FDOT

FINAL REPORT

LONG-TERM PERFORMANCE OF BURIED HIGH DENSITY POLYETHYLENE PLASTIC PIPING

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May 2001

FOREWORD

This study is a follow-up of the earlier Florida Department of Transportation-funded project (P.I: Dr. D. V. Reddy) at Florida Atlantic University entitled "Evaluation of Plastic Piping for Pipe for Pipe Culverts and Storm Sewers". It is a new stand-along experimental and analytical investigation addressing the long-term properties and life cycles with accelerated testing simulated by super-ambient temperature levels. Considerable attention is focused in longitudinal bending of un jointed and jointed pipe and environmental stress cracking of un-notched and notched pipe rings in flexural creep. The investigation also contains a sizable amount of two-dimensional and three dimensional finite element analysis of viscoelastic pipe-soil interaction. The findings will enable the setting up of performance limits and the development of practical guidelines for the selection, design, specification and installation of HDPE piping for subsurface drainage of transportation facilities. The performance indicators will be changes in design standards.

ACKNOWLEDGEMENTS

The Principal Investigator would like to thank the Florida Department of Transportation (Contract # BB-466) for its generous financial support. Gratitude is expressed to Mr. R. Powers, Assistant State Corrosion Engineer, and Mr. R. Kessler, State Corrosion Engineer, Materials Division FDOT, Gainesville, FL, Contract Monitors, and Mr. S. McLemore, State Drainage Engineer, Drainage Division FDOT, Tallahassee, for their continuing interaction with invaluable input, encouragement, and guidance.

The administrative support of Dr. S.E. Dunn, Professor and Former Chairman, Department of Ocean Engineering and Dr. J. T. Jurewicz, Dean of Engineering, Florida Atlantic University, is gratefully acknowledged.

ABSTRACT

The primary goal of this study was to evaluate the service life of HDPE (High density polyethylene) notched/unnotched joint pipes. The following experimental tasks were carried out: i) procurement of materials, and fabrication of test setups; ii) creep evaluation: The performance of buried pipes (notched/unnotched), subjected to live loading, was studied in soil chambers for three levels of loading (service, 2/3 and 1/3 of service). The long-term behavior was accelerated with super-ambient temperatures; iii) field monitoring: Strains and diametral changes were measured for 10,000 hours. Type I and Type II with/without notch ring specimens were tested in flexural creep for environmental stress cracking. The analytical investigations of viscoelastic pipe-soil interaction were as follows: i) extrapolation of the long-term performance at ambient temperature, based on the Bi-directional and the Arrhenius methods and ii) 2-D Finite Element Analysis with an approximate extension to 3-D performance evaluation, using the software CANDE, iii) 3-D Finite Element Analysis.

The findings include: i) the deflection threshold (7.5% vertical change of diameter) as the governing failure condition, ii) similar life predictions, for Bi-directional and Arrhenius methods, with service lives of about 80 and 30 years at ambient temperature, for unnotched and notched pipes, respectively, subjected to maximum loading, iii) reasonable agreement between analytical (2-D and 3-D) and experimental values, and iv) reduced creep modulus for the notched ring specimens.

Jointed pipe, embedded in soil with varying properties, was also investigated both experimentally and analytically. The results show that longitudinal bending moment can lead to leakage.

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CHAPTER 1

INTRODUCTION

High-density linear polyethylene is a plastic material composed of carbon and hydrogen atoms joined together forming high molecular weight products as shown in Fig. l. l. Generally, along the polymer main chain are side chains whose substituents may be short or long. The longer the main chain, the greater the number of atoms, and consequently, the greater the molecular weight. The molecular weight and the molecular weight distribution determine many of the mechanical and chemical properties of the end product.

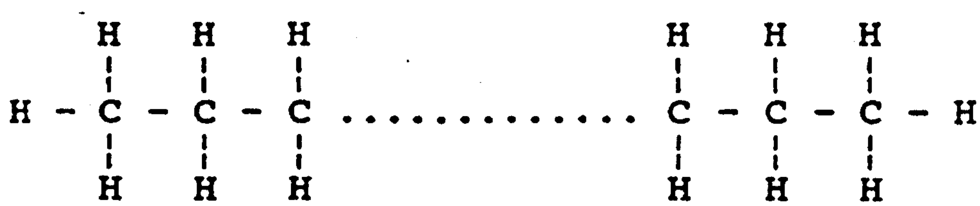


Fig. 1.1 A polyethylene molecular chain

The arrangement of the molecular chains is predictive of the property characteristics of polyethylene. Although shown flat and lying in a plane in Fig.l.l, the molecular chains are three-dimensional and lie in wavy planes. Branching off the main chains are side chains that may be of different lengths. The number, size, and type of these side chains determine, in large part, the properties of density, stiffness, tensile strength, flexibility, hardness, brittleness, elongation, creep characteristics, and melt viscosity that distinguishes the manufacturing effort and service performance of polyethylene pipe.

High-density polyethylene pipe (HDPE) has good potential for economic use for marine oil and gas pipelines, under drains, storm sewers, culverts, and other subsurface drainage structures. In view of its inherent chemical and corrosion resistance, lightweight, toughness, flexibility, easy splicing, and consequent easy handling, and installation, HDPE piping is being used extensively for gas pipelines. In the transportation industry, over forty states use HDPE pipe as part of a 40% annual growth for the use of thermoplastic, HDPE and polyvinyl chloride, (PVC) pipe in transportation construction projects, [Goddard, 1995]. The long-term performance of HDPE is of particular interest, in view of highly organic and salt-water (coastal) conditions.

Recently, based on field experience in California, concerns have been expressed, [Johnson, 1993], [Strand, 1993], and [Hall and Foreman, 1993], about certain inadequacies of high-density polyethylene piping. These include long-term strength and stiffness (dimensional reliability) characteristics, delamination of the interior liner, inconsistency of physical properties, buckling, opening of joints leading to infiltration and exfiltration of water, tearing of corrugations and circumferential cracking of inner liner, flammability, the requirement for excessive trench widths. But thirty state DOT

(Department of Transportation) reports indicated favorable performance of this type of pipe, in response to a survey by Tennessee DOT, Table 1 .1 [Klaiber, 1996].

Table 1.1 State Responses to Tennessee DOT HDPE Pipe Survey

State	Diameter of pipe (in.)	Minimum cover (in.)	Problems?
Alabama	Up to 36	12	No
Alaska	-	-	No
Arizona	12-24; >24 by approval	-	No
Arkansas	-	-	No
California	-	-	No
Colorado	-	-	One culvert burned
Connecticut	-	-	No
Delaware	-	-	No
Indiana	-	-	No
Iowa	Up to 24	-	No
Kansas	-	-	No
Kentucky	12 to 36	12	No
Maine	12 to 24	-	No
Maryland	15 to 36	24	No
Michigan	-	24	No
Minnesota	12-24	24	No
Mississipi	12-24	-	No
Montana	Up to 18	-	No

State	Diameter of pipe (in.)	Minimum cover (in.)	Problems?
Nebraska	12-24	-	No
New Jersey	-	24	Infiltration of fines at joints
New Mexico	-	-	No
New York	-	12-15	When wet conditions, HDPE will float.
North Carolina	-	-	No
Ohio	-	-	No
Oklahoma	-	-	No
Oregon	12-24	-	No
Pennsylvania	-	-	No
South Carolina	12-36	-	No
Tennessee	12-36	-	One pipe burned
Texas	-	-	No
Vermont	-	-	No
Virginia	12-36	-	No
Wisconsin	8-36	12-180	No

Additionally, many national organizations like AASHTO (American Association of State Highway and Transportation Officials) and TRB (Transportation Research Board) have approved its use.

The necessary considerations to ensure long-term performance of HDPE pipe are as follows: 1) resin quality (strength and cracking), 2) profile stability (buckling resistance), 3) adequate installation stiffness and backfill control, and 4) installed pipe deflection levels. Items 1 and 2 are especially important in these long-term applications due to the time dependent nature of the materials involved. Local buckling can occur when sufficient compressive strain due to any combination of deflection and ring compression occurs for each specific profile. Cracking occurs due to localized tension stresses (strains) and stress concentration factors in the profile. For long-term applications, both pipe deflection levels and the specific grade of the material used must be controlled.

CHAPTER 2

LITERATURE REVIEW

2.1 *Thermoplastic pipe for nonpressure applications*

More than half of the entire thermoplastic pipe produced is used for nonpressure applications. Most drainage systems, including those for building foundations, leaching fields, agriculture, and road construction now consist of thermoplastic piping, mostly PE and PVC. Both PE and PVC are increasingly used for larger-diameter sewers and culverts. Thermoplastics, being nonconductors, are immune to the corrosion process induced by electrolyte, such as acids and salts. In addition, plastic pipe materials are not vulnerable to biological attack. This results in negligible costs for maintenance and external protection such as painting, plastic coating, or cathodic protection. Their lower specific gravity contributes to ease of handling, storage, and installation, as well as lower transportation costs. They also offer very good abrasion resistance, even when conveying slurries. High deformation capacity provides a positive pipe-soil interaction that is capable of supporting earth fills and surface live loads of considerable magnitude without fracture. Therefore, a sizable number of DOT (Department of Transportation) reports have indicated favorable performance of this type of pipe, and many national organizations including AASHTO (American Association of State Highway and Transportation Officials) approve its use.

However, primarily based on some recent experiences in three field sites in California, concerns have been expressed about the inadequacies of HDPE flexible piping, and, by implication, about all thermoplastics for this application area; e.g. Johnson [1993), Strand [1993], and Hall and Foreman [1993]. These concerns which must be resolved, include long-term strength and stiffness (dimensional reliability) characteristics: delamination of the interior liner, inconsistency of physical properties, buckling, opening of joints leading to infiltration, and exfltration of water, tearing of corrugations and circumferential cracking of the inner liner, flammability, and the requirement for excessive trench widths. The development of data and methodologies for the safe and reliable use of HDPE, PVC and other thermoplastics to allow them to be used in competition with other pipe materials, is essential to assure cost-effective applications, which, in turn, would enhance the utilization of public funds for highway construction and maintenance operations.

To ensure long-term performance, the individual pipe wall profile must be evaluated in regard to its specific geometry, and the stresses and strains quantified to properly determine the long-term capacity of the specific materials allowed. Local buckling will occur when sufficient compressive strain due to any combination of deflection and ring compression occurs for each specific profile. Cracking occurs due to localized tension stresses (strains) due to stress concentration factors and residual stresses in the profile. For long-term applications, both pipe deflection levels and the specific grade of the plastic used must be controlled. Specific items for control include the following:

1) Resin quality (strength and cracking)
2) 2) Profile stability (buckling resistance)
3) 3) Adequate installation stiffness and backfill control.
4) 4) Pipe deflection levels.

Items 1 and 2 are especially important in long-term applications.

The values of long-term performance limits depend very much on the design method. The proof of any design theory should be how accurately it predicts the location, and the mode of failure of the product under anticipated loading conditions. Unfortunately, current non-pressure pipe design procedures do not pass this test, regardless of major pipe types [Goddard, 1994]. Performance limits that have been suggested for the design of buried gravity flow thermoplastic pipes include: 1) deflection, 2) wall buckling, 3) wall strain, 4) wall crushing, 5) longitudinal bending, 6) stress concentration, and 7) yielding.

A study of polyethylene pipe specifications carried out at California State University by Gabriel, Bennett, and Schneier [1996], indicated that the HDB testing has only marginal value in its ability to predict the long-term service performance of gravity flow non-pressure pipes, and that its cost/benefit aspects are not persuasive. However, a quantitative evaluation has not yet been made to set up performance limits and develop practical guidelines for selection, design, specification, and installation.

Moser [1993, 1994] observed that "the normal and real modulus is the instantaneous stress divided into the instantaneous short-term strain parameter for design and most materials must be designed on a life basis". This was based on Hydrostatic Design Basis (HDB) strength testing of the PVC pipe that had been in service for 15 years, in which the modulus after unloading was the same as that when the pipe was manufactured. The properties of HDPE pipe (viscoelastic material) are dependent on time, temperature, stress, and rate of loading. Instantaneous testing cannot be expected to simulate material behavior when subjected to stress or deformation for extended period of time. For life prediction, consideration should be given to the estimation of long-term property values of the modulus and strength under exposure conditions (pipe-soil interaction) that simulate the end-use applications. The use of a pseudoviscoelastic modulus for the elastic modulus implies the tacit use of a principle of viscoelasticity known as the "correspondence principle". This principle states that the stresses in a viscoelastic body subjected only to constant applied forces, will be exactly the same as they are in an elastic body subjected to the same set of tractions [Christensen, 1971]. In contradistinction to constant internally pressurized pipe in the gas industry, non-pressure pipe is subjected to mixed force and displacement boundary

2.2 HDPE manufacturing, classification and properties

Polyethylene is possibly the best-known member of the polyolefin family, derived from polymerization of olefin gases. PE is a partly crystalline and partly amorphous material. The properties of PE are determined by its molecular structure. PE consists of backbone of long molecular chain from which short chain branches occasionally project. The length, type, and frequency of distribution of these branches, as well as other parameters such as molecular weight and distribution, determine the degree of crystallinity and network of molecules that anchor the crystal-like regions to one another. These structural characteristics affect the short and long-term mechanical properties. The extent of crystallinity of PE is reflected by density. The higher density materials have more crystalline regions, which results in greater stiffness and tensile strength.

To protect the polymer during processing, storage, and service, PE is blended with small quantities of heat stabilizers, anti-oxidants, and ultra-violet (UV) screens or stabilizers. The primary specification for identifying and classifying PE piping materials is ASTM D3350, entitled "Standard Specification for Polyethylene Pipe and Fitting Materials", Table 2.1. This specification identifies polyethylene pipe and fitting materials according to a cell class format based on physical property criteria. The PE pipe compounds are classified according to density, melt index, flexural modulus, tensile strength at yield, environmental stress crack resistance, hydrostatic design basis at 23 oC (73.4 OF), color and UV stabilizers. The order of these various properties is constant as shown in Table 2.1.

Due to the limitation of the current environmental stress crack resistance (ESCR) tests (ASTM D 1693), an alternative test, the single point notched constant tensile load

(SP-NCTL) test (ASTM D 5397), was utilized in the study of Geosynthetic Research Institute [Hsuan, 1999]. The cell classification should be modified to reflect changes in SCR tests. The current cell class number for the ESCR is "T'. This number should be changed to "0", if the SP-NCTL test is adopted. The specification should not require two different SCR tests. The cell class "0" in ASTM d3350 is referred to "unspecified". Instruction for the SP-NCTL test procedure and requirement should then be incorporated into the appropriate section (s) of the specification to guide the user.

Table 2.1 Primary Properties: Newly adopted Cell Classification Limits for PE Materials in Accordance with ASTM D3350

Property	Test Method	0	1	2	3	4	5	6	7	8	9
1. Density (g/cc)	D 1505	Unspecified	0.910 - 0.925	0.926 - 0.940	0.941 - 0.955	> 0.955					Specify value
2. Melt Index (g/10 min)	D 1238	Unspecified	>1.0	1.0 to 0.4	<0.4 to 0.15	< 0.15					Specify value
3. Flexural Modulus(MPa)	D 790	Unspecified	<138	138 - 276	276 - 552	552 - 758	758 - 1103	> 1103			Specify value
4. Yield Strength (MPa)	D 638	Unspecified	<15	15 - 18	18 - 21	21 - 24	24 - 28	> 28			Specify value
5. Resistance to Slow Crack Growth											
Method A (hr): Compression mold 2.4 MPa, 80°C notch depth (Table 1 in F1473)	F 1473	Unspecified				0.15	1	3	10	30	Specify value
Method B:	D 1693	Unspecified									Specify value
a. Test condition			A	B	C	C					
b. Test duration (hr)			48	24	192	600					
c. Failure, max, %			50	50	20	20					
6. Hydrostatic Design Basis (MPa) 23°C	D 2837	Unspecified	5.52	6.89	8.62	11.03					Specify value

2.3 Pipe-soil interaction

Pipe-soil interaction addresses the mutual contributions of pipe and soil in a successful structural system, as soil supports much of the vertical pressure in arching action, over the pipe. The basic concept of the theory is that the load due to weight of the soil column above the buried pipe is modified by arching action, in which a part of its weight is transferred to the adjacent side prisms, with the result that in some cases the load on the pipe may be less than the weight of the overlaying column of soil. Or, in the other cases, the load on the pipe may be increased by an inverted arch action, in which the load from the side prisms is transferred to the soil over the pipe. The transferred force, associated with arching action at the plane of the relative movement, is the resultant of the vertical and horizontal components of force, Spangler [1982].

The "bedding" condition has a very important effect on both circumferential and longitudinal bending moments. For instance, active lateral earth pressure can reduce the circumferential moment by 25 %, Spangler [1982]. The longitudinal bending moments can also be affected similarly. Rajani et al. [1996] have indicated that flexural action due to inadequate bedding support or swelling of underlying clay imposes longitudinal tensile stresses, Fig. 2.1. Tensile stresses in the pipe can also be induced if clays with a high montmorillonite mineral content undergo substantial volume change, when subjected to seasonal wet and dry conditions. Clark [1971] and Morris [1967] have reported that volumetric shrinkage for clays in Texas can be in the range of 14-40 percent.

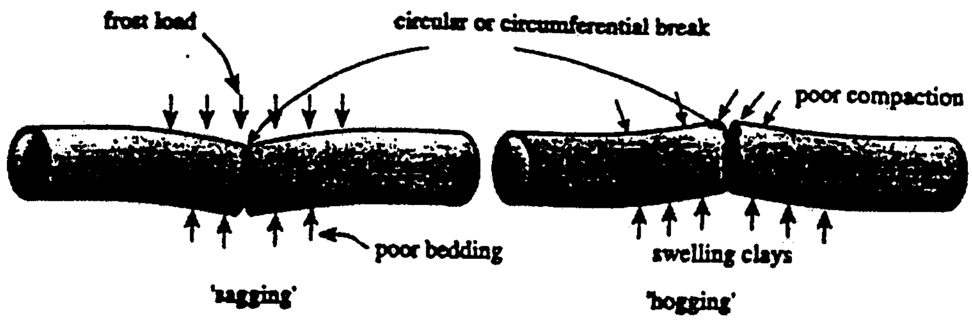


Fig. 2.1 Bending or flexural failure [Rajani et al. 1996]

A simple relationship to express soil-pipe interaction in the transverse plane is that given by the Iowa Method (Modified Spangler Equation, ASTM D2412, 1995), CPPA [1996], which is applicable up to a deflection of 5 % of the diameter i.e.

$$\Delta y = \frac{K(D_L W_C + W_L)}{0.149PS + 0.061E'} \qquad (2.1)$$

where

Δy = Deflection,

K = Bedding constant, dimensionless (ASTM D 3839, X1.3.2)

D_L = Deflection lag factor (ASTM D3839, X1.3.1)

$W_C = \gamma HOD$ = Soil column load on pipe

γ = Unit weight

H = Burial depth

OD = Outside diameter of pipe

W_L = Live load

PS = $EI/0.149Fr^3$ = Pipe stiffness

E = Flexural modulus of the pipe

I = Moment of inertia of the pipe wall F =

actual load applied

r = mean radius

E'= Backfill modulus

This clearly indicates that the deflection of a soil-embedded pipe depends on the relative stiffness of the pipe and soil. There is a likelihood of long-term decomposition in organic soil, which can reduce the arching action. Also, the physico-chemical stability of certain limestone gravel can be detrimentally affected by dissolution due to groundwater changes. The change in the degree of compaction near the pipe, and the consequent change in K, can occur during installation, and/or service due to soil saturation or pumping. This can also cause separation of the pipe wall from the soil. Therefore, it is important to address the possible decrease of the arching effect in the life prediction of HDPE pipe. The same type of soil changes can induce significant longitudinal stresses due to differential settlement-induced beam action with non-uniform subgrade modulus.

2.4 Failure mechanisms of buried HDPE pipe

The major failure modes for thermoplastic pipes include buckling, and ductile/brittle failures. Slow crack growth or rapid crack propagation characterizes some of these. For pressurized pipes, ductile and brittle failures are of the utmost importance, as buckling is seldom a major concern. In contrast, buckling is the most common failure mechanism in non-pressure applications, with the remaining two failure modes being possible only in highly unusual conditions. Note that in this discussion "brittle" is one that is produced in a long time period under relatively low stress, is accompanied by little or no ductility, and is initiated at an intrinsic weakness, (i.e. impurities, notches) in the material. Slow crack growth (SCG), which is actually the same process, will here be used to describe failures that initiate from larger artificial defects introduced in installation or service.

2.4.1 Stress cracking

Stress cracking is a macro-brittle cracking phenomenon that occurs at a constant stress significantly less than the yield or break stress of the material. It is initiated at an internal or external "defect" in the material such as an inclusion or scratch. In HDPE components, although the stress crack is not associated with any apparent adjacent material deformation, the fracture face itself provides evidence of ductility on a microscopic scale. In most cases, failure occurs as a result of some unknown material performance characteristic, or some unexpected local service condition that initiates a crack at a "flaw" in the material. It is necessary to identify such unexpected failure initiating defects, and to understand at what rate induced cracks will propagate, and how much they reduce the service life [Reddy, 1996].

The predominant mode of premature failure of thermoplastic pipe is a quasibrittle fracture initiated at stress concentrating surface notch geometry and/or unexpected point stress, Peggs and Kanninen [1995]. Such failures occur due to the fundamental stress cracking susceptibility. The stress cracking is often called "Slow Crack Growth (SCG)", which occurs at stress levels lower than the tensile yield strength, and at any time during the life of a pipe.

The material does not become brittle; it simply shows the appearance of brittleness. Stress cracking is a synergistic function of applied stress, temperature, and many material parameters (e.g. molecular weight and its distribution, commoner type and content, and crystallinity). Stress cracking is most commonly thought to occur when the tie molecules, which links crystalline and amorphous regions, slowly slip out from the region of crystallinity involving entangled loose ends of tie molecules [Lustiger, 1983]. Fracture thus occurs between crystalline regions involving amorphous polymer only, without apparent deformation, and with relatively smooth fracture face morphology in HDPE. In contrast, when HDPE is subjected to rapid increase in stress, as in a typical uniaxial tensile test, the tie molecules do not have time to slip out of their entanglement, but instead, pull segments of the crystalline region with them, producing the necking and elongation associated with yielding.

In the design of HDPE for storm-water sewer applications, a number of performance limits need to be considered. In addition to well-established limit states, such as buckling and excessive deflection, the maximum circumferential bending stresses in the pipe have to be considered to avoid tensile yield or rupture of the pipe. Recently, it has also been suggested that buried plastic pipe may be susceptible to slow crack growth following environmental stress cracking or some other crack initiation mechanism. It has been established that slow crack growth will only occur in a tensile stress field, Kuhlman, Weed, and Campbell [1995]. Furthermore, index tests developed for the gas pressure pipeline industry, reveal that the speed at which slow crack growth occurs is affected by the magnitude of that maximum tensile stress. Materials exhibiting low ductility can fail prematurely in a crack-like fashion (brittle fracture) by slow crack growth.

The potential for stress cracking of plastic pipe is not a function of material properties alone, as geometry plays an important role, Gabriel, Bennett, and Schneir [1996]. The NCTL (Notch Constant Tensile Load), ASTM D5397, does not address the relationship between stiffness and stress crack initiation with the focus on geometry. It is necessary to identify unexpected failure-initiated defects and to understand their rate of propagation, and the associated possible effects on excessive deflection and buckling. Stress cracking failure in pipe, which is well presented in the Gas Research Institute's Field Failure Catalog for Polyethylene Gas Piping, occurs predominantly at notch geometry associated with joints. It also happens at locations where rocks impinge against the pipe surface, and at locations that have been improperly squeezed off while making repairs, Peggs and Kanninen [1995]. The stress-cracking problem in pipe was identified in the late 1970's. It was subject of much research in the early. 1980's, resulting in significant improvements in stress cracking resistance of pipe grade resins.

2.4.2 Creep and creep rupture

HDPE is viscoelastic material for which the history of deformation has an effect on the response. For example, if a load is continuously applied, it creates an instantaneous initial deformation that then increases at a decreasing rate. The stress and strain are related by a modulus that depends on the duration and is independent of the magnitude of the applied stress and strain for a given temperature, Fig. 2.2. Viscoelastic behavior becomes nonlinear at high stress or strain or elevated temperatures, Figs. 2.2 and 2.3.

