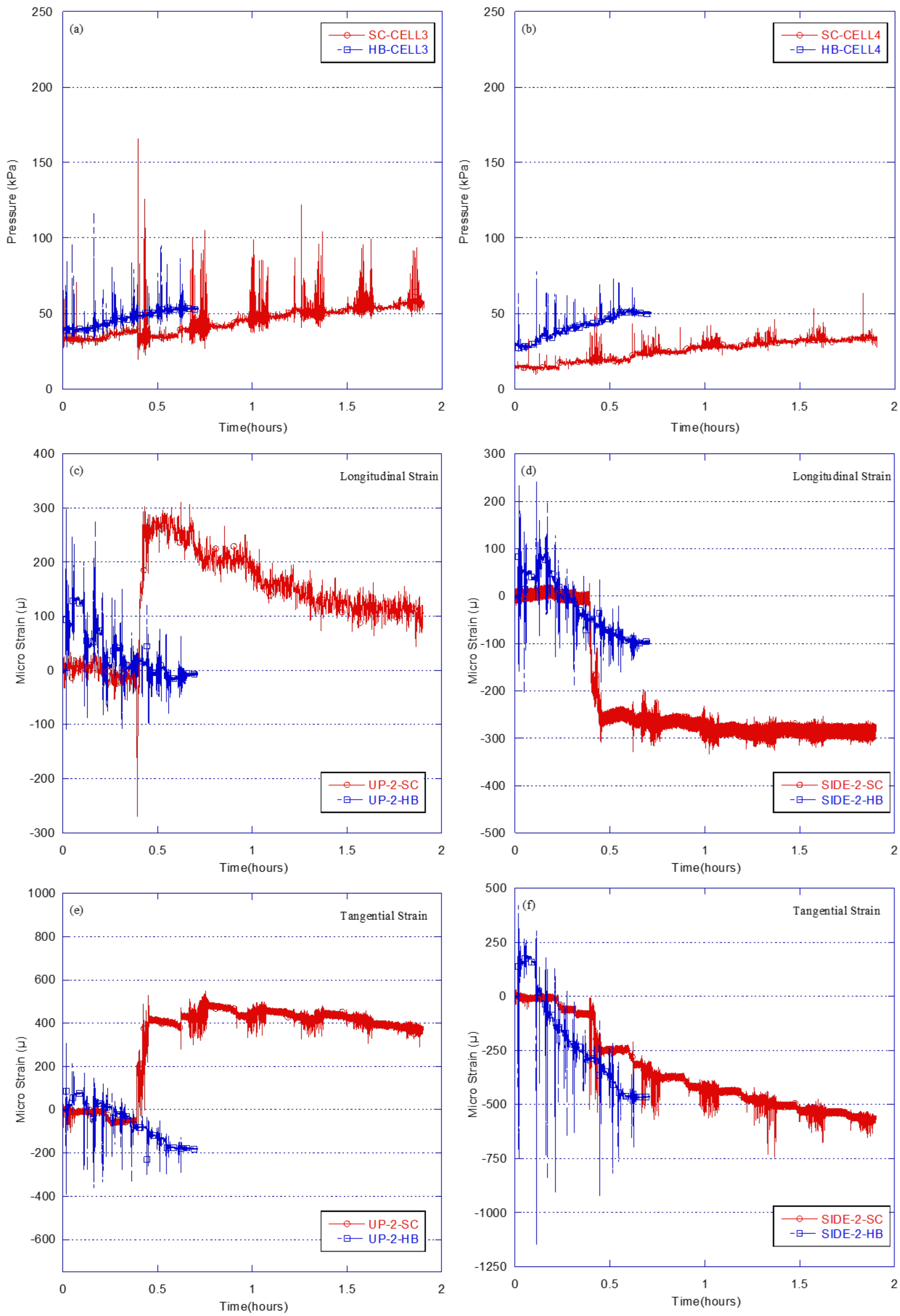

Figure 5.4 Comparison of downward earth pressure and strains along pipe versus time between Test SC-4 and Test HB-16 (HDPE drainage pipe)