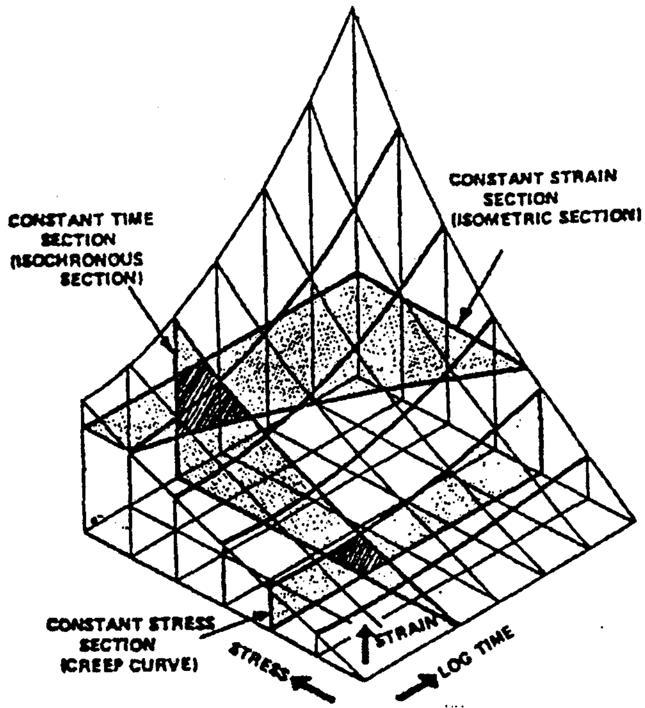


Fig. 2.2 Constant stress-strain time coordinates

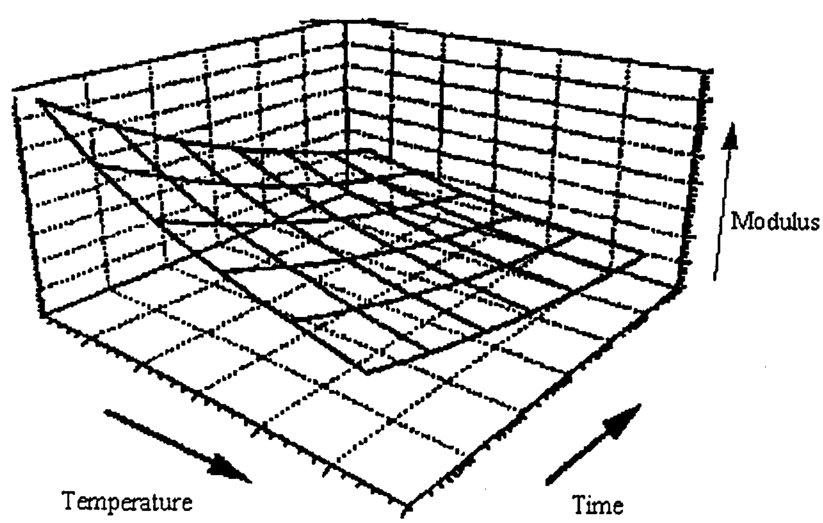


Fig. 2.3 Schematic of the viscoelastic behavior of polymers

Creep, expressed in terms of the decreasing modulus contributing to increasing deformation, (i.e. loss of stiffness), and creep-rupture, expressed in terms of decreasing life with increasing stress and temperature, are important parameters for life prediction. The transition from ductile to brittle behavior enables the realistic estimation of life from the creep-rupture plot.

Woods, Krause-Singh, and Hindman [1996] conducted constant load tensile stress-rupture testing on HDPE pipe material, based on ASTM D 638, and observed the occurrence of the ductile-brittle transition at a very early stage with a high stress level; no knee was seen in the tensile stress vs. time plot. The ductile phase is "bypassed" at higher stress levels and the correspondence is to a "rapid load" test.

The predominant mode of premature failure of thermoplastic pipe, as indicated earlier is quasi-brittle fracture, initiated at stress concentrating surface notch geometries, imperfections (initial pinpoint depressions, etc.) and/or unexpected point stresses. Prediction of life, based on only long-term material properties, ignoring the geometry, would overestimate the predicted life. Geometry, associated with the pipe curvature and the connectivity of the corrugations with lining, can effect the creep and creep-rupture behavior. It can also reduce the buckling strength at the wall. It is necessary to identify unexpected failure-initiating defects and to understand at what rate induced cracks will propagate, and how much they affect the reduction of service life. The creep and creep-rupture schematics for life prediction are shown in Figs. 2.2, 2.3, and 2.4.

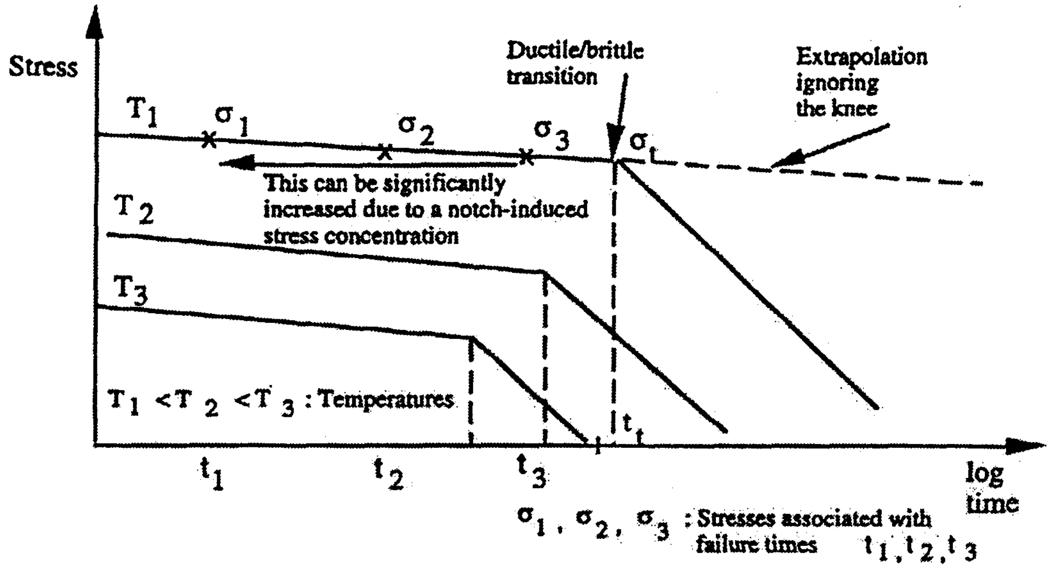


Fig. 2.4 Creep-rupture behavior for semi-crystalline polymers

2.4.3 Buckling

The circumferential and longitudinal moments can induce local buckling in the corrugated wall of the HDPE pipe. The more flexible the pipe, the lower the resistance to buckling. Caution should be exercised when considering large diameter pipes or pipes in shallow burial. Moser [1990] developed a circumferential buckling equation that has been shown to be conservative for thermoplastic pipe, with the modification of the Euler buckling formula, as follows:

$$P_{cr} = 2\sqrt{\frac{E'}{1-v}\left(\frac{EI}{R^3}\right)} \text{----------------} \quad (2.2)$$

where

P_{cr} = Critical buckling pressure (MPa, psi)

E'= Soil modulus (MPa, psi)

ν = Poisson's ratio (dimensionless)

E = Modulus of elasticity (MPa, psi)

I = Moment of inertia (mm^4/mm., $in.^4$/in.)

R = Pipe radius (mm, in.)

AASHTO and ASCE use a somewhat different approach; the current AASHTO, [1992] version is as follows:

$$f_{cr} = 0.77(R / A\phi)\sqrt{\frac{BE'EI}{0.149R^3}} \quad \text{--------------------(2.3)}$$

where

B = Water buoyancy factor (dimensionless) = $1 - 0.33h_w/h$

h_w = Height of water above top of pipe (m, ft.)

h = Height of ground surface above top of pipe (m, ft.)

E = Long-term modulus of elasticity (50 year) (MPa, psi)

I = Moment of inertia (mm^4/mm, $in.^4$/in.)

E' = Soil modulus (MPa, psi)

F_{cr} = Critical buckling stress (MPa, psi)

R = Effective radius (mm, in.) = c + ID/2

c = Distance from the inside surface to the neutral axis (mm, in.)

A_ϕ = Pipe wall area (0.083 mm^2/mm, $in.^2$/ft.)

HDPE is a viscoelastic material that shows creep behavior. Therefore, the buckling strength of HDPE pipes decreases for long-term service. The AASHTO standard specification for highway bridges (Section 18.2.2. buckling) clearly requires the use of the 50-year modulus of elasticity for conservative buckling analysis, instead of the initial modulus of elasticity.

Based on the hoop compression tests carried out by Selig, DiFrancisco, and McGrath [1993], Moore and Laidlaw [1997] evaluated local buckling in the sidewall of the corrugation, the valley and the crown. Local sidewall buckling was characterized by the development of waviness in the element or sidewall. The phenomenon typically commenced atone location, spread, and became more pronounced at higher hoop strains, thus involving most of the pipe circumference. Valley buckling typically featured a lateral torsional response. This was generally at a location, where the sidewall buckling was also present, with possible significant interaction between the two elements of the profile. In his field inspection of pipe, buried under Route I-279 north of Pittsburgh, PA, Selig [1990-1993], observed buckling of the unsupported parts of the liner (between corrugation crests). These buckles were located in the bottom half of the pipe [Selig, 1995]. This is a natural consequence of the ring compression of the wall.

Inaddition, circumferential cracking of inside crests was also observed in the corrugated sections with the area covered by the coupling. He mentioned that this was probably a longitudinal stress problem associated with coupling.

For a pipe tested under hoop compression, [Selig et al. 1993] carried out a numerical prediction of critical hoop strain using a stiffened plate model and expressed buckling in terms of critical hoop strain. Local soil support was found to have an important effect on the edge restraint that influences the buckling strength, Moore and Laidlaw [1997). It was assumed that the pipe was subjected to a uniform component of radial stress acting around the pipe circumference, due to arching. However, when the arching action is affected by degradation in soil properties, the vertical pressure in the soil above the pipe is greater than the lateral pressure, and an ovaling deformation results. Interactive longitudinal and circumferential bending can cause the local wall buckling due to changes in bedding uniformity over a long-term, possible poor installation, or ground saturation. Therefore, it is necessary to investigate the buckling strength under combined circumferential and longitudinal bending. The time-dependent buckling strength needs to be correlated with creep and creep-rupture; the effect of possible damage should be considered for the long-term performance of HDPE pipe.

2.5 Performance limits

Prior to developing a design procedure, performance limits must be established. The performance limits of buried HDPE pipe are related to stress, strain, deflection, or buckling. The values of these limits depend on the design method used. The following is a list of performance limits that are suggested in the literature for the design of buried, HDPE pipe and culverts [Goddard, 1994].

i) Deflection: This limit is quite important due to relatively low bending stiffness compared to concrete or metal pipes. Also, the stiffness decreases with time during the service period. Excessive deformation can limit the flow or joint leakage. The limits are set to avoid pipe-flattening, reversal of curvature, limit bending stresses, or bending strains. However, deflection of pipes that are flexible in bending is controlled mainly by the method of installation and in-situ soil envelope *nronerties. Fig. 2.5.*

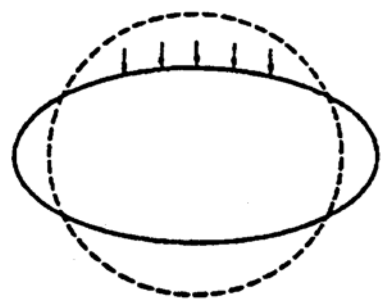


Fig. 2.5 a) Ring deflection in a flexible pipe [Moser, 1994]

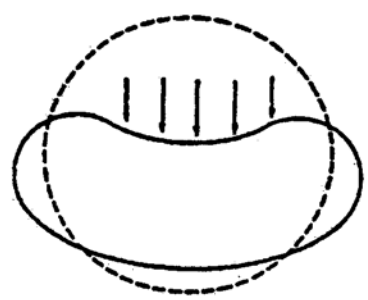


Fig. 2.5 b) Reversal of curvature due to over-deflection [Moser, 1994]

Wall buckling: Insufficient bending stiffness or stiffness of soil envelope can cause wall buckling, Fig. 2.6. Buckling should be considered because it represents pipe cave in. Large diameter pipe design may be governed by buckling, particularly when subjected to high soil pressure in low stiffness soil.

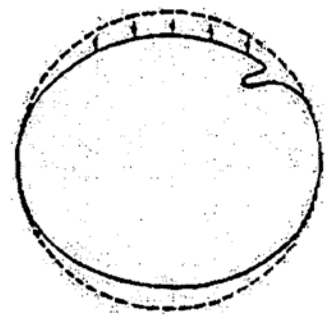


Fig. 2.6 Localized wall buckling [Moser, 1994]

iii) Wall crushing: Wall stress in compression can lead to wall crushing if excessive. If the ring compressive stress exceeds the compressive strength of the wall of the pipe, wall crushing can generally occur at the 3 and 9 o'clock positions on a pipe, Fig 2.7.

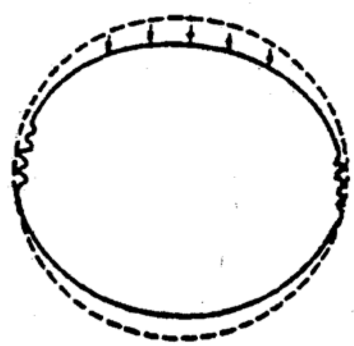


Fig. 2.7 Wall crushing at the 3 and 9 o'clock positions [Moser, 1994]

The situation is generally only of concern with thinner walled pipes under deep burial. The thrust in the wall is as follows:

$$T = \frac{PD}{2} \quad \text{------------------------------------} (2.4)$$

in which

T = Thrust (kN/mm, lb/mm)

P = Distributed design load (psi, kPa)

D = Diameter of the pipe (in., mm)

iv) Longitudinal bending: Circumferential cracking evidences that longitudinal tensile stress condition caused this type of failure. Bending action due tc inadequate bedding support imposes additional tensile stresses. The inevitable variation of the spring coefficient for bedding, along the pipe length, can cause longitudinal stresses and opening/cracking of the joint or lateral buckling. So the flow inside of the pipe may be limited or leaks.

v)

2.6 Current AASHTO design Procedure

2.6.1 Loads

The AASHTO code specifies that the pipes should support the overburden load from the soil, which mainly consists of a block (prism) extended from the ground level to the top of the pipe, plus the effects of shear forces along the edge of the block. The formula developed by Martson and Spangler is widely used to evaluate the overburden load (commonly called prism load or Martson load). In addition to the direct load imposed by soil overburden, the pipe must also support the loads applied on the ground surface. However, the intensity of surface loads is known to decrease with increasing depth.Therefore, the consequence of traffic, or other surface loads, on deeply buried pipes is relatively minor but can be of importance in shallowly buried pipes. Also, the effects of the dead weight of the pipe and the fluid transported do not contribute significantly to the overall stress in the case of plastic pipes and can be neglected.

2.6.2 Design

In current practice, the structural capacity of corrugated HDPE pipes is evaluated on the basis of wall resistance to thrust (AASHTO '96) and wall resistance to buckling (AASHTO '96) to ensure that the pipe is not damaged by excessive deformation during shipping, handling, or installation.

AASHTO M294-94 specifies values for minimum pipe stiffness (PS) at 5% vertical deflection to ensure sufficient stiffness to perform backfill properly. These values are obtained through conducting ASTM D2412 tests and vary from 50 psi for 12" diameter pipes to 22 psi for 36" diameter pipes. AASHTO M294-98 covers diameters up to 48", whereas the provisional AASHTO MP7-97 addresses pipes up to 60".

The 1997 AASHTO Revision for Section 30 specifies a minimum depth of cover above the pipe of 24 inches before allowing vehicles or construction equipment to cross the trench surface. It states that the hydro-hammer type compactors shall not be used over the *pipe.* In addition, it sets the minimum depth of soil envelope above the crown and the bedding to 12 and 4 to 6 inches. This AASHTO Revision also requires that the minimum width of the trench be equal to 1.5 times the outside pipe diameter plus 12 inches (1.5

2.6.3 Pipe resistance and stiffness

Structural strength and rigidity against external loads for HDPE pipes are established by load tests performed according to ASTM D2412. In the load test, equal and opposite concentrated loads are applied on opposite ends of the diameter. The pipe stiffness and related buckling resistance are determined from the load deflection data.

2.6.3 Design life

The service lives of corrugated HDPE pipes are dependent upon many factors such as load magnitude, duration and history, temperature, and moisture, as well as longterm durability performance with regards to aggressive environments. Under adverse loading and environmental conditions, corrugated HDPE pipes subjected to the action of a constant load may fail after a certain period, referred to as the endurance line. This phenomenon, known as creep rupture, exists for all structural materials. As the ratio of the sustained stress to the short-term strength increases, the endurance time (i.e. time to rupture) decreases.

The design procedure specified by AASHTO Standards recognizes the time dependence of the stress-strain relationship by allowing the use of long-term (e.g. 50year-service life expectancy) tensile strength regression value. Also, the AASHTO code requires the use of 50-year modulus of elasticity when designing for buckling (AASHTO'96) and sets the allowable long-term strain to 5%.

2.7 Service life

The current AASHTO code requirements and practice are adequate for a conservative design of corrugated HDPE pipes buried at 17 feet or less, provided that [FDOT, 1999]:

(a) the backfill soil has a minimum stiffness E'=2,000 psi and a 95% minimum compaction; (b) only HDPE pipes with annular corrugations are allowed; (c) the minimum width of the trench is equal to 1.5 times the outside pipe diameter (O.D.) plus 12 in. (1.5 O.D. + 12 in.); (d) the minimum cover above the crown of the pipe is 24 inches before allowing vehicles or construction equipment to cross the trench; (e) the irregularities of the bedding surface (grade control) are limited to 1 % of a single section of pipe; (f) the so-called bell-and-spigot extruded joints, such as ADS Pro-Link Ultra or Hancor Hi-Q Sure-Lok, meeting the AASHTO requirements are used.

2.8 Life prediction

There is an identified need to investigate the long-term behavior in relatively short laboratory time scale, by evaluating the effect of soil degradation mechanisms at field-related temperatures and stresses, compounded by synergistic effects, with accelerated testing, high stress, elevated temperatures, and/or aggressive liquids.

It is noteworthy that the type of material qualification testing, used for natural gas distribution piping, has very effectively screened out one failure mode: ductile failure.

dependence of polyethylene and other thermoplastic materials, it is both possible and necessary to accelerate the failure mechanism. The key is the use of time-temperature shifting functions that can reliably connect high temperature/high pressure performance to actual service conditions.

The long-term properties can be predicted based on viscoelastic behavior: i) the Arrhenius equation [Koerner, 1994], which describes the temperature dependency of the degradation reaction on time and temperature, ii) the Bi-directional method, which determines the curve that fits the time-to-failure test data at elevated temperatures to enable predictions of times-to-failure at lower temperatures, [Popelar, 1993]

2.8.1. Evaluation of the long-term properties using Arrhenius equation

A considerable amount of data shows that most chemical reactions for degradation have a strong dependence on the temperature, time, applied stress level, and the concentration/quantity of chemicals involved in the reaction. In fact, such dependence can be used advantageously to develop relationships that can be used for extrapolation purposes. A common form of this important extrapolation tool is as follows:

$$In\ (t/t_o)=(E_{act}/R)(l/T - 1/T_o) \text{ --------------------------(2.6)}$$

where

t=time to given strength loss, usually 50%, at the test conditions

T=temperature of the test environment, in OK

t_o=time to the same given strength loss as for t, but in the in-situ environment

T_o=temperature of the in-situ environment, in ^{O}K

R=universal gas constant, which is 8.314 J/mole

E_{act}=effective activation energy, J/mole

In the Arrhenius plot, degradation is plotted as the logarithm of the reciprocal of time versus the reciprocal of temperature using Equation 2.6. The schematic of the plot is provided in Fig. 2.10. It is noted that the temperature has an exponential effect on the time required for a specified level of degradation based on this model, and the data used in Equation 2.6 is obtained at a constant level of degradation (indicated by the modulus decay) in the material. The extrapolation for failure time is similar to that used in the WLF Method. The WLF and Arrhenius equations are accurate for linear amorphous polymers, but catastrophic failure that occurs at ductile-brittle transition makes the prediction difficult for semi-crystalline polymers. This problem should be addressed, and the life predictions given by the two methods compared, and their equivalence studied using the procedure developed by Miyano [1996].

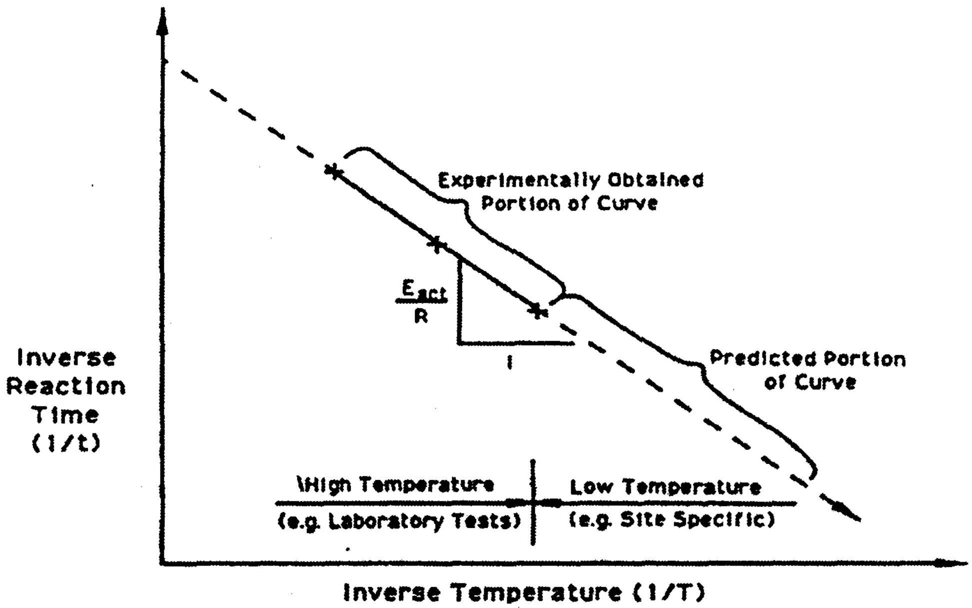


Fig. 2.10 Generalized Arrhenius plot, for a specified stress level, used for life prediction from super-ambient temperature experimental data

2.8.2. Evaluation of the long-term properties using Bi-directional shifting method

The Bi-directional Shifting Function Method, Popelar et al. [1990], enables the construction of master curves for nonpressurized HDPE sewer pipe material using creep test data. In this procedure, no curve fitting is needed, which enables even a single data point, representing any viscoelastic phenomenon determined at a given test temperature, to be shifted to another temperature. Based on the time-temperature superposition principle, the horizontal and vertical shift functions, a_T and br, respectively, are given by:

$$a_T = \exp\left[-0.109\ (Ts-T_t)\right] \text{------------------------------------} (2.7)$$

$$b_T = \exp[0.0116 (T_s - T_t)] \text{ -- } (2.8)$$

where

a_T= Time shift function

b_T = Stress (or deflection) shift function

T_t = Laboratory test temperature (°C)

T_S = Service temperature (°C)

CHAPTER 3

EXPERIMENTS

3.1.Introduction

Two types of corrugated HDPE pipe specimens of nominal inside diameters 12 in. (300 mm) were considered. Both types have the same cell classification, i.e. 335420C with density = 33.97E-3-34.48E-3 lb/in^3 (0.941-0.955 g/cm^3), melt index=0.4-0.15, flexural modulus = 110,000-160,000 psi (758-1,103 MPa), tensile strength at yield = 80,000-110,000 psi (552-758 MPa), and Color and UV stabilizer = black with 2% minimum carbon black. There were small geometrical property differences between the two pipes.

The purpose was to study the changes of diameter and the strains (in function of time) of Types I and II buried pipes subjected to an AASHTO loading.

The long-term behavior was accelerated with super-ambient temperatures to provide the data for life prediction (20, 40 and 50 $^{\circ}$C).

7.5% vertical deflection is the failure criterion; so, readings have been taken up to failure or 10, 000 hours.

3.2. Materials and specimen configuration

3.2.1. Specimen details

Cell classification: 335420C

Type of soil: ASTM D2321 Class II, SW/SP, and 90% degree of compaction

3.2.3. Characteristic length

The characteristic length is important because the supports at the end of the pipe have to be located where the moment is zero (Fig. 3.3), to eliminate the bending effects of restraints.