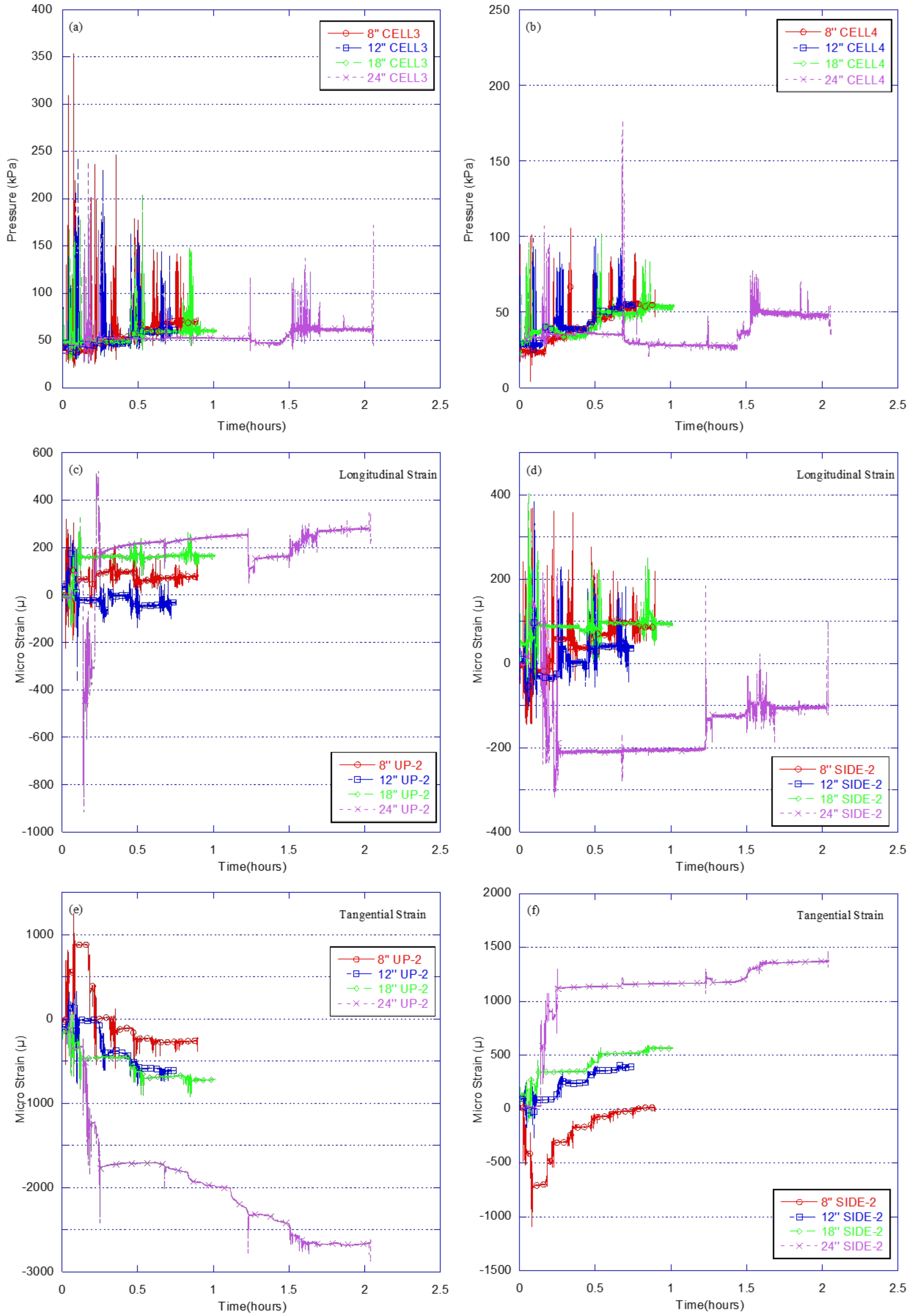

Figure 5.5 Effect of lift thickness on downward earth pressure and strains along pipe versus time for SDR-35 pipe in 2B stone

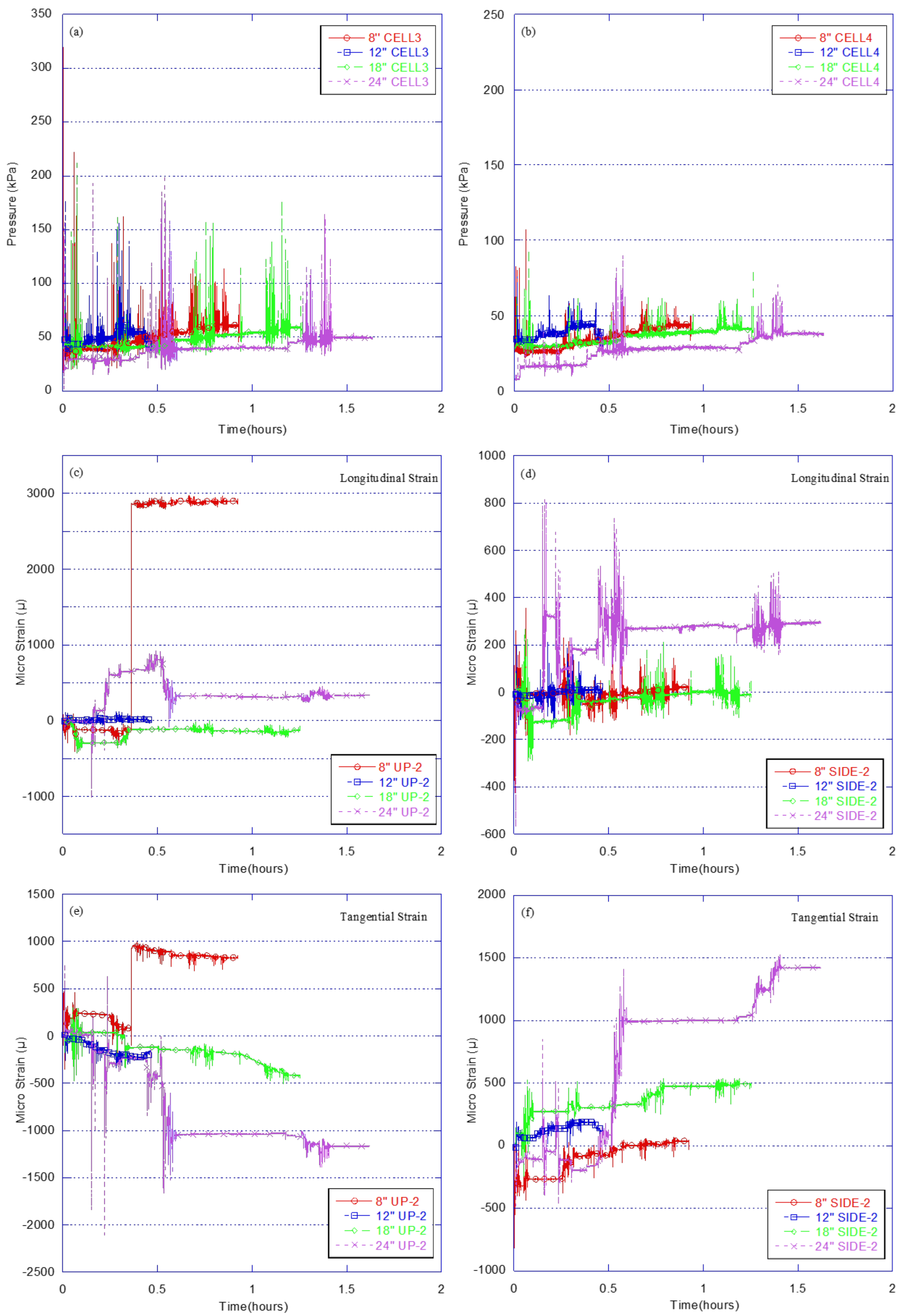

Figure 5.6 Effect of lift thickness on downward earth pressure and strains along pipe versus time for SDR-35 pipe in 2A aggregates