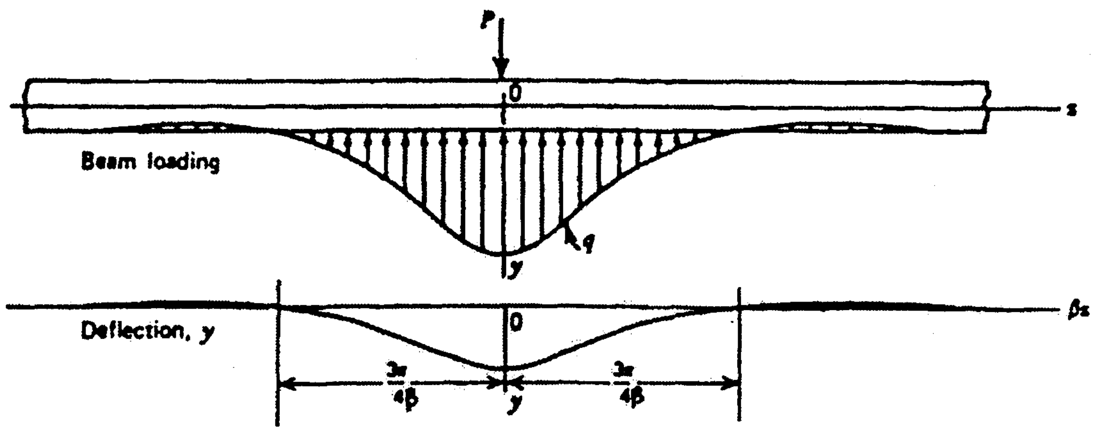


Fig. 3.3 Infinite pipe on elastic soil foundation

λ=3π / 2β = characteristic length of the pipe ______________ (3.1)

$$\beta = \sqrt[4]{\frac{Bk}{4E_P I}} \qquad \text{(3.2)}$$

where

$$k = 0.65 \sqrt[12]{\frac{E_S B^4}{E_P I}} \frac{E_S}{B(1-\mu^2)} \qquad \text{(3.3)}$$

- k = Coefficient of subgrade reaction
- E_S = Modulus of elasticity of soil
- B = Average diameter of the pipe
- E_P = Modulus of elasticity of the pipe

μ = **Poisson's ratio of soil**

I = Moment of inertia of the cross section of the pipe

3.2.4. Minimum cover

The loads on the pipe for minimum cover primarily are due to the surface loading. A minimum amount of soil cover is needed to spread the surface loading and to create a more favorable soil pressure distribution around the pipe. Some States specify their minimum cover requirement according to the type of pavement (rigid or flexible). Others specify the same minimum cover, and the location to which the cover is measured (top of the pavement for rigid pavements and top of the subgrade for flexible pavements). Minimum cover requirements are listed in Table 3.1 [CPPA, 96].

Table 3.1 Minimum Cover Requirements for Corrugated Polyethylene Pipe

Inside Diameter In. (mm)	Minimum Cover ft (m)	Inside Diameter In. (mm)	Minimum Cover ft (m)
3 (75)	1 (0.3)	18 (450)	1 (0.3)
4 (100)	1 (0.3)	21 (525)	1 (0.3)
6 (150)	1 (0.3)	24 (600)	1 (0.3)
8 (200)	1 (0.3)	30 (750)	1 (0.3)
10 (250)	1 (0.3)	36 (900)	1 (0.3)
12 (300)	1 (0.3)	42 (1050)	1 (0.3)
15 (375)	1 (0.3)	48 (1200)	1 (0.3)

The minimum cover specified is mostly between 300 and 600 mm. This is comparable to the minimum cover of 300 mm specified in AASHTO Section 18. The maximum fill heights specified from 3 to 18.3 m.

A higher-quality backfill envelope, achieved through the use of an improved material or the compaction, does allow for a theoretical reduction in this cover, but in reality, minimum cover of finished installations should not be less than 1' (0.3 m). Paving material (asphalt or concrete) greatly reduces all structural distress including deflections. However, it is not usually possible to take the design advantage of the paving material because the pipe must support construction loads prior to placement of paving material. Loads during construction are sometimes much heavier than the design load. The cover over the pipe may need to be increased to allow heavier equipment. It can often be reduced during paving, if equipment loads are fairly light and well distributed.

According to Katona (1995), currently, the tentative guideline for minimum cover of plastic pipe, as suggested by the AASHTO Flexible Culvert Committee, is taken directly from the metal culvert industry, the American Iron and Steel Institute (AISI). The AISI specification for corrugated metal culverts requires a minimum of 12 in., cover owing to the concern due to construction loads prior to paving. Corrugated plastic pipes are considerably more flexible in ovaling deformation than are typical corrugated steel pipes of the same diameter. Consequently, the minimum 12 in. cover is more than adequate for plastic pipe.

3.2.5. Calculation of the load

The most typical dimensions for a tire truck (AASHTO H20) are shown in Figs. 3.4 and 3.5:

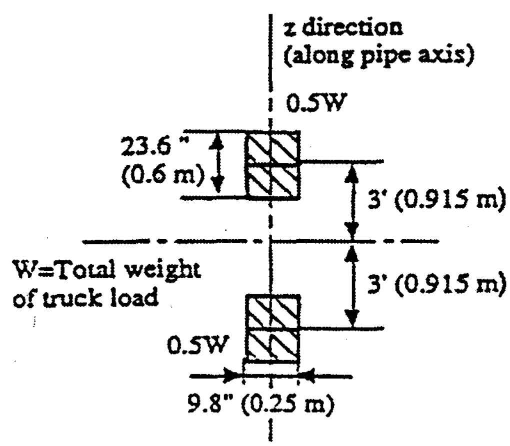


Fig. 3.4 ASHTO H20 highway loading configuration [AASHTO, 1992]

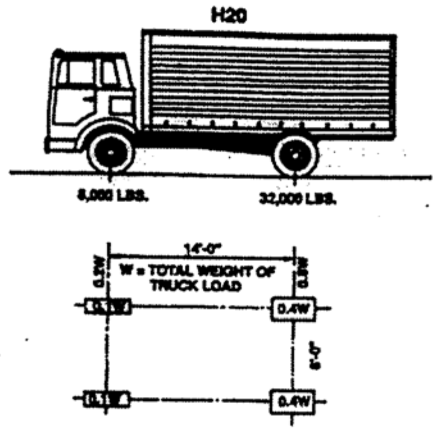


Fig. 3.5 Plan of simplified AASHTO H20 highway loading on the centerline of the pipe-soil system

The H-truck loading comprises two axle loads: 80 percent of the total gross weight (32,000 lb) is assigned to the rear axle and the remaining 20 percent (8,000 lb) is assigned to the front axle. This loading definition does not necessarily represent a real truck. Rather, it is a reference design vehicle developed by U.S. bridge engineers to serve as a worst case or umbrella loading for all vehicles whose actual load distributions (e.g. axial loads or spacing or both) are less severe than the H-truck loading.

It was decided to use

- a footprint of 24 in. x 10 in.
- 5,600 lb for the maximum allowable load
- 3,700 lb for 2/3 of the maximum load
- 1, 9001b for 1/3 of the maximum load

3.2.6. Combinations of specimens

I, II= Type I, II pipe

N= Notched at Valley, U= Unnotched

20, 40, 50: Temperature °C

M=5,600 lb

Total Number of Specimens: 26

Type I Notched specimens

20°C	40°C	50°C
----	NM (2)	NM (1)

Type I Unnotched specimens

20°C	40°C	50°C
----	UM * (2)	UM * (1)
----	-----	-----
----	U1/3 (2)	U1/3 (1)

Type II Notched specimens

20°C	40°C	50°C
NM (2)	NM (2)	NM (1)

Type II Unnotched specimens

20°C	40°C	50°C
UM * (2)	UM (2)	UM * (1)
U2/3 (2)	-----	-----
U1/3 (2)	U1/3 (2)	U1/3 * (1)

* specimens with strain gages (Fig. 3.8)

3.2.7. Installation of measuring devices

3.2.7.1. Dial gages

Four dial gages were mounted on the guide tube to measure vertical and horizontal changes of inside diameter at mid-section. Figs. 3.6 and 3.7 show the pilot testing of the dial gage installation.

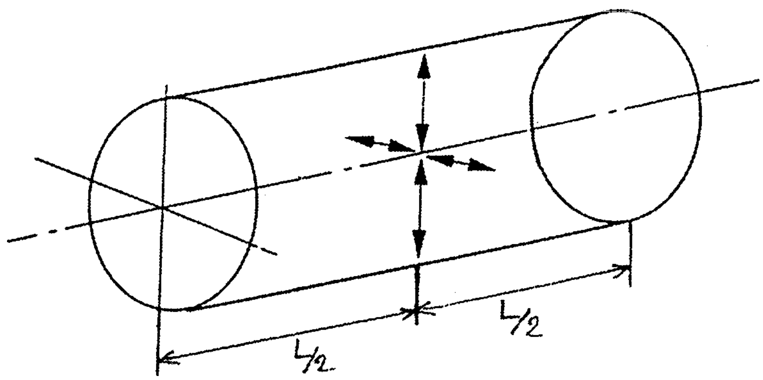


Fig. 3.6 Locations for measurement of diametral changes

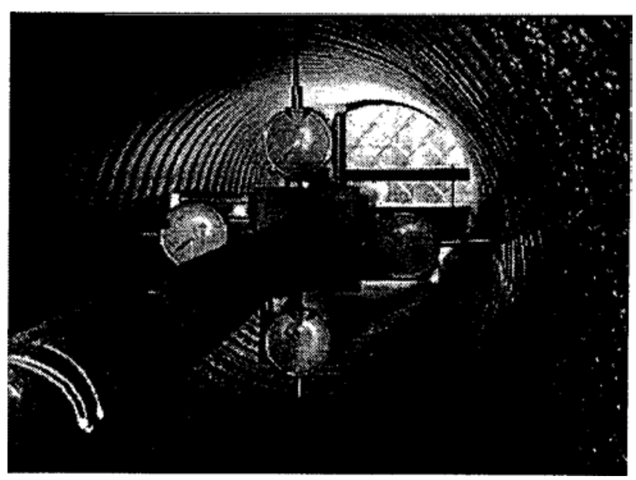


Fig. 3.7 Set up of dial gages

3.2.7.2. Strain gages

Specimens #1, #5, #6, #15, #16, #21 and #22 were mounted with two strain gages at the shoulders (one circumferential and one longitudinal), located at 45° and 135° (C45 and L135) from the right middle of the pipe (Fig. 3.8). The 45° and 135° correspond to the maximum stress locations, Reddy [1999]. A third gage (L270) to measure longitudinal strain was located at the bottom.

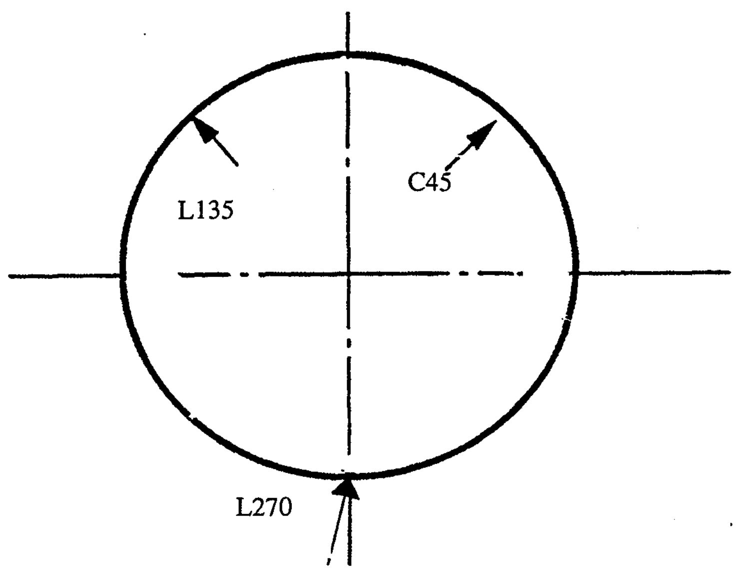


Fig. 3.8 Locations of strain gages

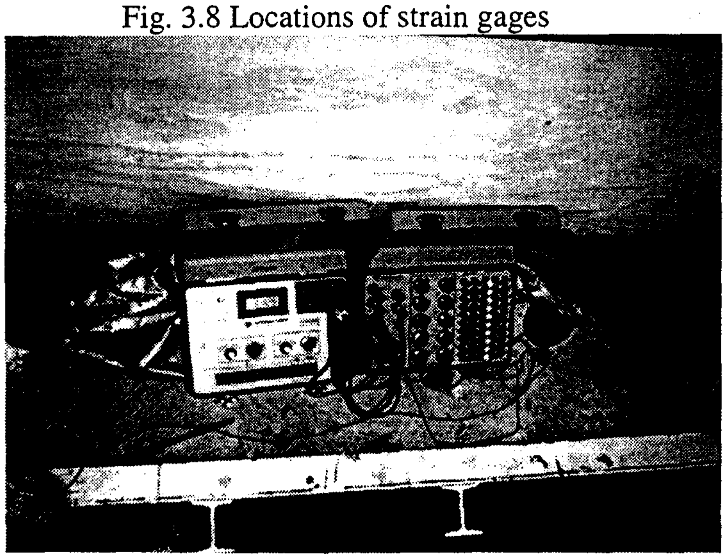


Fig. 3.9 Reading of strain gages

3.2.8. Soil chambers

3.2.8.1. Schematic of the test setup

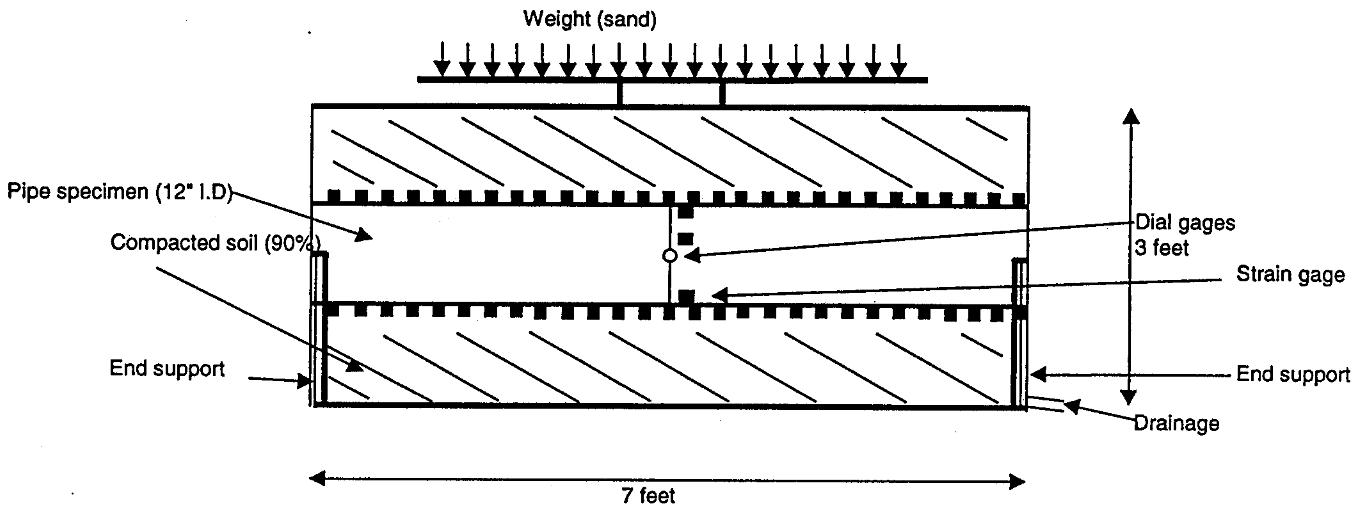


Fig. 3.10 Schematic of the test setup

3.2.8.2. Design of the soil chambers

Drawings for the final design of the soil chambers are presented in Figs. 3.11 to 3.14.

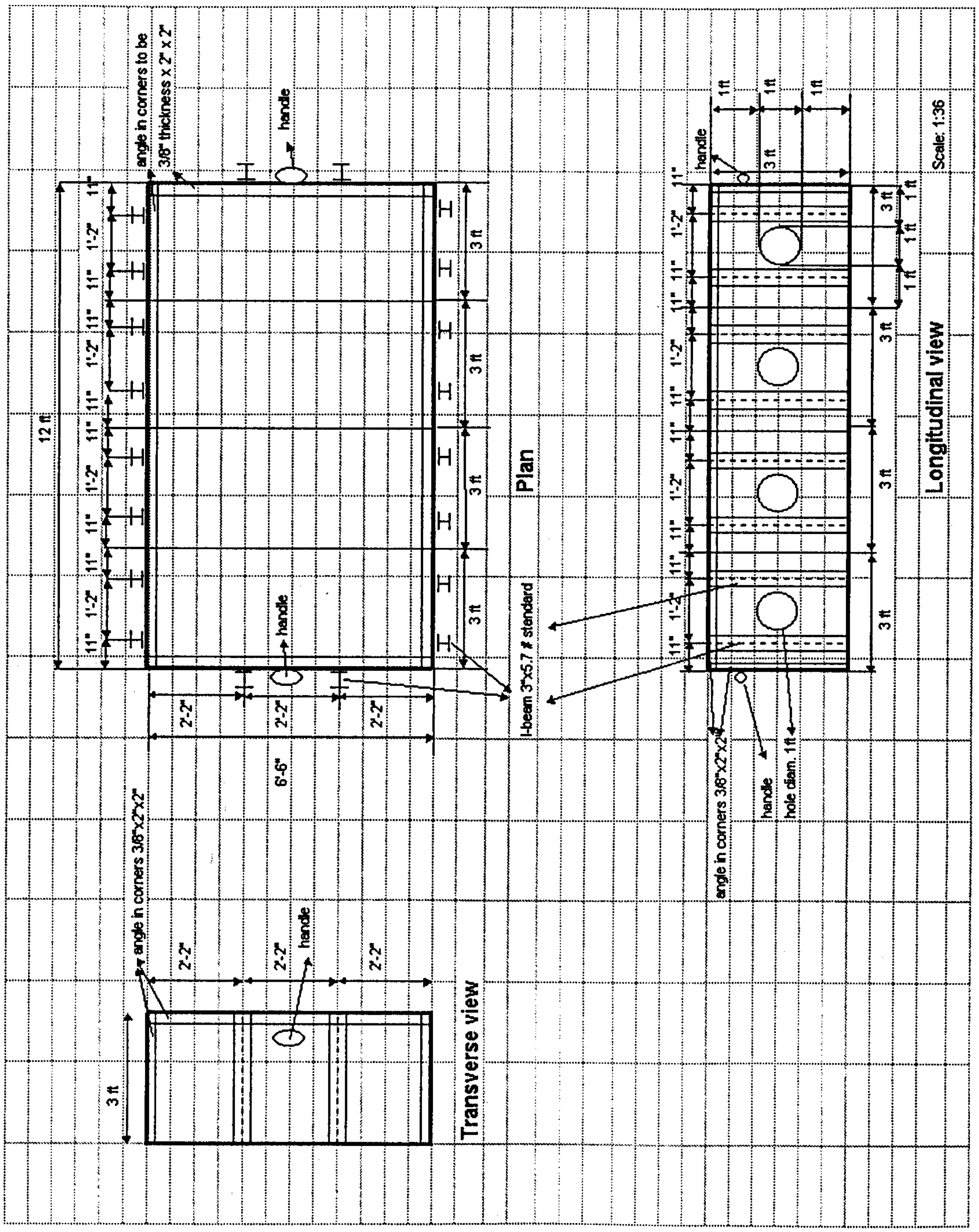


Fig. 3.11 Engineering drawings for typical test soil chamber

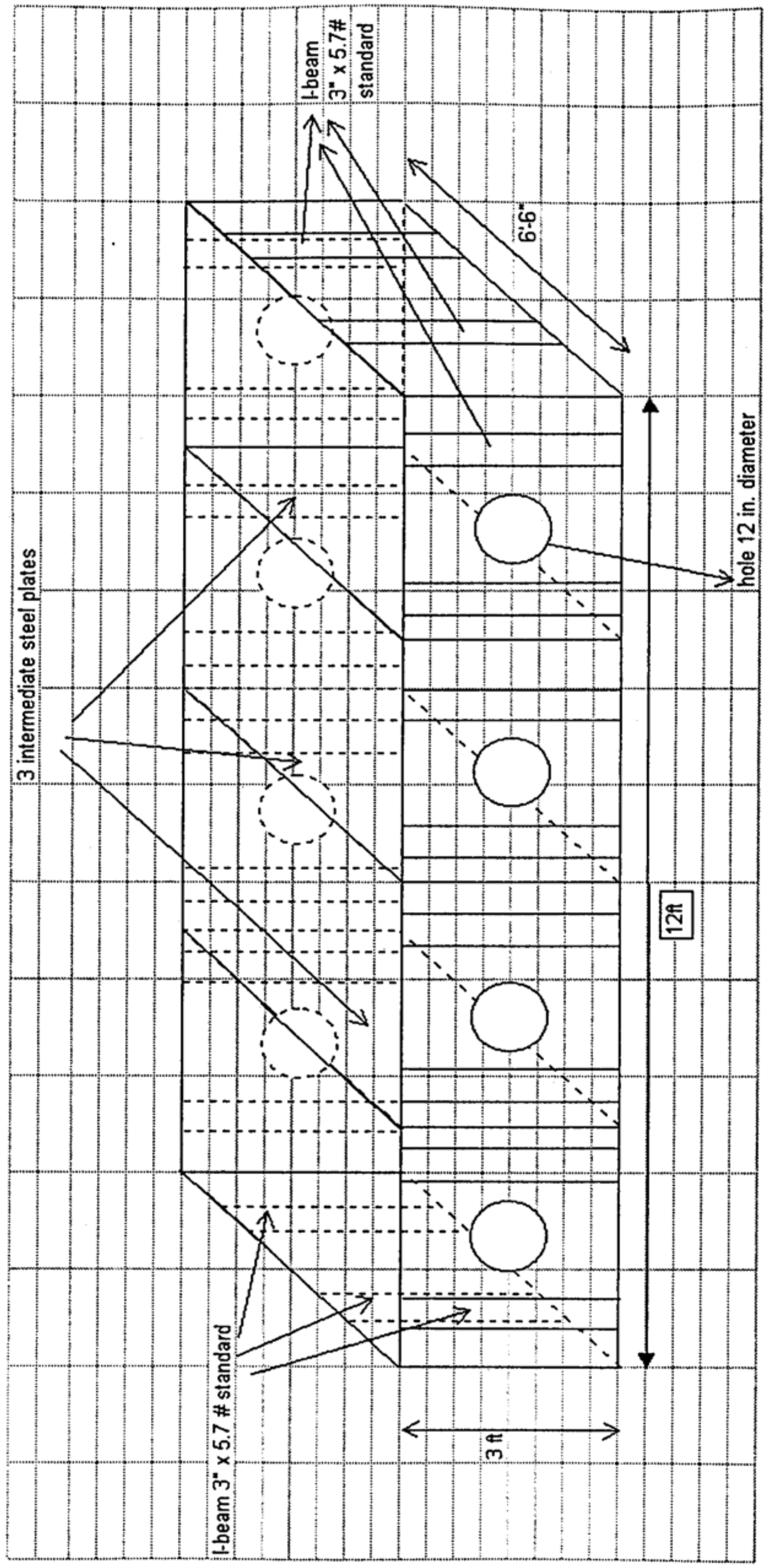


Fig. 3.12 General pictorial view for typical test soil chamber

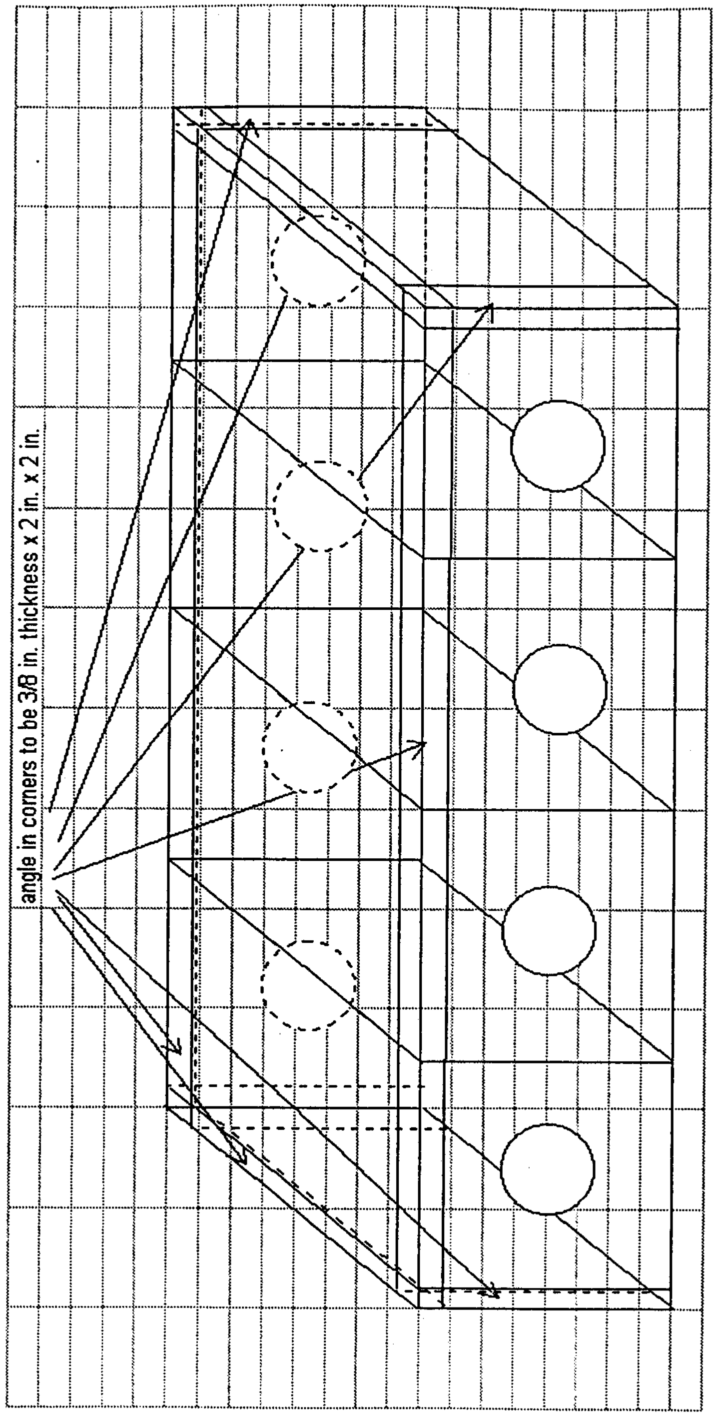


Fig. 3.13 Pictorial view focusing on corner angles

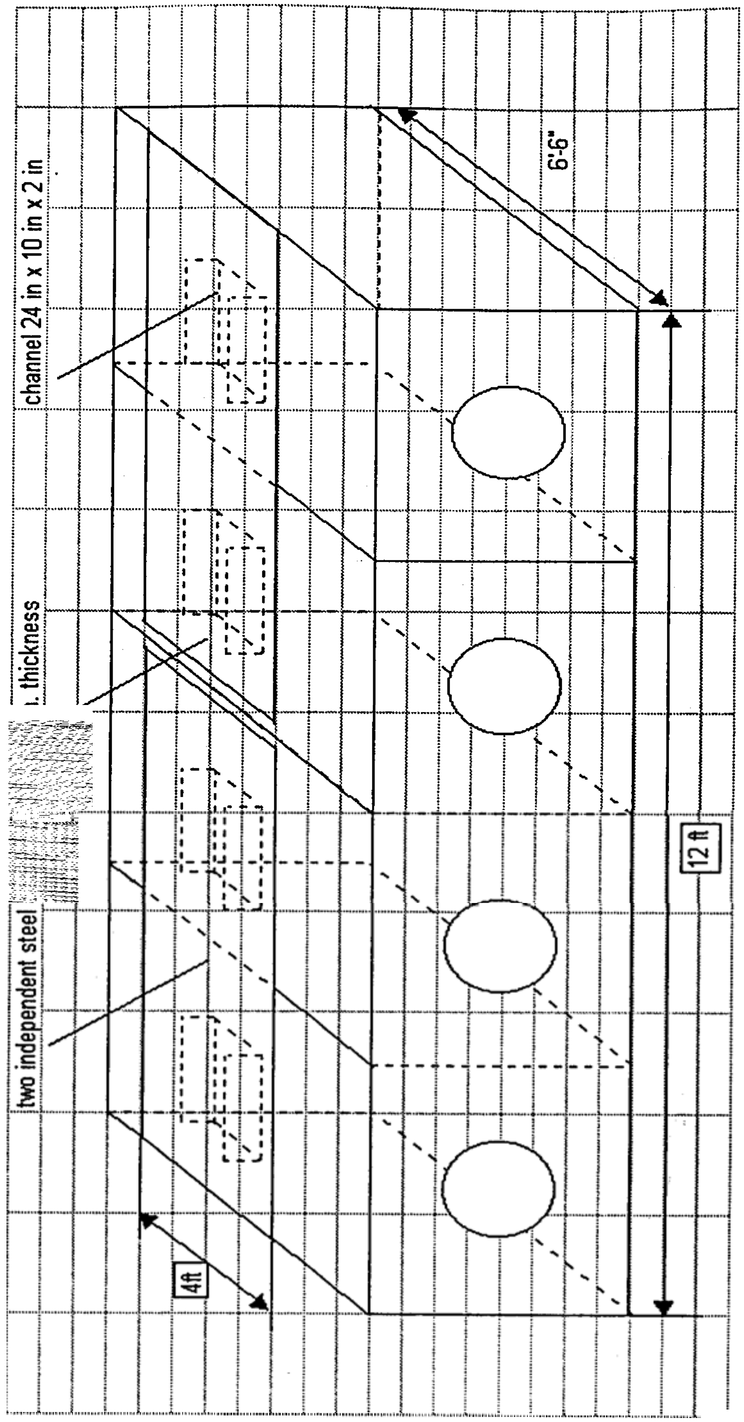


Fig. 3.14 View focusing on the steel plate covers 6'x4'x0.5"

Seven soil chambers have been ordered and arranged on the test site like shown in Fig. 3.15.

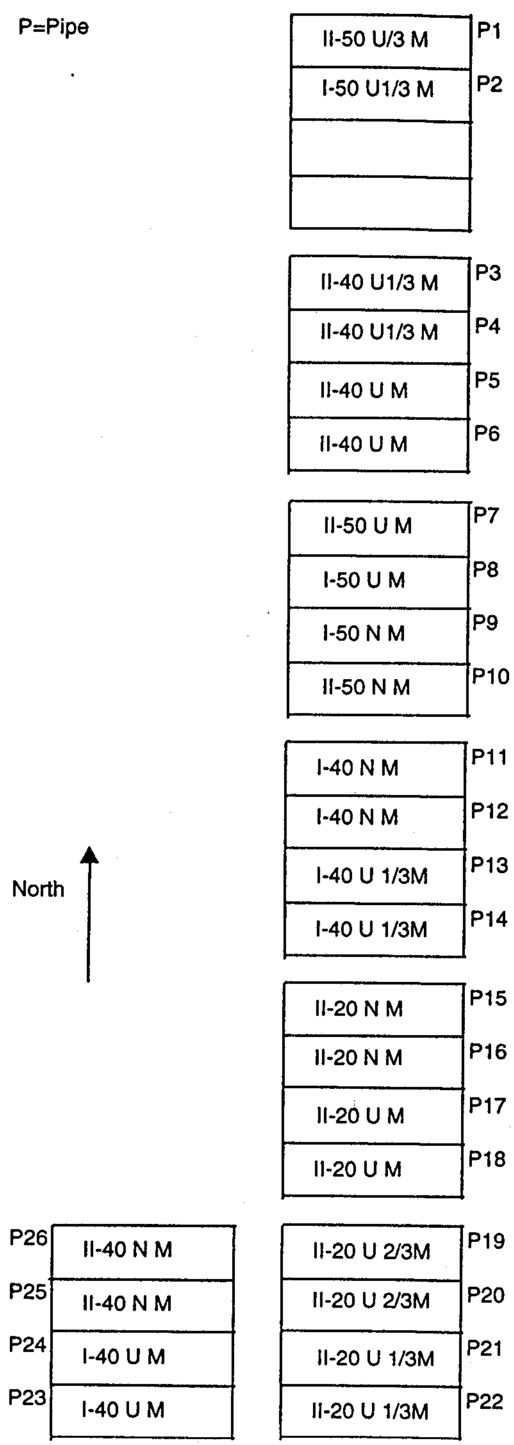


Fig. 3.15 Arrangement of the soil chambers (at the test site) and specimen details

3.2.9. Power supply

The three-dimensional long-term behavior was accelerated with super-ambient temperatures to provide the data for life prediction (20, 40 and 50 $^{\circ}$C). Sixty eating coils (I kW each) were used. This required the installation of 60 kW powering.

An evaluation of the required outlets, breakers and wiring was completed by "Fire Line Electric" (Fig. 3.16).

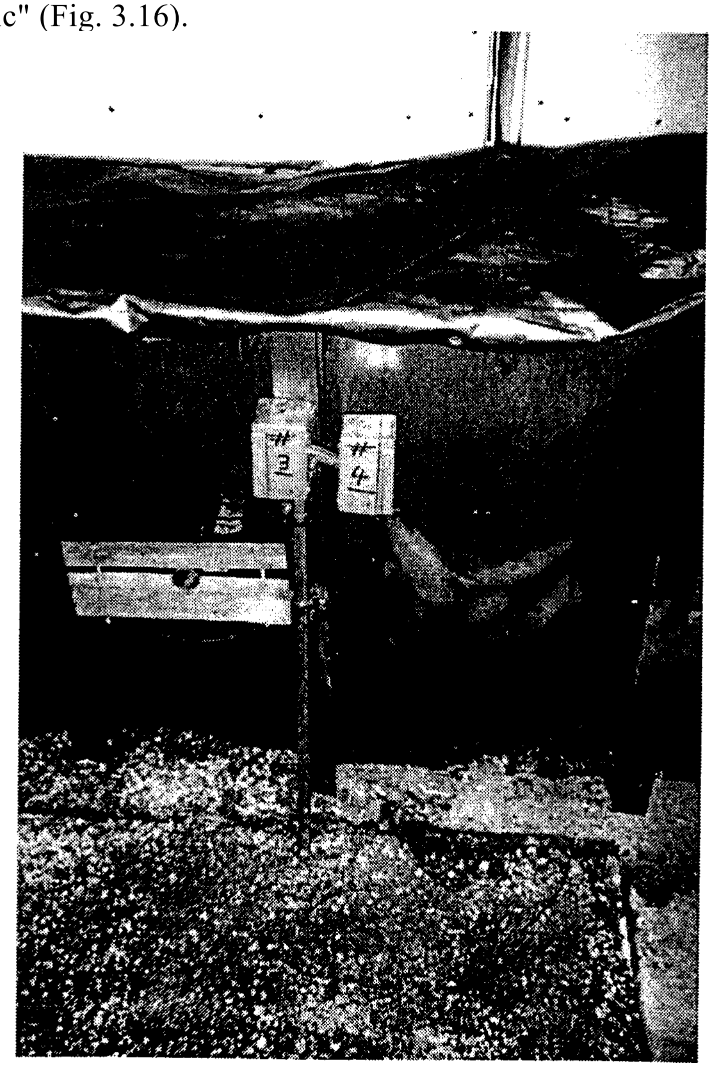


Fig. 3.16 Installation of the power line (2x 4 outlets) for the heaters

Six heaters were installed for each of the specimens #1, #2, #7, #8, #9 and #10. The arrows show the locations of the heaters in Fig. 3.17. Each heater is one-inch diameter and 15 in. long.

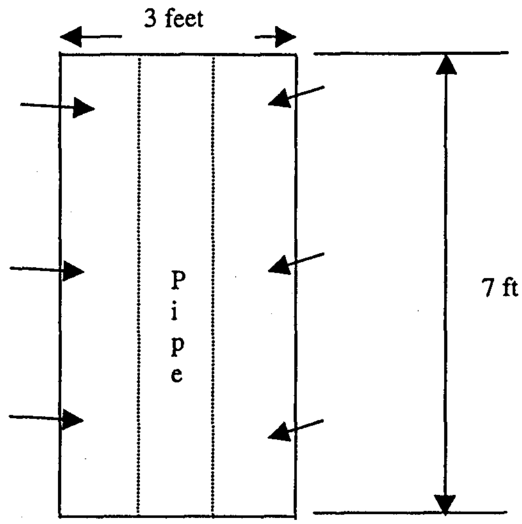


Fig. 3.17 Set up of 6 heaters (150 kW each) for one specimen (top view)

3.3. Performance of buried pipe, subjected to live load

3.3.1. Fabrication and installation of soil chambers

The steel soil chambers were made by the company "Sun Metal" at Pompano Beach. A crane was used to set up the soil chambers, as shown on Figs. 3.18 and 3.19. The weight of chamber block with four soil chambers was 5,000 lb

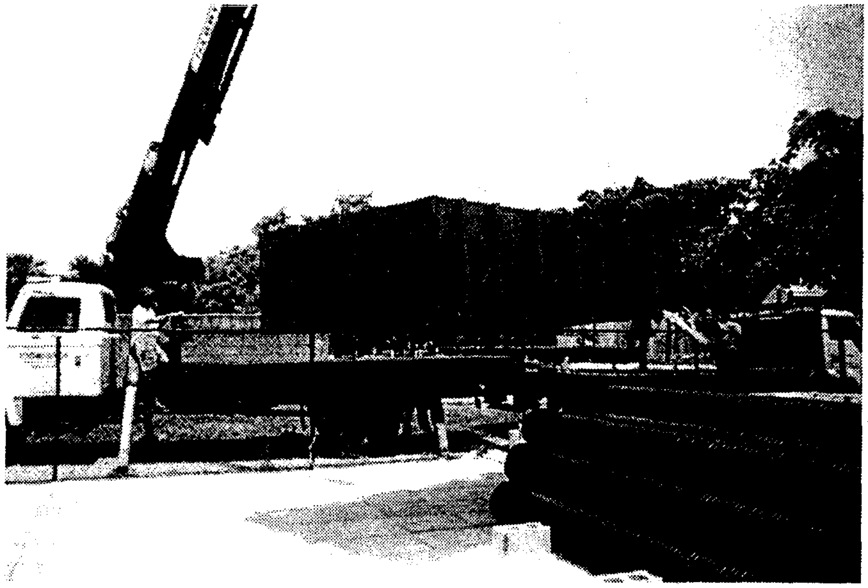


Fig. 3.18 Delivery of soil chambers

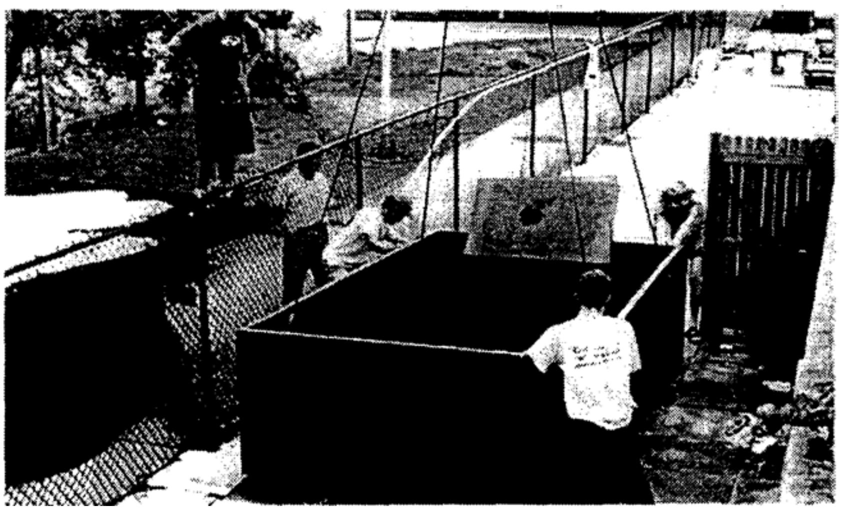


Fig. 3.19 Set up of soil chambers

3.3.2. Filling the soil chambers with sand

Three tons of "South Florida" sand was used per chamber. Twenty-six soil chambers were filled up.

Fig. 3.20 Filling up of the soil chamber

Fig. 3.21 Soil chambers (half full) after compaction

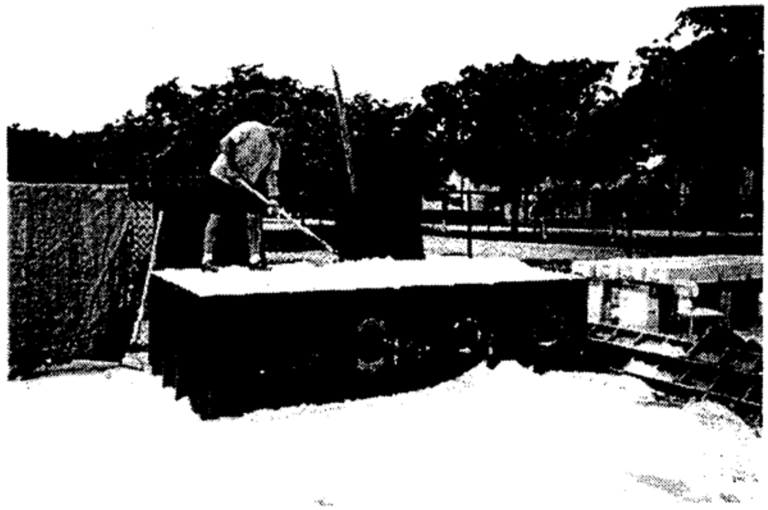


Fig. 3.22 Soil chambers (full) after compaction

3.3.3. Application of the load

Two specimens were loaded simultaneously by using 2 channels 24"x 10"x2" which represent the most typical dimension for a tire truck (Fig. 3.23). A steel plate 4'X6'x 0.5" (see Fig. 3.14) is used to distribute the load evenly.

Because one box was used for 2 specimens, the maximum load applied for each is 5,600 lb x 2 = 11, 200 lb (448 sand bags of 50 lb each).

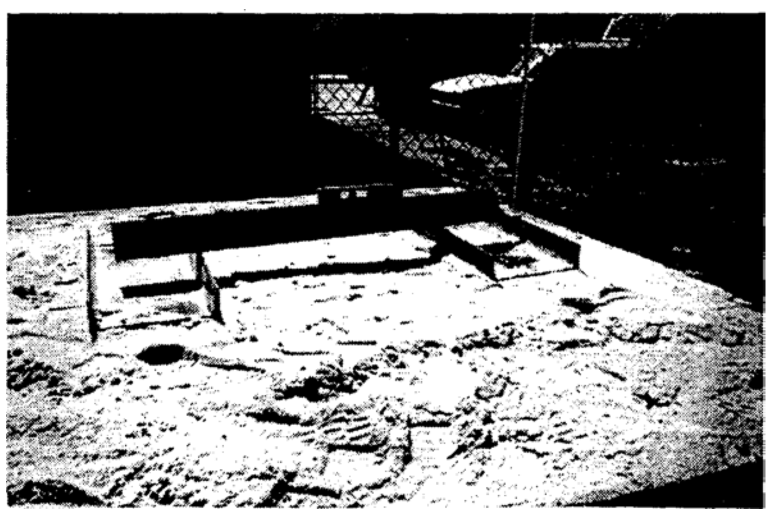


Fig. 3.23 Set up of structural sections for footprint loading

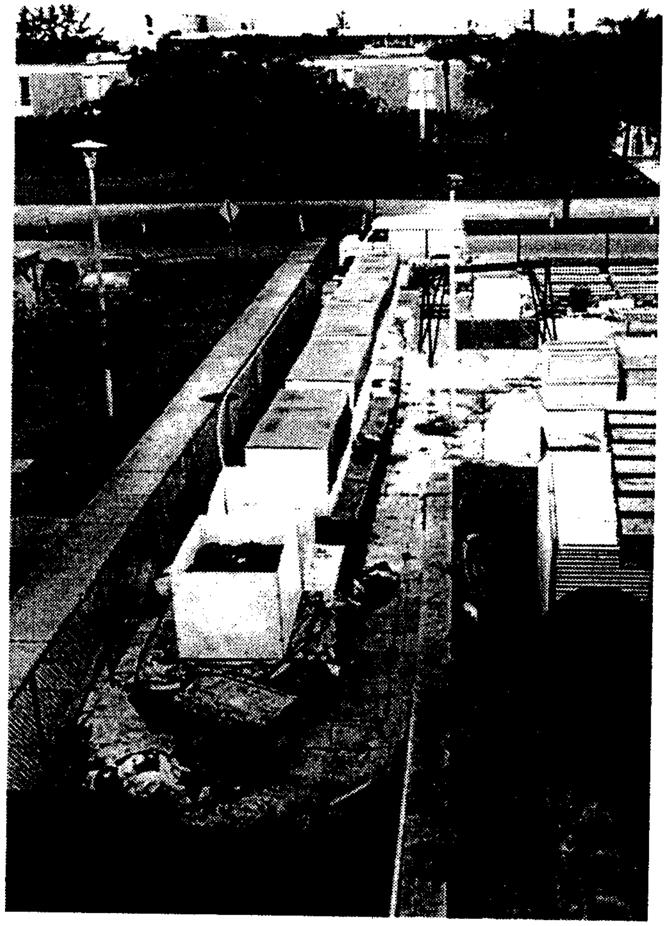


Fig. 3.24 End view of the test

CHAPTER 4

RESULTS OF THE EXPERIMENTAL INVESTIGATION

This chapter is divided into three parts: i) Sieve analysis, ii) Soil compaction and iii) Test results of the performance of buried pipe, subjected to live load.

4.1. Sieve analysis

The South Florida soil (Mason sand), which was used for the performance of buried pipe test, was classified as SP (poorly-grained sands and gravely sands, little or no fines) in **Class 11** (coarse-grained one, clean) [ASTM D2321 and D2487]. The analysis indicated the percentage passing sieve No 200 (0.075 mm=0.003 in.) was less than 5% the coefficient of uniformity, Cu=3.75 < 6, and the coefficient of curvature C_c=0.82 < 1, as calculated by equations 5.2 and 5.3. Therefore, the backfill modulus, E', can be increased to 2,000 psi (13.8 MPa) with relative compaction, 85 to 95%, based on ASTM D3839.

$$Cu = D60/D10 \text{ ------------------------------------ } (4.1)$$

$$C_c = \frac{(D_{30})^2}{(D_{10} \times D_{60})} \quad \text{-----------------------------} (4.2)$$

where

D_{10}, D_{30}, and D_{60} are the particle size diameters corresponding to 10, 30, and 60%, respectively, passing on the cumulative particle size distribution curve.

The percentages of the total weight of soil that passed through different sieves are plotted in Figs. 4.1.

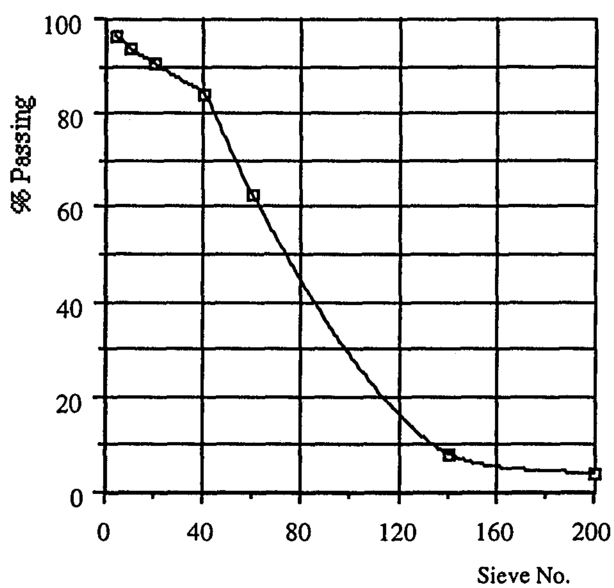


Fig. 4.1 Sieve analysis of the South Florida soil sample

4.2. **Soil compaction**

Laboratory (Standard Proctor Test, ASTM D698) and in-situ compaction tests were carried out to verify the required degree of compaction of the soil.

Fig. 4.2 and 4.3 Compaction below the

1) The soil was mixed with varying amounts of water and then compacted in three equal layers by a hammer (5.51b / 2.5 kg) that delivers 25 blows to each layer in the mold (1/30 ft' / 9.43x105 M M). The moisture content of the soil for each test was determined by drying it in the oven. With known moisture content, the dry unit weight y d can be calculated as follows:

$$\gamma_d = \frac{(W / V_m)}{(1 + 0.01w)} ------------(4.3)$$

where γ_d =dry unit weight

W = weight of compacted soil in the mold

V_m= volume of the mold

w = moisture content (%)

2) In-situ compactions of the soil in bedding, haunch, and backfill zones in the chamber were carried out by using a compactor tool (Figs. 4.2 and 4.3) after the mold was buried. The molds were carefully taken out after proper compaction process and the moisture contents and dry unit weights of the samples found in a similar manner to that for the standard compaction test.

Laboratory Standard Proctor Tests were carried out prior to the in-situ compaction tests and the relationship between dry unit weight and moisture content the soil was evaluated Fig. 4.4. It was found that the maximum dry unit weight was 1051b / ft^3 with the optimum moisture content 10.5%. Based on the laboratory and in-situ test results, the degree of compaction can be determined as follows:

$$R(\%) = \frac{\gamma_{d(in-situ))}}{\gamma_{d(\max - lab))}} 100 \quad ----- (4.4)$$

where R = relative compaction

$\gamma_{d(in\text{-}situ)}$ = dry unit weight of in-situ-sample

$\gamma_{d(max\text{-}lab)}$=maximum dry unit weight, obtained in the laboratory

The required degree of compaction of the soil was achieved for each specimen installation. Table 4.1 shows the relative compaction, for bedding and backfill regions. Proper in-situ compactions were carried out with small variations (91-96%) and the relative compactions were higher than the minimum, required (85% Standard Proctor, ASTM D2321) for the soil.