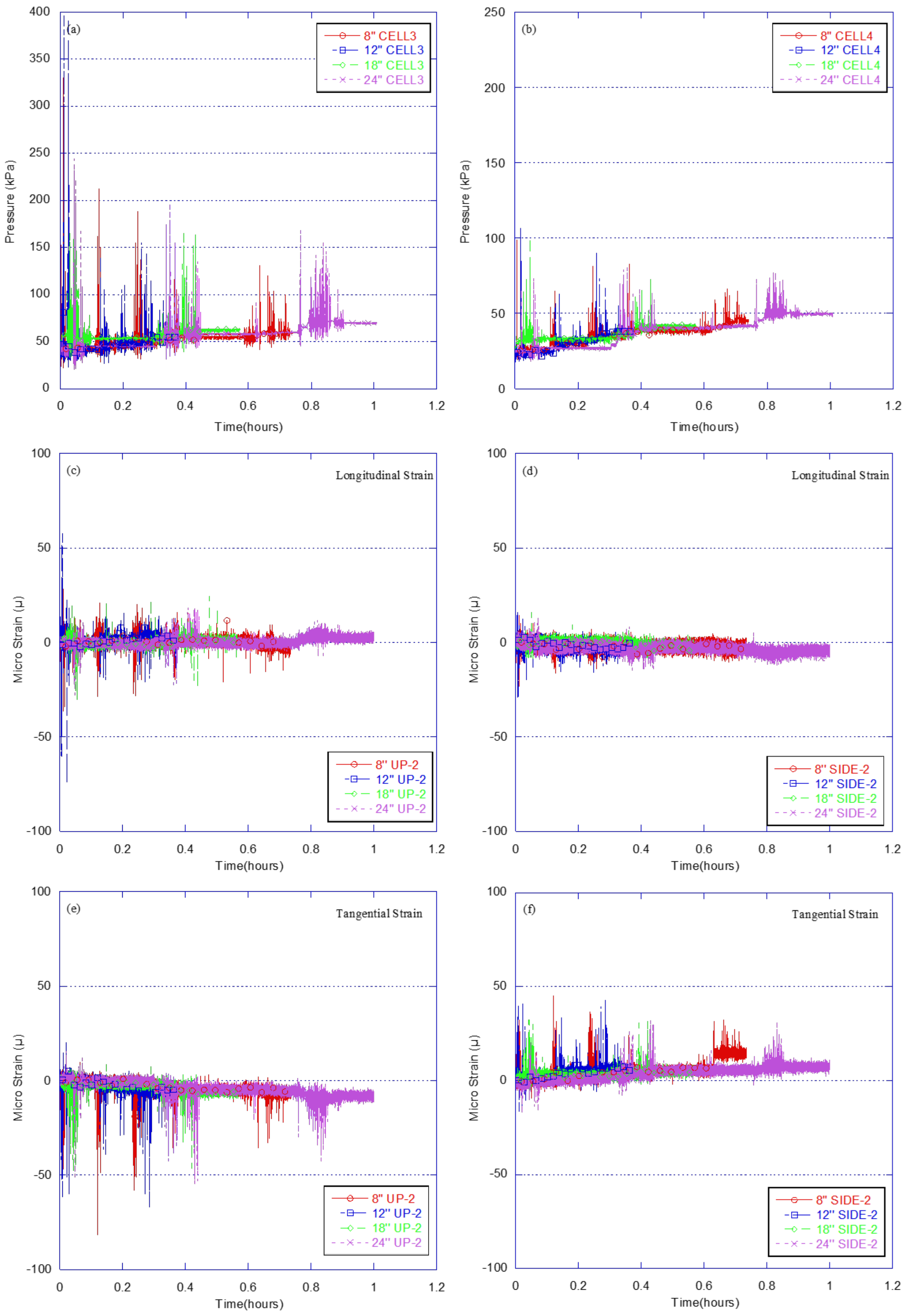

Figure 5.7 Effect of lift thickness on downward earth pressure and strains along pipe versus time for reinforced concrete pipe