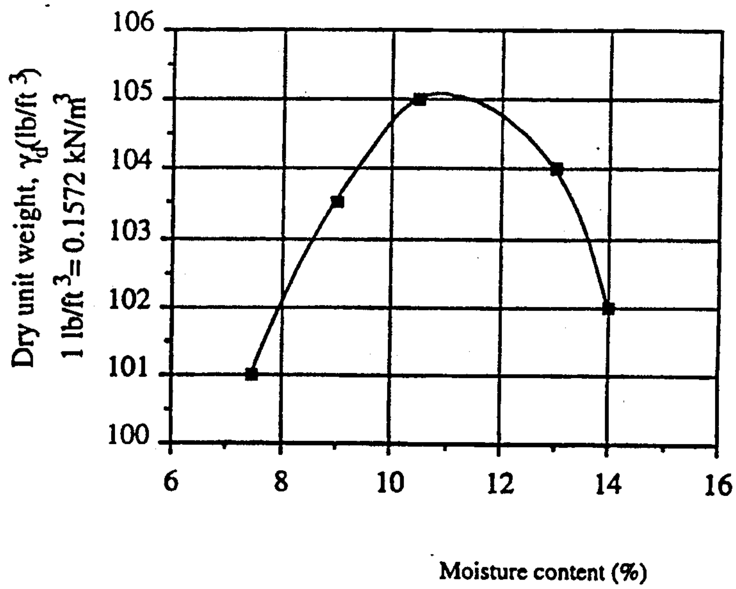


Fig. 4.4 Plot of dry unit weight vs. moisture content for the laboratory test results

Table 4.1 Relative Compaction at Bedding and Backfill Zones in the Soil Chamber

Soil samples (Beddings)	Relative compaction, R (%)	Soil samples (Backfills)	Relative compaction, R (%)
1	96	1	95
2	96	2	93
3	94	3	91
4	92	4	92
5	95	5	95
6	94	6	94

4.3. Test results of the performance of buried pipe, subjected to live loading

4.3.1. Vertical changes of

Vertical changes of diameter are presented for Type I and II buried pipes under different loadings (5,600 lb, 3,700 lb, 1,900 lb), temperatures (20°C, 40°C and 50°C), and unnotched or notched (at valley) specimens, Figs. 4.5 to 4.18. The straight line-relationships were determined by linear regression.

0.9 in. vertical deflection corresponds to 7.5 % vertical change in diameter (failure criterion). The complete data is presented in the Appendix A.

APPENDIX A

Deflection Data for Notched and Un-notched Pipes

Deflections (1/1000 in.)

Un-notched Pipes

Type I, 40°C

Load applied = 1, 900 lb. (pipe 13)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	25	1	465	1	2	415	1	775	1	2
6	144	186	161	458	-6	155	402	-12	694	-80	-92
9	216	190	165	456	-8	157	395	-19	692	-82	-101
16	384	210	185	456	-8	177	390	-24	683	-91	-115
19	456	211	186	454	-10	176	376	-38	677	-97	-135
24	576	212	187	446	-18	169	374	-40	672	-102	-142
27	648	217	192	443	-21	171	356	-58	668	-106	-164
39	936	232	207	447	-17	190	348	-66	657	-117	-183
41	984	233	208	444	-20	188	348	-66	648	-126	-192
48	1152	238	213	441	-23	190	347	-67	645	-129	-196
56	1344	258	233	439	-25	208	345	-69	640	-134	-203
63	1512	262	237	438	-26	211	345	-69	638	-136	-205
72	1728	262	237	437	-27	210	339	-75	634	-140	-215
80	1920	265	240	433	-31	209	333	-81	627	-147	-228
88	2112	271	246	432	-32	214	324	-90	623	-151	-241
97	2328	276	251	430	-34	217	316	-98	615	-159	-257
103	2472	280	255	428	-36	219	312	-102	605	-169	-271
119	2856	281	256	426	-38	218	306	-108	600	-174	-282
126	3024	283	258	424	-40	218	299	-115	596	-178	-293
134	3216	284	259	424	-40	219	294	-120	594	-180	-300
149	3576	285	260	422	-42	218	289	-125	585	-189	-314
159	3816	285	260	422	-42	218	286	-128	582	-192	-320
185	4440	286	261	422	-42	219	283	-131	569	-205	-336
214	5136	289	264	422	-42	222	278	-136	548	-226	-362
225	5400	289	264	422	-42	222	272	-142	540	-234	-376
248	5952	289	264	422	-42	222	248	-166	540	-234	-400
260	6240	290	265	422	-42	223	232	-182	540	-234	-416
270	6480	290	265	422	-42	223	215	-199	540	-234	-433
317	7608	290	265	422	-42	223	205	-209	540	-234	-443
368	8832	295	270	418	-46	224	198	-216	537	-237	-453

<u>Un-notched Pipes</u> - continued

Type I, 40°C

Load applied = 1, 900 lb. (pipe 14)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	5	1	605	1	2	250	1	900	1	2
6	144	175	170	590	-14	156	248	-1	865	-34	-35
9	216	183	178	589	-15	163	215	-34	855	-44	-78
16	384	196	191	589	-15	176	215	-34	835	-64	-98
19	456	198	193	587	-17	176	215	-34	828	-71	-105
24	576	200	195	587	-17	178	215	-34	819	-80	-114
27	648	205	200	586	-18	182	214	-35	915	16	-19
39	936	222	217	586	-18	199	212	-37	808	-91	-128
41	984	222	217	585	-19	198	212	-37	799	-100	-137
48	1152	230	225	585	-19	206	210	-39	790	-109	-148
56	1344	242	237	585	-19	218	210	-39	786	-113	-152
63	1512	250	245	584	-20	225	210	-39	785	-114	-153
72	1728	250	245	584	-20	225	208	-41	780	-119	-160
80	1920	250	245	583	-21	224	207	-42	779	-120	-162
88	2112	252	247	582	-22	225	207	-42	774	-125	-167
97	2328	256	251	582	-22	229	205	-44	768	-131	-175
103	2472	262	257	581	-23	234	205	-44	768	-131	-175
119	2856	263	258	581	-23	235	202	-47	760	-139	-186
126	3024	266	261	580	-24	237	197	-52	758	-141	-193
134	3216	270	265	580	-24	241	197	-52	750	-149	-201
149	3576	272	267	580	-24	243	195	-54	748	-151	-205
159	3816	276	271	578	-26	245	194	-55	748	-151	-206
185	4440	277	272	578	-26	246	188	-61	745	-154	-215
214	5136	289	284	578	-26	258	186	-63	740	-159	-222
225	5400	296	291	576	-28	263	183	-66	736	-163	-229
248	5952	296	291	574	-30	261	179	-70	680	-219	-289
260	6240	296	291	572	-32	259	176	-73	660	-239	-312
270	6480	296	291	565	-39	252	173	-76	664	-235	-311
317	7608	296	291	555	-49	242	170	-79	644	-255	-334
368	8832	302	297	551	-53	244	165	-84	638	-261	-345

Un-notched Pipes - continued

Type I, 50°C

Load applied = 1, 900 lb (pipe 2),

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	345	1	660	1	2	230	1	355	1	2
3	72	461	43	658	-2	41	224	-6	338	-17	-23
5	120	489	52	653	-7	45	222	-8	325	-30	-38
13	312	538	79	650	-10	69	220	-10	325	-30	-40
28	672	814	142	650	-10	132	218	-12	282	-73	-85
38	912	847	168	650	-10	158	180	-50	272	-83	-133
45	1080	886	178	642	-18	160	178	-52	250	-105	-157
56	1344	905	192	640	-20	172	176	-54	230	-125	-179
79	1896	925	202	638	-22	180	174	-56	220	-135	-191
87	2088	986	212	632	-28	184	167	-63	220	-135	-198
91	2184	1020	222	632	-28	194	157	-73	198	-157	-230
101	2424	1070	248	632	-28	220	152	-78	190	-165	-243
148	3552	1140	286	632	-28	258	150	-80	188	-167	-247
175	4200	1275	302	630	-30	272	148	-82	186	-169	-251
188	4512	1312	316	630	-30	286	147	-83	186	-169	-252

Type I, 50°C

Load applied = 5, 600 lb (pipe 8)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	238	1	190	1	2	185	1	209	1	2
3	72	388	150	205	16	166	169	-16	205	-4	-20
5	120	425	187	214	25	212	165	-20	200	-9	-29
13	312	489	251	236	47	298	164	-21	190	-19	-40
28	672	512	274	243	54	328	157	-28	186	-23	-51
38	912	575	337	245	56	393	148	-37	167	-42	-79
45	1080	616	378	250	61	439	135	-50	158	-51	-101
56	1344	694	456	252	63	519	135	-50	150	-59	-109
79	1896	754	516	252	63	579	132	-53	145	-64	-117
87	2088	825	587	250	61	648	131	-54	140	-69	-123
91	2184	912	674	250	61	735	128	-57	132	-77	-134
124	2976	1057	819	268	79	898	119	-66	105	-104	-170
148	3552	1087	849	268	79	928	114	-71	99	-110	-181
188	4512	1148	910	278	89	999	112	-73	85	-124	-197

Un-notched Pipes - continued

Type II, 20°C

Load applied = 1, 900 lb. (pipe 21)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	189	1	323	1	2	883	1	571	1	2
6	144	474	285	186	-136	149	833	-49	551	-19	-68
9	216	594	405	175	-147	258	818	-64	529	-41	-105
16	384	624	435	169	-153	282	808	-74	519	-51	-125
19	456	626	437	159	-163	274	803	-79	516	-54	-133
24	576	632	443	149	-173	270	800	-82	503	-67	-149
27	648	637	448	146	-176	272	803	-79	501	-69	-148
39	936	666	477	142	-180	297	793	-89	492	-78	-167
41	984	670	481	138	-184	297	785	-97	490	-80	-177
48	1152	679	490	132	-190	300	785	-97	489	-81	-178
56	1344	704	515	125	-197	318	777	-105	484	-86	-191
63	1512	711	522	119	-203	319	765	-117	471	-99	-216
72	1728	715	526	115	-207	319	763	-119	454	-116	-235
80	1920	722	533	109	-213	320	763	-119	447	-123	-242
88	2112	729	540	103	-219	321	758	-124	433	-137	-261
97	2328	742	553	95	-227	326	758	-124	429	-141	-265
103	2472	754	565	93	-229	336	753	-129	431	-139	-268
119	2856	762	573	91	-231	342	748	-134	419	-151	-285
126	3024	769	580	91	-231	349	747	-135	417	-153	-288
134	3216	769	580	88	-234	346	747	-135	415	-155	-290
149	3576	769	580	87	-235	345	743	-139	409	-161	-300
159	3816	779	590	83	-239	351	740	-142	406	-164	-306
185	4440	781	592	81	-241	351	735	-147	403	-167	-314
214	5136	785	596	79	-243	353	728	-154	399	-171	-325
225	5400	789	600	79	-243	357	725	-157	396	-174	-331
248	5952	792	603	77	-245	358	721	-161	393	-177	-338
260	6240	794	605	77	-245	360	718	-164	386	-184	-348
270	6480	824	635	75	-247	388	714	-168	384	-186	-354
317	7608	844	655	75	-247	408	690	-192	380	-190	-382
368	8832	862	673	71	-251	422	680	-202	374	-196	-398

Un-notched Pipes - continued

Type II, 20°C

Load applied = 1, 900 lb. (pipe 22)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	55	1	372	1	2	616	1	586	4	5
6	144	340	285	235	-136	149	614	-1	583	1	0
9	216	460	405	224	-147	258	603	-12	579	-3	-15
16	384	490	435	218	-153	282	596	-19	572	-10	-29
19	456	492	437	208	-163	274	592	-23	570	-12	-35
24	576	498	443	198	-173	270	591	-24	565	-17	-41
27	648	503	448	195	-176	272	582	-33	565	-17	-50
39	936	532	477	191	-180	297	580	-35	556	-26	-61
41	984	536	481	187	-184	297	572	-43	556	-26	-69
48	1152	545	490	181	-190	300	570	-45	550	-32	-77
56	1344	570	515	174	-197	318	566	-49	546	-36	-85
63	1512	577	522	168	-203	319	562	-53	543	-39	-92
72	1728	581	526	164	-207	319	555	-60	539	-43	-103
80	1920	588	533	158	-213	320	555	-60	533	-49	-109
88	2112	595	540	152	-219	321	546	-69	533	-49	-118
97	2328	608	553	144	-227	326	543	-72	526	-56	-128
103	2472	620	565	142	-229	336	540	-75	526	-56	-131
119	2856	628	573	140	-231	342	539	-76	523	-59	-135
126	3024	635	580	140	-231	349	538	-77	523	-59	-136
134	3216	635	580	137	-234	346	535	-80	521	-61	-141
149	3576	635	580	136	-235	345	526	-89	521	-61	-150
159	3816	645	590	132	-239	351	522	-93	516	-66	-159
185	4440	647	592	130	-241	351	516	-99	513	-69	-168
214	5136	651	596	128	-243	353	513	-102	508	-74	-176
225	5400	655	600	128	-243	357	509	-106	502	-80	-186
248	5952	658	603	126	-245	358	503	-112	496	-86	-198
260	6240	660	605	126	-245	360	502	-113	487	-95	-208
270	6480	690	635	124	-247	388	499	-116	479	-103	-219
317	7608	710	655	124	-247	408	499	-116	467	-115	-231
368	8832	728	673	120	-251	422	495	-120	456	-126	-246

Un-notched Pipes - continued

Type II, 20°C

Load applied = 3, 700 lb. (pipe 19)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	173	1	226	1	2	237	1	526	1	2
6	144	182	119	219	-7	112	224	-12	445	-80	-92
9	216	192	129	217	-9	120	217	-19	443	-82	-101
16	384	225	149	217	-9	140	212	-24	434	-91	-115
19	456	228	152	215	-11	141	198	-38	428	-97	-135
24	576	228	155	207	-19	136	196	-40	423	-102	-142
27	648	316	157	204	-22	135	178	-58	419	-106	-164
39	936	330	157	208	-18	139	170	-66	408	-117	-183
41	984	350	177	205	-21	156	170	-66	399	-126	-192
48	1152	360	187	202	-24	163	169	-67	396	-129	-196
56	1344	381	208	200	-26	182	167	-69	391	-134	-203
63	1512	386	213	199	-27	186	167	-69	389	-136	-205
72	1728	390	217	198	-28	189	161	-75	385	-140	-215
80	1920	397	224	194	-32	192	155	-81	378	-147	-228
88	2112	403	230	193	-33	197	146	-90	374	-151	-241
97	2328	415	242	191	-35	207	138	-98	366	-159	-257
103	2472	430	257	189	-37	220	134	-102	356	-169	-271
119	2856	442	269	187	-39	230	128	-108	351	-174	-282
126	3024	448	275	185	-41	234	121	-115	347	-178	-293
134	3216	452	279	185	-41	238	116	-120	345	-180	-300
149	3576	456	283	183	-43	240	111	-125	336	-189	-314
159	3816	474	301	183	-43	258	108	-128	333	-192	-320
185	4440	775	602	183	-43	559	105	-131	320	-205	-336
214	5136	796	623	183	-43	580	100	-136	299	-226	-362
225	5400	868	695	183	-43	652	94	-142	291	-234	-376
248	5952	905	732	183	-43	689	70	-166	291	-234	-400
260	6240	914	741	183	-43	698	54	-182	291	-234	-416
270	6480	920	747	183	-43	704	37	-199	291	-234	-433
317	7608	975	802	183	-43	759	27	-209	291	-234	-443
368	8832	989	816	179	-47	769	20	-216	288	-237	-453

Un-notched Pipes - continued

Type II, 20°C

Load applied = 3, 700 lb. (pipe 20)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	330	1	517	1	2	397	1	767	1	2
6	144	495	165	502	-14	151	395	-1	732	-34	-35
9	216	528	198	501	-15	183	362	-34	722	-44	-78
16	384	550	220	501	-15	205	362	-34	702	-64	-98
19	456	598	268	499	-17	251	362	-34	695	-71	-105
24	576	600	270	499	-17	253	362	-34	686	-80	-114
27	648	615	285	498	-18	267	361	-35	782	16	-19
39	936	618	288	498	-18	270	359	-37	675	-91	-128
41	984	638	308	497	-19	289	359	-37	666	-100	-137
48	1152	642	312	497	-19	293	357	-39	657	-109	-148
56	1344	644	314	497	-19	295	357	-39	653	-113	-152
63	1512	645	315	496	-20	295	357	-39	652	-114	-153
72	1728	650	320	496	-20	300	355	-41	647	-119	-160
80	1920	660	330	495	-21	309	354	-42	646	-120	-162
88	2112	670	340	494	-22	318	354	-42	641	-125	-167
97	2328	680	350	494	-22	328	352	-44	635	-131	-175
103	2472	690	360	493	-23	337	352	-44	635	-131	-175
119	2856	698	368	493	-23	345	349	-47	627	-139	-186
126	3024	700	370	492	-24	346	344	-52	625	-141	-193
134	3216	712	382	492	-24	358	344	-52	617	-149	-201
149	3576	712	382	492	-24	358	342	-54	615	-151	-205
159	3816	712	382	490	-26	356	341	-55	615	-151	-206
185	4440	712	382	490	-26	356	335	-61	612	-154	-215
214	5136	845	515	490	-26	489	333	-63	607	-159	-222
225	5400	910	580	488	-28	552	330	-66	603	-163	-229
248	5952	920	590	486	-30	560	326	-70	547	-219	-289
260	6240	950	620	484	-32	588	323	-73	527	-239	-312
270	6480	960	630	482	-34	596	320	-76	531	-235	-311
317	7608	1080	750	482	-34	716	317	-79	511	-255	-334
368	8832	1080	778	478	-38	740	312	-84	482	-284	-368

Un-notched Pipes - continued

Type II, 20°C

Load applied = 5, 600 lb. (pipe 17)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	420	1	375	1	2	1023	650	567	1	651
6	144	480	60	360	-15	45	988	615	532	-35	580
9	216	586	166	359	-16	150	978	605	522	-45	560
16	384	642	222	359	-16	206	958	585	502	-65	520
19	456	646	226	357	-18	208	951	578	495	-72	506
24	576	654	234	357	-18	216	942	569	486	-81	488
27	648	655	235	356	-19	216	1038	665	582	15	680
39	936	683	263	356	-19	244	931	558	475	-92	466
41	984	684	264	355	-20	244	922	549	466	-101	448
48	1152	693	273	355	-20	253	913	540	457	-110	430
56	1344	719	299	355	-20	279	909	536	453	-114	422
63	1512	727	307	354	-21	286	908	535	452	-115	420
72	1728	735	315	354	-21	294	903	530	447	-120	410
80	1920	734	314	353	-22	292	902	529	446	-121	408
88	2112	740	320	352	-23	297	897	524	441	-126	398
97	2328	748	328	352	-23	305	891	518	435	-132	386
103	2472	757	337	351	-24	313	891	518	435	-132	386
119	2856	763	343	351	-24	319	883	510	427	-140	370
126	3024	770	350	350	-25	325	881	508	425	-142	366
134	3216	778	358	350	-25	333	873	500	417	-150	350
149	3576	791	371	350	-25	346	871	498	415	-152	346
159	3816	796	376	348	-27	349	871	498	415	-152	346
185	4440	812	392	348	-27	365	868	495	412	-155	340
214	5136	818	398	348	-27	371	863	490	407	-160	330
225	5400	890	470	346	-29	441	859	486	403	-164	322
248	5952	942	522	344	-31	491	803	430	347	-220	210
260	6240	963	543	342	-33	510	783	410	327	-240	170
270	6480	980	560	335	-40	520	787	414	331	-236	178
317	7608	1014	594	325	-50	544	767	394	311	-256	138

Un-notched Pipes - continued

Type II, 20°C

Load applied = 5, 600 lb. (pipe 18)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	130	1	232	1	2	304	1	442	1	2
6	144	330	200	225	-6	194	291	-13	361	-80	-93
9	216	416	286	223	-8	278	284	-20	359	-82	-102
16	384	416	286	223	-8	278	279	-25	350	-91	-116
19	456	418	288	221	-10	278	265	-39	344	-97	-136
24	576	422	292	213	-18	274	263	-41	339	-102	-143
27	648	426	296	210	-21	275	245	-59	335	-106	-165
39	936	445	315	214	-17	298	237	-67	324	-117	-184
41	984	450	320	211	-20	300	237	-67	315	-126	-193
48	1152	453	323	208	-23	300	236	-68	312	-129	-197
56	1344	472	342	206	-25	317	234	-70	307	-134	-204
63	1512	474	344	205	-26	318	234	-70	305	-136	-206
72	1728	478	348	204	-27	321	228	-76	301	-140	-216
80	1920	478	348	200	-31	317	222	-82	294	-147	-229
88	2112	481	351	199	-32	319	213	-91	290	-151	-242
97	2328	484	354	197	-34	320	205	-99	282	-159	-258
103	2472	492	362	195	-36	326	201	-103	272	-169	-272
119	2856	492	362	193	-38	324	195	-109	267	-174	-283
126	3024	493	363	191	-40	323	188	-116	263	-178	-294
134	3216	503	373	191	-40	333	183	-121	261	-180	-301
149	3576	508	378	189	-42	336	178	-126	252	-189	-315
159	3816	510	380	189	-42	338	175	-129	249	-192	-321
185	4440	524	394	189	-42	352	172	-132	236	-205	-337
214	5136	524	394	189	-42	352	167	-137	215	-226	-363
225	5400	536	406	189	-42	364	161	-143	207	-234	-377
248	5952	590	460	189	-42	418	137	-167	207	-234	-401
260	6240	605	475	189	-42	433	121	-183	207	-234	-417
270	6480	650	520	189	-42	478	104	-200	207	-234	-434
317	7608	845	715	189	-42	673	94	-210	207	-234	-444
368	8832	945	815	185	-46	769	87	-217	204	-237	-454

Un-notched Pipes - continued

Type II, 40°C

Load applied = 1, 900 lb (pipe 3)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	480	1	465	1	2	384	1	478	1	2
2	48	569	89	465	0	89	372	-12	458	-20	-32
3	72	575	95	465	0	95	368	-16	458	-20	-36
4	96	586	106	470	5	111	368	-16	458	-20	-36
5	120	586	106	468	3	109	362	-22	444	-34	-56
9	216	590	110	470	5	115	362	-22	444	-34	-56
13	312	591	111	470	5	116	357	-27	440	-38	-65
17	408	595	115	470	5	120	356	-28	438	-40	-68
22	528	597	117	488	23	140	352	-32	438	-40	-72
26	624	600	120	495	30	150	347	-37	429	-49	-86
30	720	602	122	500	35	157	334	-50	434	-44	-94
36	864	605	125	520	55	180	331	-53	430	-48	-101
40	960	608	128	525	60	188	323	-61	370	-108	-169
44	1056	610	130	555	90	220	320	-64	368	-110	-174
48	1152	610	130	558	93	223	308	-76	366	-112	-188
54	1296	620	140	562	97	237	302	-82	365	-113	-195
57	1368	628	148	562	97	245	300	-84	352	-126	-210
64	1536	622	142	557	92	234	290	-94	350	-128	-222
67	1608	626	146	558	93	239	288	-96	350	-128	-224
72	1728	626	146	557	92	238	285	-99	350	-128	-227
75	1800	628	148	562	97	245	283	-101	350	-128	-229
87	2088	646	166	558	93	259	283	-101	350	-128	-229
89	2136	650	170	557	92	262	275	-109	348	-130	-239
96	2304	654	174	556	91	265	268	-116	346	-132	-248
104	2496	673	193	557	92	285	268	-116	345	-133	-249
111	2664	681	201	557	92	293	264	-120	340	-138	-258
120	2880	685	205	558	93	298	262	-122	340	-138	-260
128	3072	692	212	550	85	297	257	-127	333	-145	-272
136	3264	703	223	548	83	306	252	-132	330	-148	-280
145	3480	716	236	550	85	321	244	-140	328	-150	-290
151	3624	725	245	544	79	324	238	-146	326	-152	-298
167	4008	728	248	546	81	329	238	-146	318	-160	-306
174	4176	734	254	548	83	337	234	-150	315	-163	-313
182	4368	739	259	546	81	340	225	-159	308	-170	-329
197	4728	744	264	541	76	340	222	-162	286	-192	-354
207	4968	749	269	538	73	342	218	-166	281	-197	-363
214	5136	752	272	536	71	343	215	-169	278	-200	-369
225	5400	754	274	532	67	341	215	-169	275	-203	-372
248	5952	754	274	528	63	337	214	-170	273	-205	-375
260	6240	760	280	525	60	340	212	-172	270	-208	-380
270	6480	762	282	522	57	339	212	-172	268	-210	-382
317	7608	766	286	520	55	341	208	-176	265	-213	-389
368	8832	782	288	520	55	343	206	-178	263	-215	-393