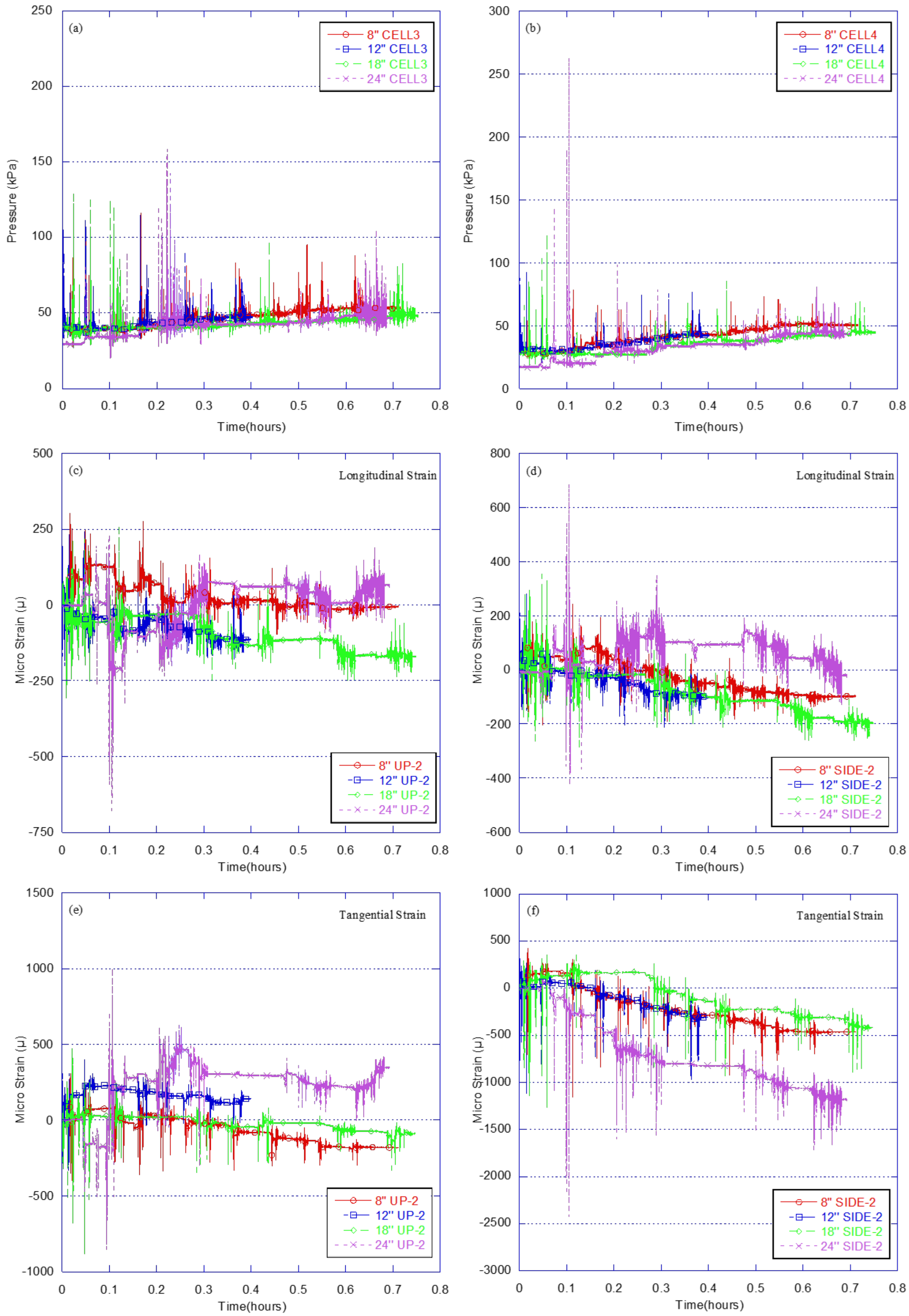

Figure 5.8 Effect of lift thickness on downward earth pressure and strains along pipe versus time for HDPE drainage pipe

REFERENCES

Allied (2004). *Compaction Handbook*. pp. 24.

Allied (2014). http://www.alliedcp.com/pdf/products/Hopac_brochure_11Mar.pdf, last accessed on Sept. 17, 2014.

CAT (2014). http://www.cat.com/en_US/products/new/attachments/compactors/vibratory-plate-compactors.html, last accessed on Sept. 17, 2014.

Converse, F.J. (1952). "Soil Compaction by Vibration." *Engineering and Science*, 15 (4), 12-14.

Demartini, C., Hansen, B., and Lee, D. (1997). *The Cracking of Stormwater Pipes and The Significance of Construction Loads*. Research and Development Section, Brisbane City Council, Queensland, pp. 8.

FRD (2014). http://www.frdusa.com/cms/frdbad/page.html?p_name=HP35%20ME%2C%20HP65%20II%20and%20HP75%20Compactor%20Drivers%20Overview, http://www.frdusa.com/cms/frdbad/page.html?p_name=HP135%20II%2C%20HP210%20II%20Compactor%20Drivers%20Overview, last accessed on Sept. 17, 2014.

Holtz, R.D., and Kovacs, W.D. (1981). *An Introduction to Geotechnical Engineering*. 2nd Edition, Prentice-Hall, pp. 733.

Hudco (2014). http://www.hudcomfg.com/compactors.html, last accessed on Sept. 17, 2014.

Kararam, A. (2009). *Nonlinear Finite Element Dynamic Analysis of the Effect of Compaction on Underground Conduits*. Ph.D. Dissertation, The University of Texas – Arlington.

Kenco (2014). http://kenco.com/products/plate-compactor/compare-models/, last accessed on Sept. 17, 2014.

Multiquip Inc. (2011). *Soil Compaction Handbook*. pp. 20.

Parsons, A.W., Krawczyk, J., and Cross, J.E. (1962). "An Investigation of the Performance on an 8.5-Ton Vibrating Roller for the Compaction of Soil." Road Research Laboratory, Laboratory Note No. LN/64/AWP. JK. JEC.

Rock Breaker (2014). http://www.rockbreaker.com/equipment/attachments/compactors.html, last accessed on Sept. 17, 2014.

Selig, E.T. and Yoo, T.-S. (1977). "Fundamentals of Vibratory Roller Behavior." *Proceedings of the Ninth International Conference on Soil Mechanics and Foundation Engineering*, Tokyo, 2, 375-380.

Stanley (2014). http://www.stanleyhydraulics.com/sites/stanleyhydraulic.com/files/pdf/HSX%

20User%20Manual%205-2013%20V1RS.pdf, last accessed on Sept. 17, 2014.

Tramac (2014). http://www.tramacbymontabert.com/products/platecompactors, last accessed on Sept. 17, 2014.

Whetten, N.L. and Weaver, J.W. (1991). “Densification of gravelly sand fill using intensive surface compaction.” *Journal of Geotechnical Engineering*, ASCE, 117(7), 1089-1094.