Un-notched Pipes - continued

Type II, 40°C

Load applied = 1, 900 lb (pipe 4)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	490	1	408	1	2	492	1	468	1	2
2	48	575	85	395	-13	72	482	-10	437	-31	-41
3	72	595	105	393	-15	90	475	-17	430	-38	-55
4	96	605	115	395	-13	102	475	-17	425	-43	-60
5	120	615	125	395	-13	112	473	-19	420	-48	-67
9	216	635	145	400	-8	137	470	-22	412	-56	-78
13	312	650	160	400	-8	152	460	-32	424	-44	-76
17	408	650	160	395	-13	147	458	-34	426	-42	-76
22	528	655	165	396	-12	153	457	-35	426	-42	-77
26	624	658	168	398	-10	158	455	-37	435	-33	-70
30	720	660	170	398	-10	160	460	-32	425	-43	-75
36	864	660	170	415	7	177	445	-47	440	-28	-75
40	960	665	175	408	0	175	445	-47	442	-26	-73
44	1056	665	175	405	-3	172	440	-52	435	-33	-85
48	1152	668	178	405	-3	175	438	-54	432	-36	-90
54	1296	670	180	403	-5	175	438	-54	420	-48	-102
57	1368	670	180	403	-5	175	435	-57	415	-53	-110
64	1536	672	182	406	-2	180	431	-61	411	-57	-118
67	1608	674	184	400	-8	176	431	-61	405	-63	-124
72	1728	674	184	400	-8	176	430	-62	403	-65	-127
75	1800	674	184	402	-6	178	430	-62	403	-65	-127
87	2088	675	185	407	-1	184	428	-64	406	-62	-126
89	2136	675	185	402	-6	179	428	-64	397	-71	-135
96	2304	676	186	412	4	190	426	-66	395	-73	-139
104	2496	676	186	412	4	190	426	-66	394	-74	-140
111	2664	676	186	415	7	193	423	-69	381	-87	-156
120	2880	677	187	410	2	189	424	-68	376	-92	-160
128	3072	677	187	412	4	191	422	-70	373	-95	-165
136	3264	677	187	410	2	189	418	-74	368	-100	-174
145	3480	677	187	406	-2	185	414	-78	362	-106	-184
151	3624	677	187	395	-13	174	411	-81	355	-113	-194
167	4008	677	187	397	-11	176	403	-89	340	-128	-217
174	4176	677	187	392	-16	171	400	-92	333	-135	-227
182	4368	677	187	392	-16	171	386	-106	330	-138	-244
197	4728	681	191	395	-13	178	380	-112	328	-140	-252
207	4968	683	193	395	-13	180	378	-114	326	-142	-256
214	5136	688	198	395	-13	185	376	-116	320	-148	-264
225	5400	688	198	398	-10	188	370	-122	310	-158	-280
248	5952	705	215	395	-13	202	368	-124	304	-164	-288
260	6240	705	215	410	2	217	365	-127	283	-185	-312
270	6480	705	215	413	5	220	357	-135	276	-192	-327
317	7608	730	240	458	50	290	333	-159	252	-216	-375
368	8832	755	248	458	50	298	331	-161	250	-218	-379

Un-notched Pipes - continued

Type II, 40°C

Load applied = 5, 600 lb (pipe 5)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	425	1	205	1	2	180	1	247	1	2
2	48	505	80	195	-10	70	180	0	240	-7	-7
3	72	508	83	190	-15	68	177	-3	238	-9	-12
4	96	510	85	188	-17	68	178	-2	238	-9	-11
5	120	512	87	186	-19	68	178	-2	238	-9	-11
9	216	520	95	86	-119	-24	175	-5	235	-12	-17
13	312	630	205	186	-19	186	160	-20	230	-17	-37
17	408	658	233	175	-30	203	160	-20	196	-51	-71
22	528	665	240	172	-33	207	158	-22	195	-52	-74
26	624	673	248	168	-37	211	158	-22	195	-52	-74
30	720	689	264	164	-41	223	155	-25	192	-55	-80
36	864	710	285	142	-63	222	90	-90	190	-57	-147
40	960	765	340	137	-68	272	88	-92	190	-57	-149
44	1056	788	363	135	-70	293	85	-95	173	-74	-169
48	1152	790	365	125	-80	285	81	-99	170	-77	-176
54	1296	805	380	108	-97	283	78	-102	168	-79	-181
57	1368	800	375	108	-97	278	76	-104	164	-83	-187
64	1536	808	383	105	-100	283	75	-105	160	-87	-192
67	1608	811	386	103	-102	284	75	-105	156	-91	-196
72	1728	812	387	103	-102	285	71	-109	152	-95	-204
75	1800	816	391	102	-103	288	70	-110	148	-99	-209
87	2088	826	401	100	-105	296	68	-112	146	-101	-213
89	2136	830	405	100	-105	300	68	-112	142	-105	-217
96	2304	830	405	100	-105	300	65	-115	138	-109	-224
104	2496	848	423	100	-105	318	62	-118	135	-112	-230
111	2664	850	425	100	-105	320	58	-122	133	-114	-236
120	2880	852	427	98	-107	320	55	-125	132	-115	-240
128	3072	855	430	98	-107	323	49	-131	130	-117	-248
136	3264	860	435	95	-110	325	48	-132	128	-119	-251
145	3480	866	441	95	-110	331	41	-139	128	-119	-258
151	3624	868	443	93	-112	331	35	-145	126	-121	-266
167	4008	881	456	86	-119	337	34	-146	125	-122	-268
174	4176	880	455	64	-141	314	30	-150	124	-123	-273
182	4368	888	463	82	-123	340	25	-155	124	-123	-278
197	4728	900	475	80	-125	350	23	-157	123	-124	-281
207	4968	904	479	72	-133	346	20	-160	123	-124	-284
214	5136	907	482	70	-135	347	20	-160	123	-124	-284
225	5400	912	487	70	-135	352	18	-162	123	-124	-286
248	5952	925	500	70	-135	365	18	-162	123	-124	-286
260	6240	930	505	65	-140	365	17	-163	123	-124	-287
270	6480	937	512	65	-140	372	16	-164	123	-124	-288
317	7608	957	532	55	-150	382	15	-165	123	-124	-289
368	8832	978	553	52	-153	400	13	-167	123	-124	-291

Un-notched Pipes - continued

Type II, 40°C

Load applied = 5, 600 lb (pipe 6)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	202	1	240	1	2	162	1	522	1	2
2	48	270	68	238	-2	66	155	-7	488	-34	-41
3	72	285	83	235	-5	78	155	-7	481	-41	-48
4	96	295	93	235	-5	88	155	-7	480	-42	-49
5	120	300	98	236	-4	94	157	-5	475	-47	-52
9	216	325	123	235	-5	118	155	-7	473	-49	-56
13	312	353	151	223	-17	134	145	-17	470	-52	-69
17	408	365	163	221	-19	144	142	-20	455	-67	-87
22	528	380	178	221	-19	159	135	-27	438	-84	-111
26	624	410	208	222	-18	190	135	-27	434	-88	-115
30	720	438	236	224	-16	220	134	-28	422	-100	-128
36	864	450	248	225	-15	233	128	-34	421	-101	-135
40	960	440	238	222	-18	220	128	-34	408	-114	-148
44	1056	442	240	226	-14	226	128	-34	390	-132	-166
48	1152	446	244	228	-12	232	124	-38	390	-132	-170
54	1296	450	248	228	-12	236	122	-40	385	-137	-177
57	1368	430	228	229	-11	217	122	-40	384	-138	-178
64	1536	442	240	228	-12	228	122	-40	380	-142	-182
67	1608	442	240	228	-12	228	115	-47	378	-144	-191
72	1728	446	244	228	-12	232	112	-50	376	-146	-196
75	1800	449	247	228	-12	235	111	-51	374	-148	-199
87	2088	570	368	228	-12	356	110	-52	372	-150	-202
89	2136	570	368	228	-12	356	103	-59	366	-156	-215
96	2304	576	374	228	-12	362	102	-60	358	-164	-224
104	2496	597	395	228	-12	383	92	-70	357	-165	-235
111	2664	602	400	228	-12	388	90	-72	357	-165	-237
120	2880	610	408	228	-12	396	90	-72	356	-166	-238
128	3072	613	411	228	-12	399	88	-74	353	-169	-243
136	3264	624	422	228	-12	410	85	-77	349	-173	-250
145	3480	634	432	228	-12	420	82	-80	340	-182	-262
151	3624	643	441	228	-12	429	82	-80	338	-184	-264
167	4008	659	457	228	-12	445	80	-82	332	-190	-272
174	4176	664	462	228	-12	450	70	-92	325	-197	-289
182	4368	672	470	228	-12	458	67	-95	320	-202	-297
197	4728	685	483	228	-12	471	65	-97	318	-204	-301
207	4968	696	494	228	-12	482	61	-101	319	-203	-304
214	5136	705	503	228	-12	491	60	-102	315	-207	-309
225	5400	712	510	228	-12	498	58	-104	302	-220	-324
248	5952	730	528	228	-12	516	55	-107	295	-227	-334
260	6240	751	549	228	-12	537	50	-112	275	-247	-359
270	6480	762	560	228	-12	548	47	-115	248	-274	-389
317	7608	802	600	228	-12	588	42	-120	195	-327	-447
368	8832	815	613	228	-12	601	40	-122	188	-334	-456

Un-notched Pipes - continued

Type II, 40°C

Load applied = 5, 600 lb. (pipe 23)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	130	1	254	1	2	451	1	529	1	2
6	144	390	260	247	-6	254	438	-12	448	-80	-92
9	216	455	325	245	-8	317	431	-19	446	-82	-101
16	384	538	408	245	-8	400	426	-24	437	-91	-115
19	456	542	412	243	-10	402	412	-38	431	-97	-135
24	576	558	428	235	-18	410	410	-40	426	-102	-142
27	648	565	435	232	-21	414	392	-58	422	-106	-164
39	936	595	465	236	-17	448	384	-66	411	-117	-183
41	984	600	470	233	-20	450	384	-66	402	-126	-192
48	1152	616	486	230	-23	463	383	-67	399	-129	-196
56	1344	645	515	228	-25	490	381	-69	394	-134	-203
63	1512	657	527	227	-26	501	381	-69	392	-136	-205
72	1728	674	544	226	-27	517	375	-75	388	-140	-215
80	1920	680	550	222	-31	519	369	-81	381	-147	-228
88	2112	683	553	221	-32	521	360	-90	377	-151	-241
97	2328	695	565	219	-34	531	352	-98	369	-159	-257
103	2472	695	565	217	-36	529	348	-102	359	-169	-271
119	2856	725	595	215	-38	557	342	-108	354	-174	-282
126	3024	732	602	213	-40	562	335	-115	350	-178	-293
134	3216	735	605	213	-40	565	330	-120	348	-180	-300
149	3576	740	610	211	-42	568	325	-125	339	-189	-314
159	3816	747	617	211	-42	575	322	-128	336	-192	-320
185	4440	830	700	211	-42	658	319	-131	323	-205	-336
214	5136	855	725	211	-42	683	314	-136	302	-226	-362
225	5400	878	748	211	-42	706	308	-142	294	-234	-376
248	5952	897	767	211	-42	725	284	-166	294	-234	-400
260	6240	920	790	211	-42	748	268	-182	294	-234	-416
270	6480	930	800	211	-42	758	251	-199	294	-234	-433
317	7608	935	805	211	-42	763	241	-209	294	-234	-443
368	8832	949	815	207	-46	769	234	-216	291	-237	-453

Un-notched Pipes - continued

Type II, 40°C

Load applied = 5, 600 lb. (pipe 24)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	40	1	345	1	2	801	1	678	1	2
6	144	220	180	330	-15	165	766	-34	643	-35	-69
9	216	282	242	334	-11	231	756	-44	633	-45	-89
16	384	345	305	334	-11	294	736	-64	613	-65	-129
19	456	344	304	332	-13	291	729	-71	606	-72	-143
24	576	350	310	332	-13	297	720	-80	597	-81	-161
27	648	354	314	331	-14	300	816	16	593	-85	-69
39	936	368	328	331	-14	314	709	-91	586	-92	-183
41	984	372	332	330	-15	317	700	-100	577	-101	-201
48	1152	384	344	330	-15	329	691	-109	568	-110	-219
56	1344	403	363	330	-15	348	687	-113	564	-114	-227
63	1512	410	370	329	-16	354	686	-114	563	-115	-229
72	1728	418	378	329	-16	362	681	-119	558	-120	-239
80	1920	430	390	328	-17	373	680	-120	557	-121	-241
88	2112	441	401	327	-18	383	675	-125	552	-126	-251
97	2328	457	417	327	-18	399	669	-131	546	-132	-263
103	2472	468	428	326	-19	409	669	-131	546	-132	-263
119	2856	486	446	326	-19	427	661	-139	538	-140	-279
126	3024	498	458	325	-20	438	659	-141	536	-142	-283
134	3216	507	467	325	-20	447	651	-149	528	-150	-299
149	3576	516	476	325	-20	456	649	-151	526	-152	-303
159	3816	532	492	323	-22	470	649	-151	526	-152	-303
185	4440	548	508	323	-22	486	646	-154	523	-155	-309
214	5136	562	522	323	-22	500	641	-159	518	-160	-319
225	5400	645	605	321	-24	581	637	-163	514	-164	-327
248	5952	685	645	319	-26	619	581	-219	458	-220	-439
260	6240	715	675	317	-28	647	561	-239	438	-240	-479
270	6480	730	690	310	-35	655	565	-235	442	-236	-471
317	7608	782	742	300	-45	697	545	-255	422	-256	-511
368	8832	792	752	296	-49	703	539	-261	416	-262	-523

Un-notched Pipes - continued

Type II, 50°C

Load applied = 1, 900 lb (pipe 1)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	137	275	1	217	1	2	445	1	437	1	2
3	140	290	15	214	-3	12	315	-130	426	-11	-141
5	207	308	33	213	-4	29	307	-138	413	-24	-162
13	220	331	56	210	-7	49	300	-145	412	-25	-170
28	247	350	75	208	-9	66	287	-158	342	-95	-253
38	290	365	90	208	-9	81	236	-209	336	-101	-310
45	317	383	108	207	-10	98	220	-225	320	-117	-342
56	360	400	125	210	-7	118	177	-268	320	-117	-385
79	427	408	133	217	0	133	176	-269	308	-129	-398
87	450	434	159	217	0	159	175	-270	305	-132	-402
91	458	467	192	216	-1	191	172	-273	300	-137	-410
101	2424	485	210	215	-2	208	168	-277	295	-142	-419
148	3552	527	252	215	-2	250	158	-287	290	-147	-434
162	3888	578	303	217	0	303	158	-287	285	-152	-439
188	4512	603	328	218	1	329	156	-289	283	-154	-443

Type II, 50°C

Load applied = 5,600 lb (pipe 7)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	340	1	192	1	2	350	1	540	1	2
3	72	540	200	205	14	214	338	-12	538	-2	-14
5	120	627	287	210	19	306	318	-32	533	-7	-39
13	312	709	369	212	21	390	286	-64	526	-14	-78
28	672	798	458	215	24	482	265	-85	519	-21	-106
38	912	878	538	220	29	567	238	-112	514	-26	-138
45	1080	924	584	222	31	615	235	-115	513	-27	-142
56	1344	979	639	224	33	672	234	-116	510	-30	-146
79	1896	1024	684	230	39	723	231	-119	468	-72	-191
87	2088	1069	729	235	44	773	222	-128	450	-90	-218
91	2184	1120	780	235	44	824	207	-143	448	-92	-235
101	2424	1150	810	240	49	859	195	-155	440	-100	-255
129	**3096**	**1187**	**847**	**245**	**54**	**901**	120	-230	405	-135	-365
148	3552	1240	900	257	66	966	120	-230	402	-138	-368
188	4512	1310	970	263	72	1042	119	-231	400	-139	-370

Notched Pipes

Type I, 40°C

Load applied = 5, 600 lb (pipe 11)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	250	1	245	1	2	233	1	422	1	2
6	144	382	132	228	-16	116	187	-45	410	-11	-56
9	216	395	145	217	-27	118	183	-49	385	-36	-85
16	384	470	220	215	-29	191	175	-57	358	-63	-120
19	456	472	222	212	-32	190	166	-66	351	-70	-136
24	576	485	235	204	-40	195	160	-72	348	-73	-145
27	648	495	245	202	-42	203	150	-82	332	-89	-171
39	936	535	285	195	-49	236	133	-99	332	-89	-188
41	984	538	288	192	-52	236	124	-108	327	-94	-202
48	1152	549	299	189	-55	244	110	-122	331	-90	-212
56	1344	589	339	183	-61	278	97	-135	331	-90	-225
63	1512	596	346	177	-67	279	82	-150	329	-92	-242
72	1728	607	357	170	-74	283	76	-156	320	-101	-257
80	1920	608	358	128	-116	242	64	-168	315	-106	-274
88	2112	617	367	122	-122	245	62	-170	308	-113	-283
97	2328	623	373	122	-122	251	60	-172	300	-121	-293
103	2472	633	383	121	-123	260	60	-172	295	-126	-298
119	2856	642	392	118	-126	266	58	-174	290	-131	-305
126	3024	648	398	118	-126	272	54	-178	184	-237	-415
134	3216	665	415	117	-127	288	54	-178	176	-245	-423
149	3576	672	422	116	-128	294	52	-180	170	-251	-431
159	3816	676	426	116	-128	298	44	-188	170	-251	-439
185	4440	704	454	116	-128	326	38	-194	166	-255	-449
214	5136	710	460	116	-128	332	25	-207	164	-257	-464
225	5400	710	460	115	-129	331	18	-214	148	-273	-487
248	5952	796	546	108	-136	410	16	-216	130	-291	-507
260	6240	840	590	108	-136	454	16	-216	122	-299	-515
270	6480	850	600	105	-139	461	14	-218	114	-307	-525
317	7608	860	610	103	-141	469	10	-222	104	-317	-539
368	8832	865	615	100	-144	472	8	-224	100	-321	-545

<u>Notched Pipes</u> - continued

Type I, 40°C

Load applied = 5, 600 lb (pipe 12)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
2	48	195	2	405	1	3	450	1	490	1	2
6	144	380	185	396	-8	177	400	-49	470	-19	-68
9	216	412	217	395	-9	208	385	-64	448	-41	-105
16	384	496	301	388	-16	285	375	-74	438	-51	-125
19	456	499	304	386	-18	286	370	-79	435	-54	-133
24	576	515	320	385	-19	301	367	-82	422	-67	-149
27	648	527	332	380	-24	308	370	-79	420	-69	-148
39	936	578	383	378	-26	357	360	-89	411	-78	-167
41	984	582	387	378	-26	361	352	-97	409	-80	-177
48	1152	596	401	377	-27	374	352	-97	408	-81	-178
56	1344	640	445	369	-35	410	336	-113	403	-86	-199
63	1512	659	464	367	-37	427	332	-117	390	-99	-216
72	1728	662	467	367	-37	430	330	-119	373	-116	-235
80	1920	665	470	365	-39	431	330	-119	366	-123	-242
88	2112	678	483	365	-39	444	325	-124	352	-137	-261
97	2328	686	491	362	-42	449	325	-124	348	-141	-265
103	2472	703	508	362	-42	466	320	-129	350	-139	-268
119	2856	718	523	357	-47	476	319	-130	338	-151	-281
126	3024	725	530	355	-49	481	316	-133	336	-153	-286
134	3216	738	543	355	-49	494	314	-135	334	-155	-290
149	3576	755	560	355	-49	511	310	-139	328	-161	-300
159	3816	762	567	355	-49	518	307	-142	325	-164	-306
185	4440	779	584	355	-49	535	302	-147	322	-167	-314
214	5136	790	595	355	-49	546	295	-154	318	-171	-325
225	5400	831	636	353	-51	585	292	-157	315	-174	-331
248	5952	865	670	352	-52	618	288	-161	312	-177	-338
260	6240	910	715	350	-54	661	285	-164	305	-184	-348
270	6480	969	774	347	-57	717	281	-168	295	-194	-362
317	7608	969	774	345	-59	715	257	-192	280	-209	-401
368	8832	975	780	342	-62	718	247	-202	275	-214	-416

Notched Pipes - continued

Type I, 50°C

Load applied = 5, 600 lb (pipe 9)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	185	1	792	1	2	705	1	262	1	2
3	72	320	135	793	2	137	690	-14	250	-11	-25
5	120	380	195	794	3	198	686	-18	242	-19	-37
13	312	420	235	794	3	238	679	-25	235	-26	-51
28	672	475	290	798	7	297	676	-28	220	-41	-69
38	912	525	340	798	7	347	668	-36	207	-54	-90
45	1080	578	393	800	9	402	654	-50	200	-61	-111
56	1344	625	440	802	11	451	650	-54	188	-73	-127
79	1896	685	500	802	11	511	635	-69	167	-94	-163
87	2088	725	540	804	13	553	617	-87	164	-97	-184
91	2184	780	595	804	13	608	612	-92	153	-108	-200
101	2424	840	655	806	15	670	587	-117	136	-125	-242
140	**3360**	**1071**	**886**	807	16	**902**	560	-144	116	-145	-289
148	3552	1180	995	810	19	1014	540	-164	114	-147	-311
188	4512	1220	1035	815	24	1059	534	-170	111	-150	-320

Notched Pipes - continued

Type II, 20°C

Load applied = 5, 600 lb. (pipe 15)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	215	1	287	0	1	450	1	305	0	1
6	144	520	305	278	-9	296	400	-49	285	-20	-69
9	216	538	323	277	-10	313	385	-64	263	-42	-106
16	384	560	345	270	-17	328	375	-74	253	-52	-126
19	456	562	347	268	-19	328	370	-79	250	-55	-134
24	576	568	353	267	-20	333	367	-82	237	-68	-150
27	648	573	358	262	-25	333	370	-79	235	-70	-149
39	936	605	390	260	-27	363	360	-89	226	-79	-168
41	984	608	393	260	-27	366	352	-97	224	-81	-178
48	1152	620	405	259	-28	377	352	-97	223	-82	-179
56	1344	646	431	251	-36	395	336	-113	218	-87	-200
63	1512	654	439	249	-38	401	332	-117	205	-100	-217
72	1728	660	445	249	-38	407	330	-119	188	-117	-236
80	1920	667	452	247	-40	412	330	-119	181	-124	-243
88	2112	677	462	247	-40	422	325	-124	167	-138	-262
97	2328	690	475	244	-43	432	325	-124	163	-142	-266
103	2472	704	489	244	-43	446	320	-129	165	-140	-269
119	2856	718	503	239	-48	455	319	-130	153	-152	-282
126	3024	728	513	237	-50	463	316	-133	151	-154	-287
134	3216	728	513	237	-50	463	314	-135	149	-156	-291
149	3576	737	522	237	-50	472	310	-139	143	-162	-301
159	3816	750	535	237	-50	485	307	-142	140	-165	-307
185	4440	750	535	237	-50	485	302	-147	137	-168	-315
214	5136	766	551	237	-50	501	295	-154	133	-172	-326
225	5400	790	575	235	-52	523	292	-157	130	-175	-332
248	5952	830	615	234	-53	562	288	-161	127	-178	-339
260	6240	830	615	232	-55	560	285	-164	120	-185	-349
270	6480	850	635	229	-58	577	281	-168	110	-195	-363
317	7608	1087	872	227	-60	812	257	-192	95	-210	-402
368	8832	1110	895	224	-63	832	247	-202	90	-215	-417

Notched Pipes - continued

Type II, 20°C

Load applied = 5, 600 lb. (pipe 16)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	55	1	373	1	2	408	0	378	1	1
6	144	340	285	228	-144	141	406	-2	375	-2	-4
9	216	460	405	224	-148	257	395	-13	371	-6	-19
16	384	490	435	218	-154	281	388	-20	364	-13	-33
19	456	492	437	208	-164	273	384	-24	362	-15	-39
24	576	498	443	198	-174	269	383	-25	357	-20	-45
27	648	503	448	195	-177	271	374	-34	357	-20	-54
39	936	532	477	191	-181	296	372	-36	348	-29	-65
41	984	536	481	187	-185	296	364	-44	348	-29	-73
48	1152	545	490	181	-191	299	362	-46	342	-35	-81
56	1344	570	515	174	-198	317	358	-50	338	-39	-89
63	1512	577	522	168	-204	318	354	-54	335	-42	-96
72	1728	581	526	164	-208	318	347	-61	331	-46	-107
80	1920	588	533	158	-214	319	347	-61	325	-52	-113
88	2112	595	540	152	-220	320	338	-70	325	-52	-122
97	2328	608	553	144	-228	325	335	-73	318	-59	-132
103	2472	620	565	142	-230	335	332	-76	318	-59	-135
119	2856	628	573	140	-232	341	331	-77	315	-62	-139
126	3024	635	580	140	-232	348	330	-78	315	-62	-140
134	3216	635	580	137	-235	345	327	-81	313	-64	-145
149	3576	635	580	136	-236	344	318	-90	313	-64	-154
159	3816	645	590	132	-240	350	314	-94	308	-69	-163
185	4440	647	592	130	-242	350	308	-100	305	-72	-172
214	5136	651	596	128	-244	352	305	-103	300	-77	-180
225	5400	655	600	128	-244	356	301	-107	294	-83	-190
248	5952	658	603	126	-246	357	295	-113	288	-89	-202
260	6240	660	605	126	-246	359	294	-114	279	-98	-212
270	6480	690	635	124	-248	387	291	-117	271	-106	-223
317	7608	861	806	124	-248	558	291	-117	259	-118	-235
368	8832	928	873	120	-252	621	287	-121	248	-129	-250

<u>Notched Pipes</u> - continued

Type II, 40°C

Load applied = 5, 600 lb (pipe 25)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	190	1	330	1	2	366	1	507	1	2
6	144	328	138	315	-30	108	353	-12	426	-80	-92
9	216	365	175	319	-26	149	346	-19	424	-82	-101
16	384	435	245	319	-26	219	341	-24	415	-91	-115
19	456	440	250	317	-28	222	327	-38	409	-97	-135
24	576	462	272	317	-28	244	325	-40	404	-102	-142
27	648	470	280	316	-29	251	307	-58	400	-106	-164
39	936	525	335	316	-29	306	299	-66	389	-117	-183
41	984	530	340	315	-30	310	299	-66	380	-126	-192
48	1152	553	363	315	-30	333	298	-67	377	-129	-196
56	1344	594	404	315	-30	374	296	-69	372	-134	-203
63	1512	608	418	314	-31	387	296	-69	370	-136	-205
72	1728	624	434	314	-31	403	290	-75	366	-140	-215
80	1920	639	449	313	-32	417	284	-81	359	-147	-228
88	2112	656	466	312	-33	433	275	-90	355	-151	-241
97	2328	682	492	312	-33	459	267	-98	347	-159	-257
103	2472	700	510	311	-34	476	263	-102	337	-169	-271
119	2856	735	545	311	-34	511	257	-108	332	-174	-282
126	3024	752	562	310	-35	527	250	-115	328	-178	-293
134	3216	768	578	310	-35	543	245	-120	326	-180	-300
149	3576	794	604	310	-35	569	240	-125	317	-189	-314
159	3816	794	604	308	-37	567	237	-128	314	-192	-320
185	4440	794	604	308	-37	567	234	-131	301	-205	-336
214	5136	820	630	308	-37	593	229	-136	280	-226	-362
225	5400	840	650	306	-39	611	223	-142	272	-234	-376
248	5952	865	675	304	-41	634	199	-166	272	-234	-400
260	6240	910	720	302	-43	677	183	-182	272	-234	-416
270	6480	915	725	295	-50	675	166	-199	272	-234	-433
317	7608	940	750	285	-60	690	156	-209	272	-234	-443
368	8832	960	770	281	-64	706	149	-216	269	-237	-453

Notched Pipes - continued

Type II, 40°C

Load applied = 5, 600 lbs (pipe 26)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	52	1	456	-34	-33	488	1	706	1	2
6	144	305	253	311	-179	74	486	-1	583	-122	-123
9	216	325	273	307	-183	90	475	-12	579	-126	-138
16	384	385	333	301	-189	144	468	-19	572	-133	-152
19	456	390	338	291	-199	139	464	-23	570	-135	-158
24	576	405	353	281	-209	144	463	-24	565	-140	-164
27	648	410	358	278	-212	146	454	-33	565	-140	-173
39	936	454	402	274	-216	186	452	-35	556	-149	-184
41	984	458	406	270	-220	186	444	-43	556	-149	-192
48	1152	474	422	264	-226	196	442	-45	550	-155	-200
56	1344	509	457	257	-233	224	438	-49	546	-159	-208
63	1512	519	467	251	-239	228	434	-53	543	-162	-215
72	1728	529	477	247	-243	234	427	-60	539	-166	-226
80	1920	533	481	241	-249	232	427	-60	533	-172	-232
88	2112	541	489	235	-255	234	418	-69	533	-172	-241
97	2328	556	504	227	-263	241	415	-72	526	-179	-251
103	2472	568	516	225	-265	251	412	-75	526	-179	-254
119	2856	585	533	223	-267	266	411	-76	523	-182	-258
126	3024	595	543	223	-267	276	410	-77	523	-182	-259
134	3216	603	551	220	-270	281	407	-80	521	-184	-264
149	3576	620	568	219	-271	297	398	-89	521	-184	-273
159	3816	637	585	215	-275	310	394	-93	516	-189	-282
185	4440	646	594	213	-277	317	388	-99	513	-192	-291
214	5136	663	611	211	-279	332	385	-102	508	-197	-299
225	5400	694	642	211	-279	363	381	-106	502	-203	-309
248	5952	735	683	209	-281	402	375	-112	496	-209	-321
260	6240	755	703	209	-281	422	374	-113	487	-218	-331
270	6480	805	753	207	-283	470	371	-116	479	-226	-342
317	7608	805	753	207	-283	470	371	-116	467	-238	-354
368	8832	807	754	203	-287	467	367	-120	456	-249	-369

Notched Pipes - continued

Type II, 50°C

Load applied = 5, 600 lb (pipe 10)

Days	Hours	Vertical top		Vertical bottom		Total	Horizontal left		Horizontal right		Total
		Dial gage	Value	Dial gage	Value	Vert. Defl.	Dial gage	Value	Dial gage	Value	Hor. Defl.
1	24	340	1	192	1	2	235	1	390	1	2
3	72	540	200	205	14	214	218	-16	370	-19	-35
5	120	627	287	210	19	306	202	-32	330	-59	-91
13	312	635	295	212	21	316	192	-42	326	-63	-105
28	672	636	296	215	24	320	183	-51	322	-67	-118
38	912	640	300	220	29	329	164	-70	315	-74	-144
45	1080	645	305	222	31	336	155	-79	302	-87	-166
56	1344	670	330	224	33	363	150	-84	289	-100	-184
79	1896	675	335	230	39	374	136	-98	277	-112	-210
87	2088	680	340	235	44	384	130	-104	268	-121	-225
91	2184	818	478	235	44	522	127	-107	245	-144	-251
101	2424	930	590	240	49	639	112	-122	218	-171	-293
129	**3096**	**1187**	**847**	**245**	**54**	**901**	110	-124	207	-182	-306
148	3552	1240	900	257	66	966	108	-126	195	-194	-320
188	4512	1310	970	263	72	1042	106	-128	193	-196	-324

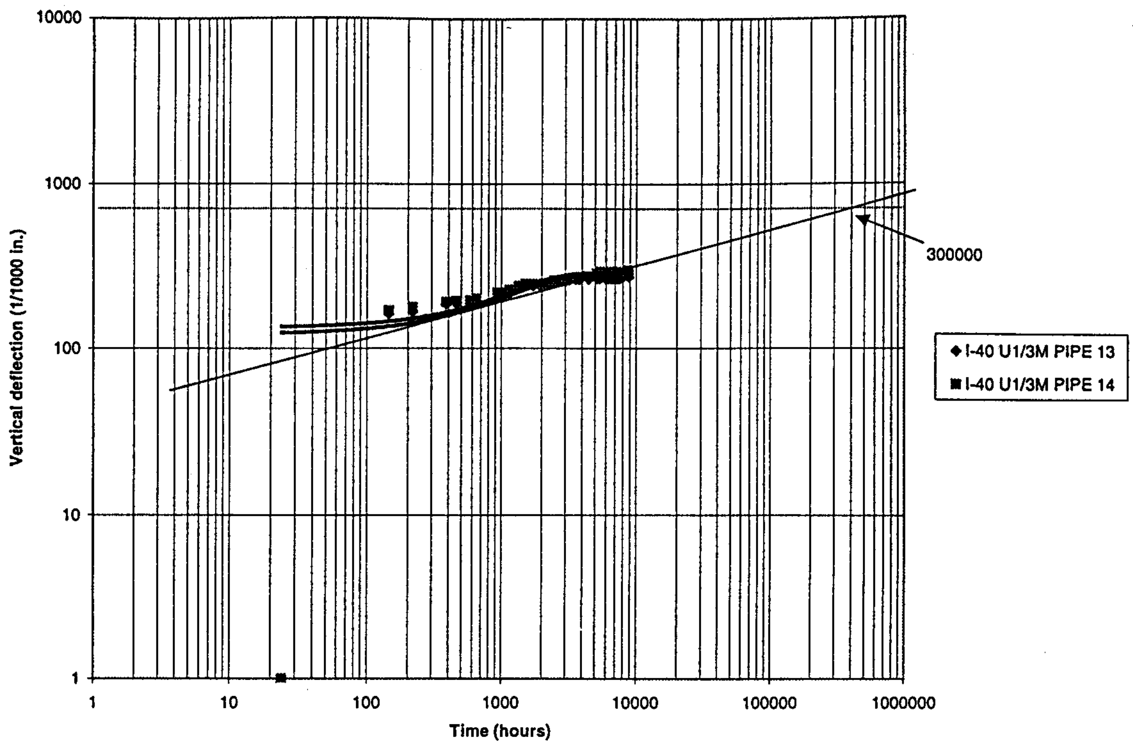


Fig. 4.5. Vertical change of diameter of Pipes 13 and 14

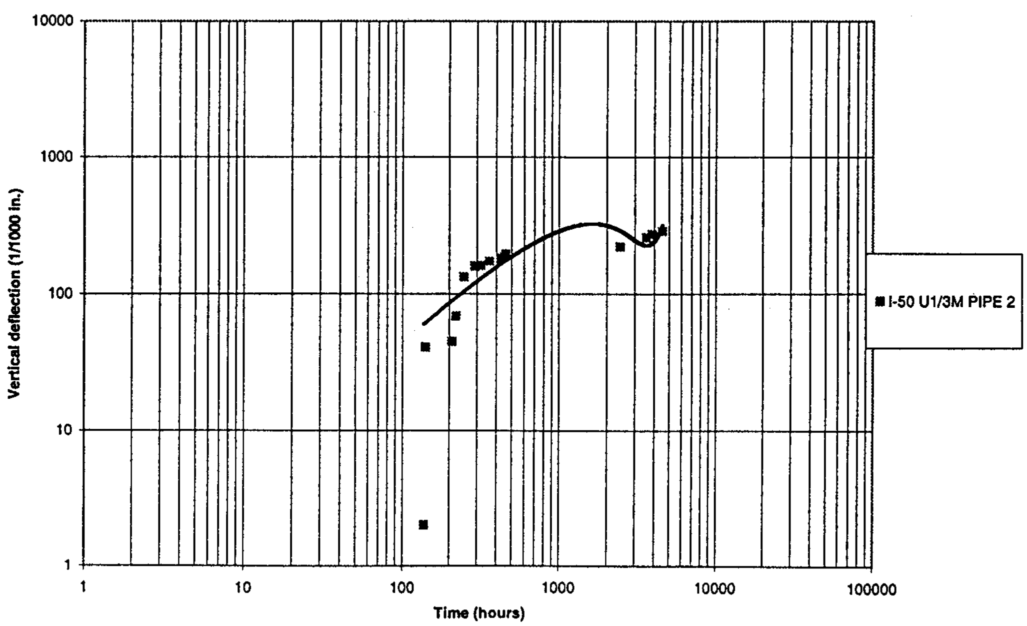


Fig. 4.6. Vertical change of diameter of Pipe 2

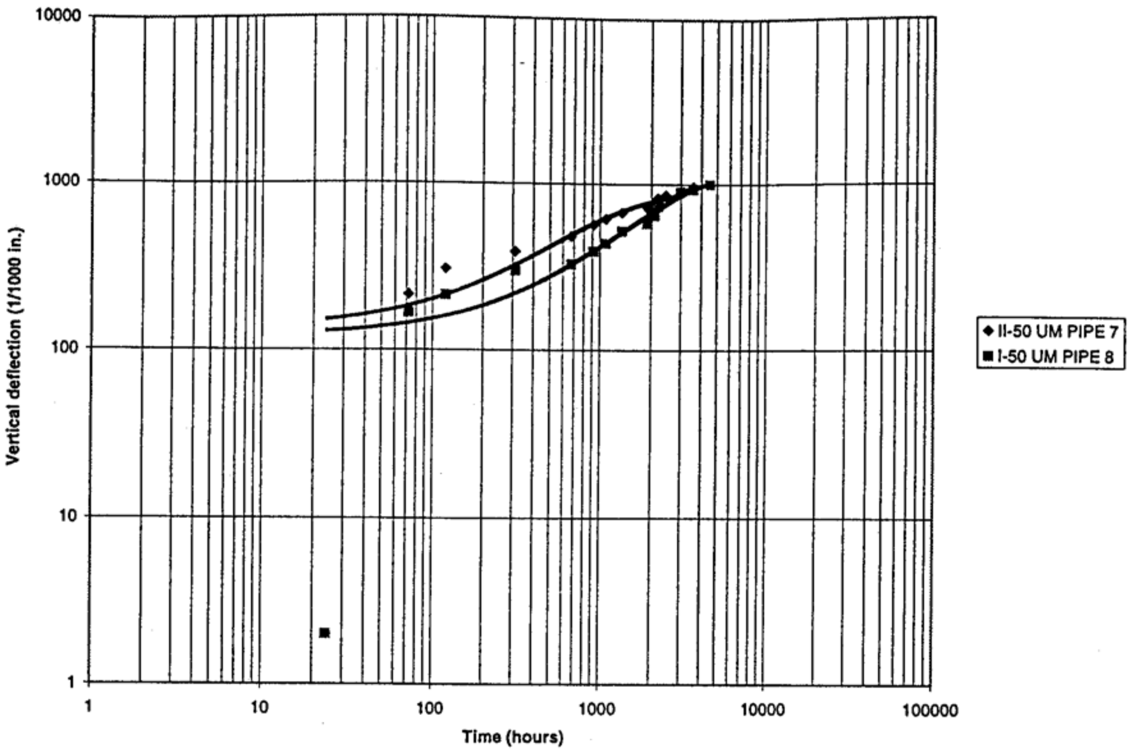


Fig. 4.7. Vertical change of diameter of Pipes 7 and 8

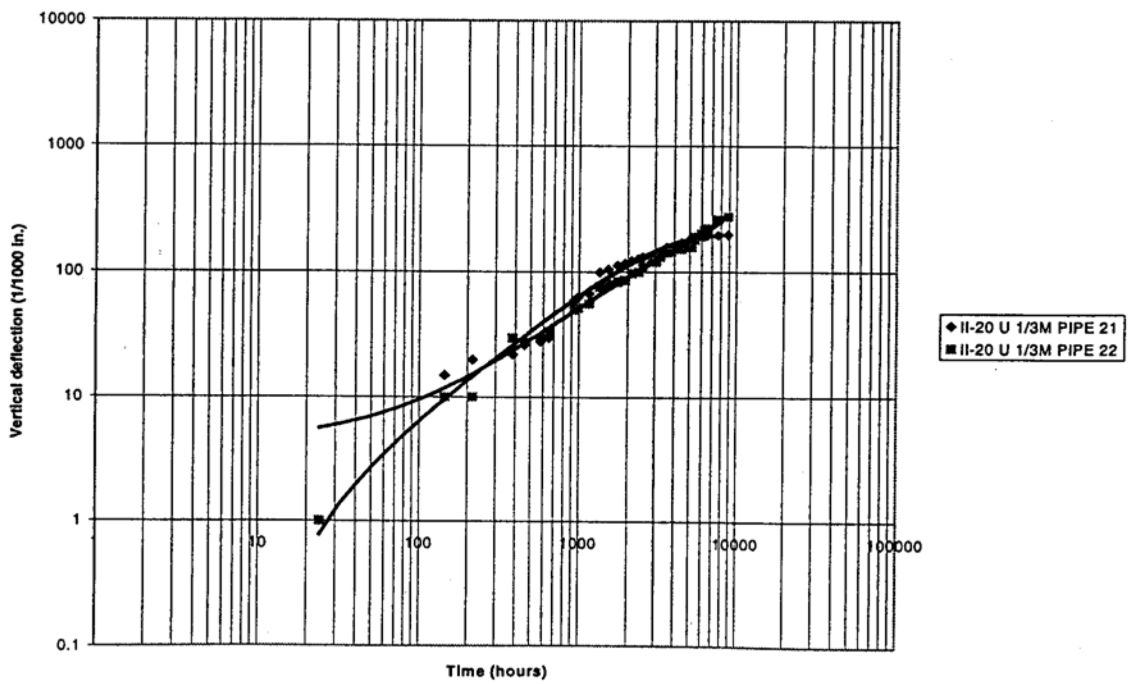


Fig. 4.8. Vertical change of diameter of Pipes 21 and 22

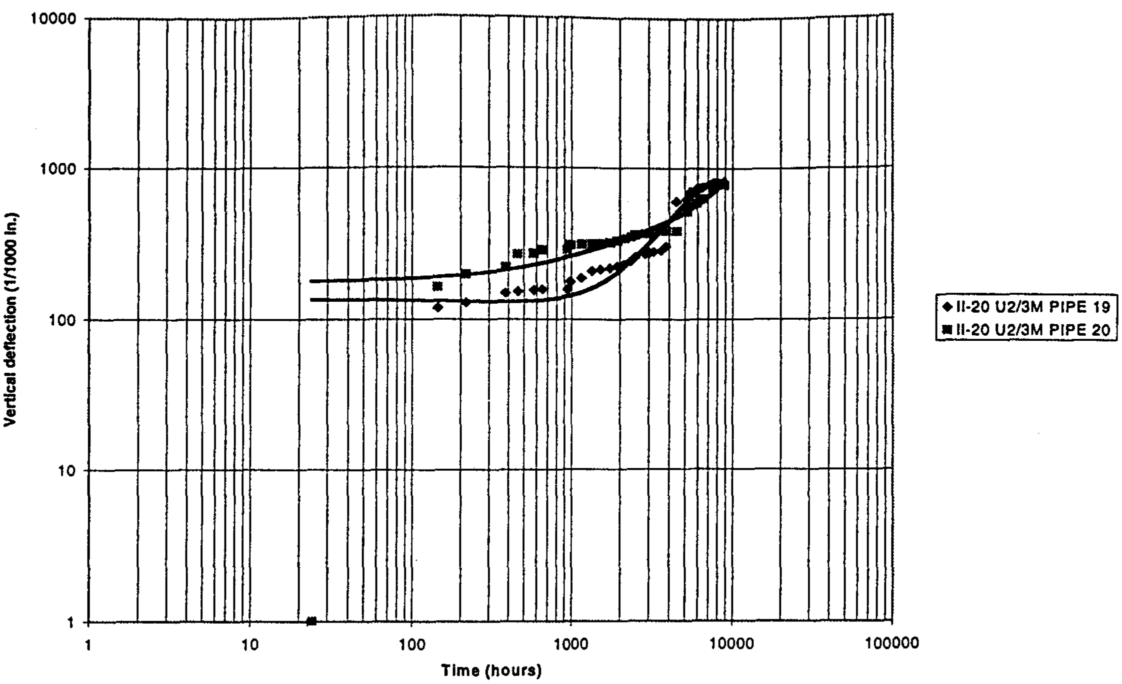


Fig. 4.9. Vertical change of diameter of Pipes 19 and 20

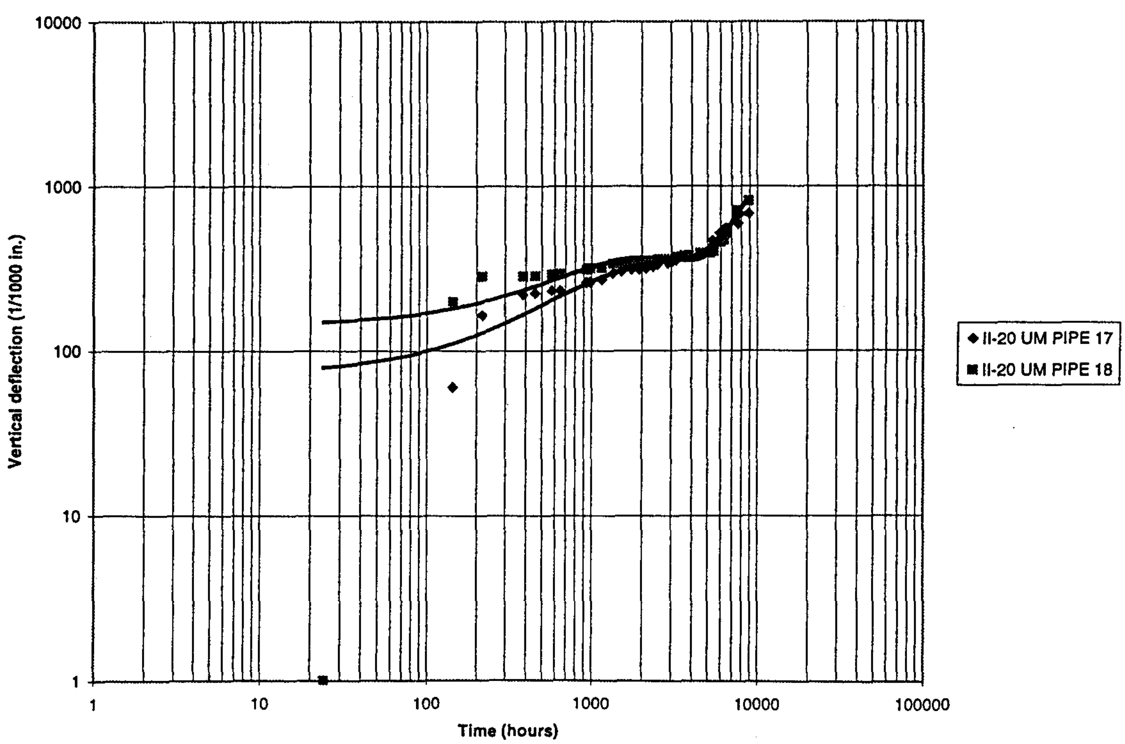


Fig. 4.10. Vertical change of diameter of Pipes 17 and 18

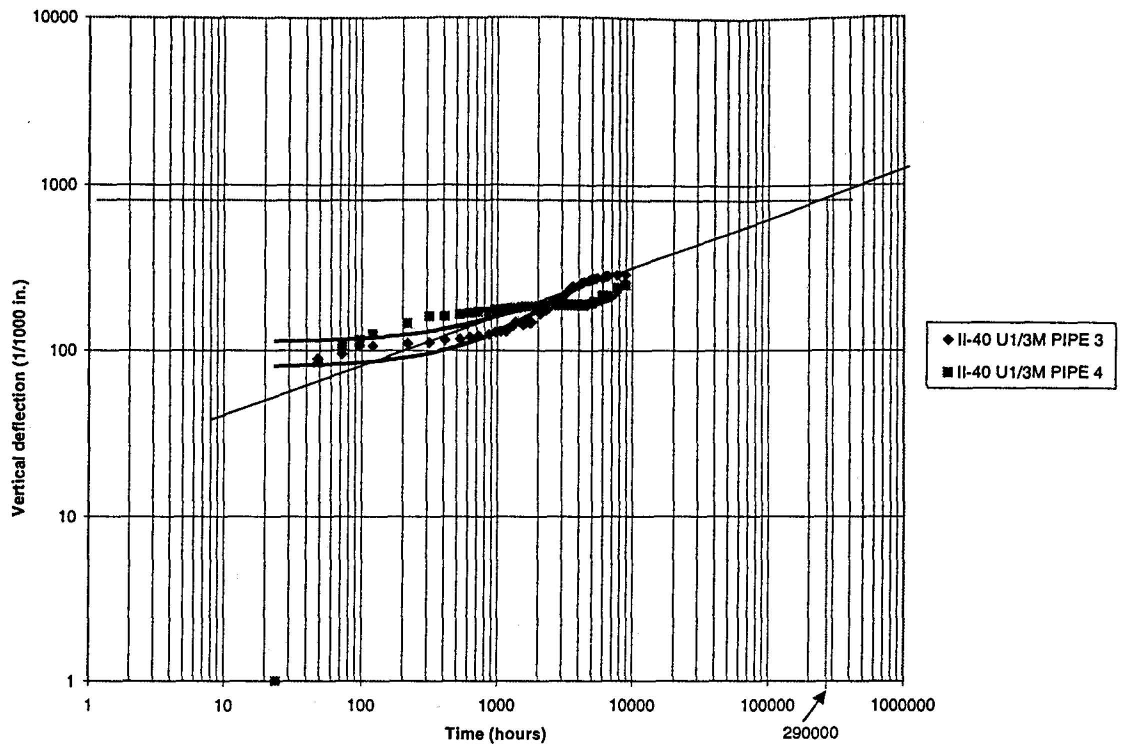


Fig. 4.11. Vertical change of diameter of Pipes 3 and 4

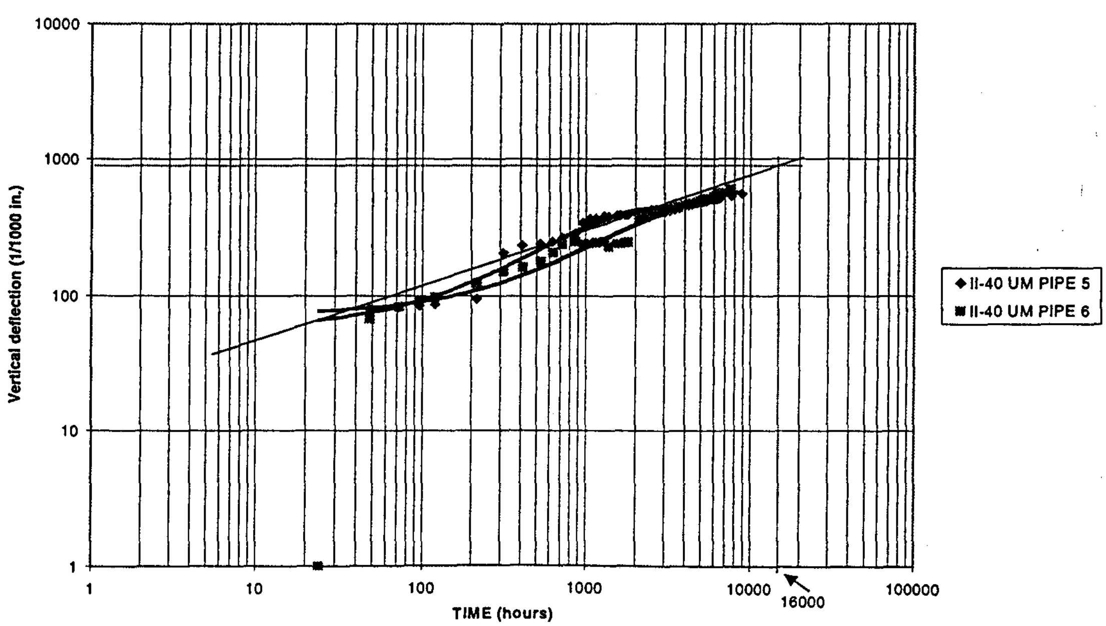


Fig. 4.12. Vertical change of diameter of Pipes 5 and 6

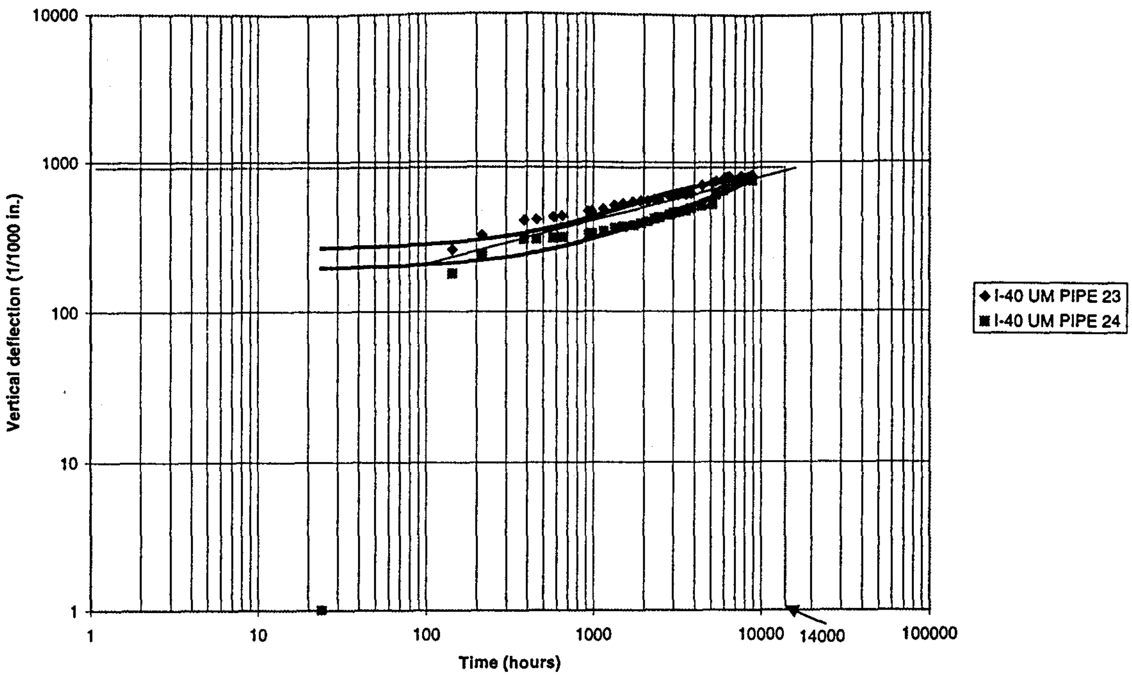


Fig. 4.13. Vertical change of diameter of Pipes 23 and 24

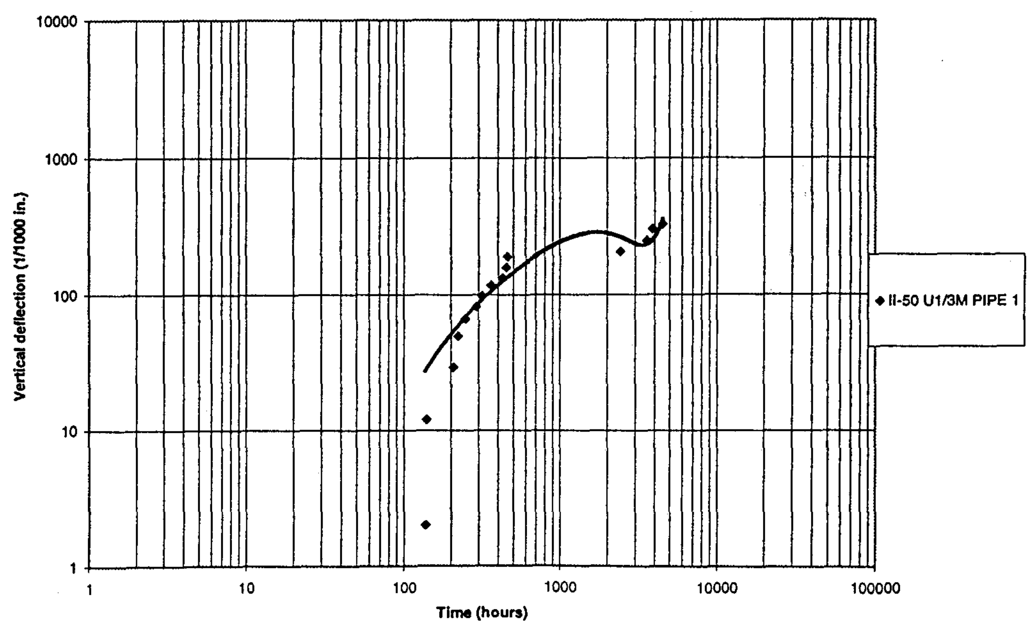


Fig. 4.14. Vertical change of diameter of Pipe 1

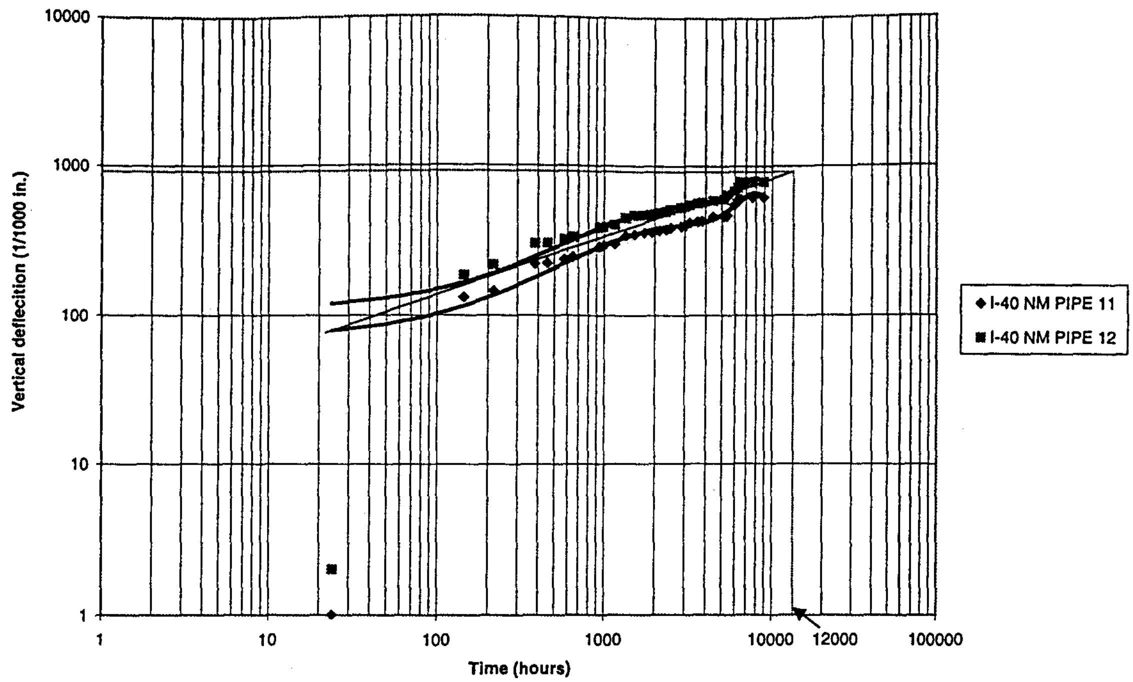


Fig. 4.15. Vertical change of diameter of Pipes 11 and 12

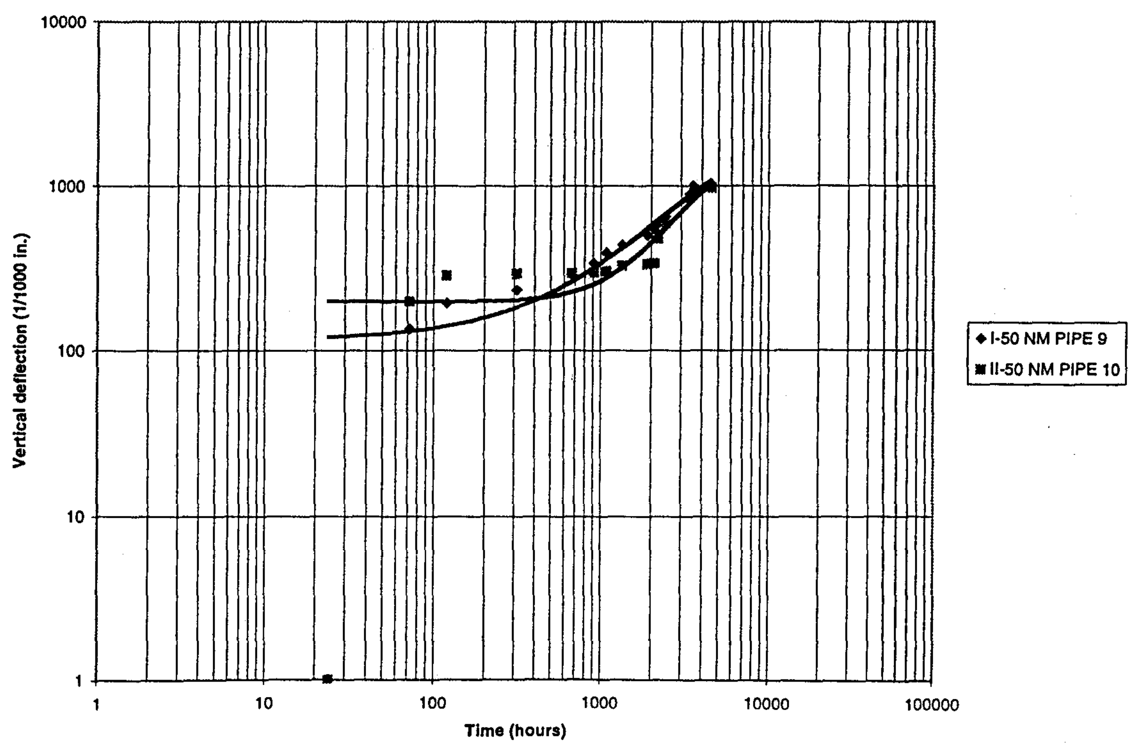


Fig. 4.16. Vertical change of diameter of Pipes 9 and 10

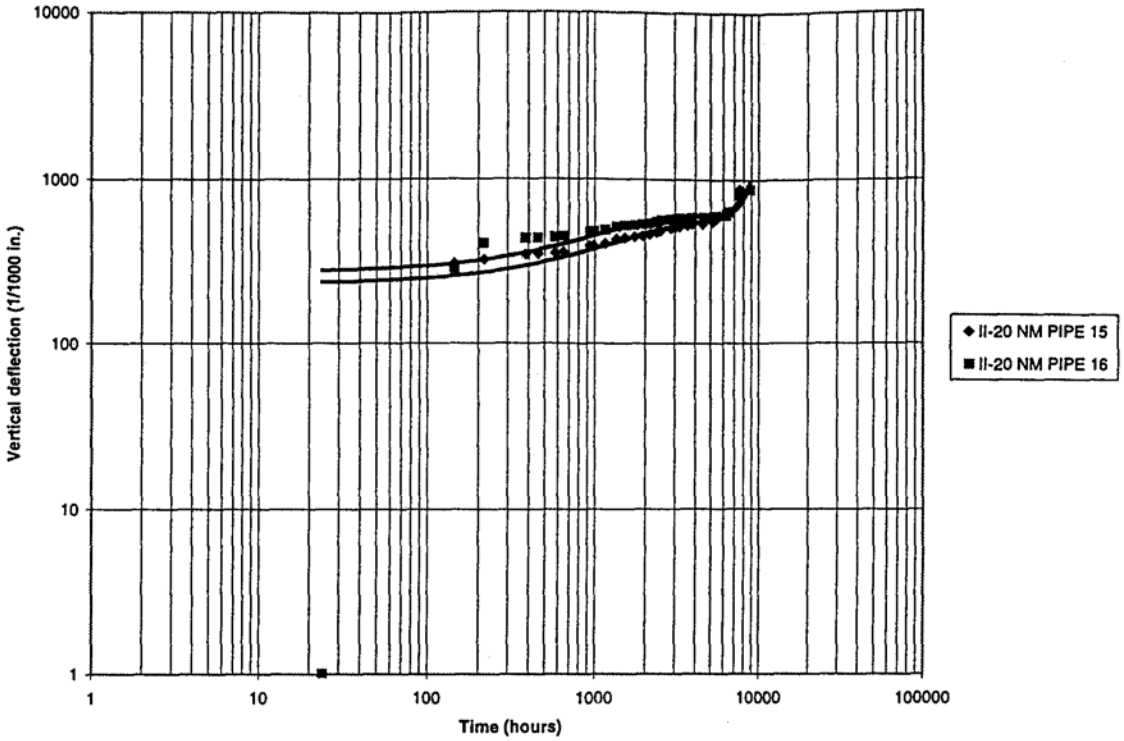


Fig. 4.17. Vertical change of diameter of Pipes 15 and 16

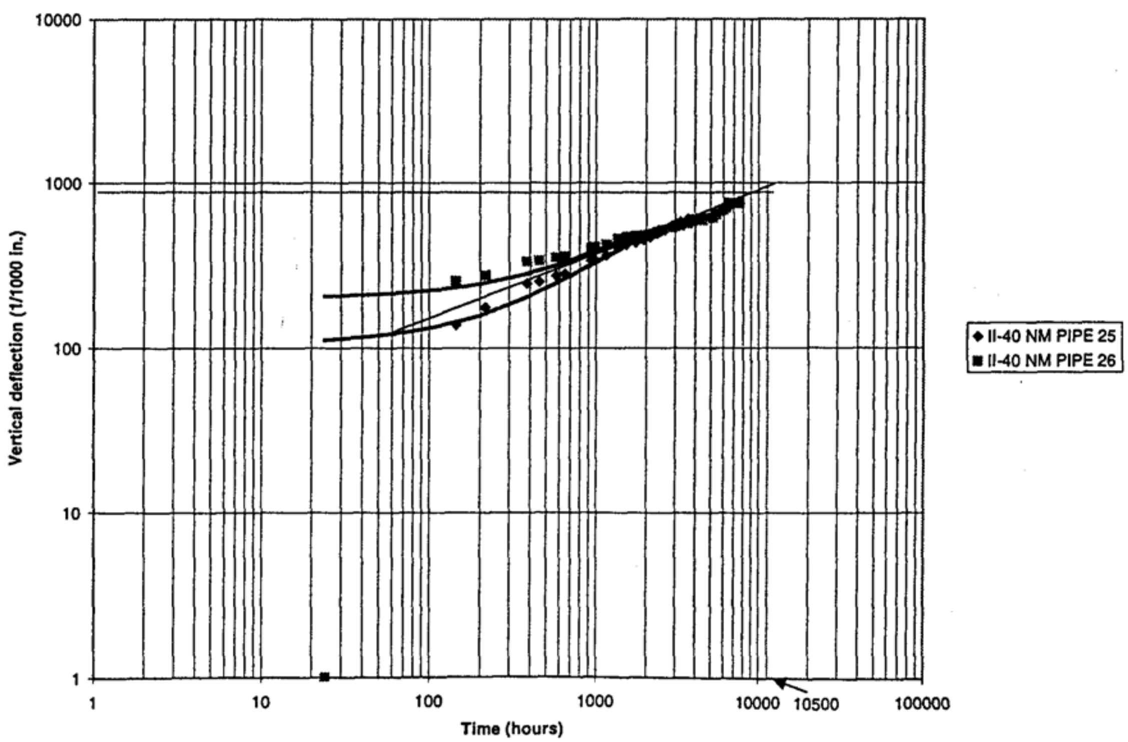


Fig. 4.18. Vertical change of diameter of Pipes 25 and 26

4.3.2. Strains. Stresses and Moments

Strains, stresses and moments are presented for Type I and II buried pipes under different loadings (5,600 lb, 1,900 lb), and temperatures (20,40 and 50°C), Table 4.2 to 4.8

Un-notched

Type I, 40°C

Table 4.2 Strains (*10⁶), Stresses (σ-psi) and Moments (M-lb in.) for Pipes 23
Load Applied(M)=5600 lb

DAYS	HOURS	ε_c 45°	E	σ	M	ε_L 135°	σ	M	ε_L 270°	σ	M
1	24	0	109892	0	0	0	0	0	0	0	0
6	144	25	109352	2.73	0.292	170	18.59	228.44	98	10.72	131.7
9	216	158	109028	17.23	1.843	240	26.17	321.58	103	11.23	138
16	384	260	108272	28.15	3.011	315	34.11	419.15	106	11.48	141.1
19	456	388	107948	41.88	4.48	400	43.18	530.61	114	12.31	151.3
24	576	497	107408	53.38	5.71	496	53.27	654.59	121	13	159.7
27	648	537	107084	57.5	6.151	542	58.04	713.21	147	15.74	193.4
39	936	631	105788	66.75	7.14	697	73.73	906.01	180	19.04	234
41	984	687	105572	72.53	7.758	793	83.72	1028.8	211	22.28	273.8
48	1152	758	104816	79.45	8.499	839	87.94	1080.6	252	26.41	324.5
56	1344	828	103952	86.07	9.207	959	99.69	1225	280	29.11	357.7
63	1512	911	103196	94.01	10.06	1009	104.12	1279.5	344	35.5	436.2
72	1728	998	102224	102.02	10.91	1029	105.19	1292.6	407	41.61	511.3
80	1920	1493	101360	151.33	16.19	1072	108.66	1335.2	447	45.31	556.8
88	2112	1753	100496	176.17	18.84	1099	110.45	1357.2	480	48.24	592.8
97	2328	2133	99524	212.28	22.71	1205	119.93	1473.7	510	50.76	623.8
103	2472	2333	98876	230.68	24.68	1245	123.1	1512.7	547	54.09	664.7
119	2856	2558	97148	248.5	26.58	1311	127.36	1565	616	59.84	735.3
126	3024	2787	96392	268.64	28.74	1335	128.68	1581.3	657	63.33	778.2
134	3216	3013	95528	287.83	30.79	1410	134.69	1655.1	710	67.82	833.4
149	3576	3158	93908	296.56	31.72	1510	141.8	1742.5	777	72.97	896.7
159	3816	3393	92828	314.97	33.69	1603	148.8	1828.5	830	77.05	946.8
185	4440	3653	90020	328.84	35.18	1699	152.94	1879.4	880	79.22	973.5
214	5136	3791	86888	329.39	35.23	1703	147.97	1818.3	982	85.32	1048
225	5400	3858	85700	330.63	35.37	1810	155.12	1906.2	1044	89.47	1099
248	5952	3891	83216	323.79	34.64	1835	152.7	1876.4	1121	93.29	1146
260	6240	3933	81920	322.19	34.46	1912	156.63	1924.7	1177	96.42	1185
270	6480	4036	80840	326.27	34.9	1970	159.25	1956.9	1284	103.8	1276
317	7608	4063	75764	307.83	32.93	2003	151.76	1864.9	1315	99.63	1224
368	8832	4113	70256	288.96	30.91	2035	142.97	1756.8	1172	82.34	1012

ε_c circumferential strain, ε_L longitudinal strain (Fig. 3.8), E moduli of elasticity (psi).

<u>Un-notched</u> - continued

<u>Type I, 40^0C</u>

Table 4.3 Strains ($*10^6$), Stresses (σ-psi) and Moments (M-lb in.) for Pipes 24
Load Applied(M)=5600 lb

DAYS	HOURS	ε_c 45^0	E	σ	M	ε_L 135^0	σ	M	ε_L 270^0	σ	M
1	24	0	109892	0	0	0	0	0	0	0	0
6	144	601	109352	65.72	7.03	146	15.97	196.24	91	9.95	122.3
9	216	734	109028	80.03	8.561	216	23.55	289.39	169	18.43	226.5
16	384	836	108272	90.52	9.683	291	31.51	387.2	133	14.4	177
19	456	964	107948	104.06	11.13	376	40.59	498.78	157	16.95	208.3
24	576	1073	107408	115.25	12.33	472	50.7	623.01	198	21.27	261.4
27	648	1113	107084	119.18	12.75	518	55.47	681.63	224	23.99	294.8
39	936	1207	105788	127.69	13.66	673	71.2	874.92	257	27.19	334.1
41	984	1263	105572	133.34	14.26	769	81.18	997.56	288	30.4	373.6
48	1152	1334	104816	139.82	14.96	815	85.43	1049.8	329	34.48	423.7
56	1344	1404	103952	145.95	15.61	935	97.2	1194.4	357	37.11	456
63	1512	1487	103196	153.45	16.41	985	101.65	1249.1	421	43.45	533.9
72	1728	1574	102224	160.9	17.21	1005	102.74	1262.5	484	49.48	608
80	1920	2069	101360	209.71	22.43	1048	106.23	1305.4	524	53.11	652.6
88	2112	2329	100496	234.06	25.04	1075	108.03	1327.5	557	55.98	687.9
97	2328	2709	99524	269.61	28.84	1181	117.54	1444.4	587	58.42	717.9
103	2472	2909	98876	287.63	30.77	1221	120.73	1483.6	624	61.7	758.2
119	2856	3134	97148	304.46	32.57	1287	125.03	1536.4	693	67.32	827.2
126	3024	3363	96392	324.17	34.68	1311	126.37	1552.9	734	70.75	869.4
134	3216	3589	95528	342.85	36.67	1386	132.4	1627	787	75.18	923.8
149	3576	3734	93908	350.65	37.51	1486	139.55	1714.8	854	80.2	985.5
159	3816	3969	92828	368.43	39.41	1579	146.58	1801.2	907	84.19	1035
185	4440	4229	90020	380.69	40.72	1675	150.78	1852.8	957	86.15	1059
214	5136	4367	86888	379.44	40.59	1679	145.88	1792.6	1059	92.01	1131
225	5400	4434	85700	379.99	40.65	1786	153.06	1880.8	1121	96.07	1181
248	5952	4467	83216	371.73	39.76	1811	150.7	1851.8	1198	99.69	1225
260	6240	4509	81920	369.38	39.51	1888	154.66	1900.5	1254	102.7	1262
270	6480	4612	80840	372.83	39.88	1946	157.31	1933.1	1361	110	1352
317	7608	4639	75764	351.47	37.6	1979	149.94	1842.5	1392	105.4	1295
368	8832	4689	70256	329.43	35.24	2011	141.28	1736.1	1249	87.75	1078

<u>Type I, 50^0C</u>

Table 4.4 Strains ($*10^6$), Stresses (σ-psi) and Moments (M-lb in.) for Pipe 8
Load Applied(M)=5600 lb

DAYS	HOURS	ε_c 45^0	E	σ	M	ε_L 135^0	σ	M	ε_L 270^0	σ	M
1	24	0	109892	0.00	0.00	0	0.00	0	0	0.00	0
3	72	48	109676	5.26	0.56	180	19.74	242.59	42	4.61	56.604
5	120	120	109460	13.14	1.41	340	37.22	457.32	80	8.76	107.61
13	312	154	108596	16.72	1.79	472	51.26	629.86	140	15.20	186.82
28	672	590	106976	63.12	6.75	670	71.67	880.74	240	25.67	315.49
38	912	860	105896	91.07	9.74	780	82.60	1014.9	340	36.00	442.43
45	1080	1025	105140	107.77	11.53	920	96.73	1188.6	480	50.47	620.15
56	1344	1680	103952	174.64	18.68	1060	110.19	1354.0	510	53.02	651.47
79	1896	2450	101468	248.60	26.59	1350	136.98	1683.2	521	52.86	649.62
87	2088	3120	100604	313.88	33.58	1555	156.44	1922.3	590	59.36	729.39
91	2184	3549	100172	355.51	38.03	1785	178.81	2197.2	670	67.12	824.73
101	2424	3880	99092	384.48	41.13	1845	182.82	2246.5	690	68.37	840.19
124	2976	4150	96068	398.68	42.65	1985	190.69	2343.3	741	71.19	874.76
148	3552	4370	94016	410.85	43.95	2050	192.73	2368.3	880	82.73	1016.7
188	4512	4870	89696	436.82	46.73	2130	191.05	2347.7	960	86.11	1058.1

Un-notched - continued

Type II, 20^{0}C

Table 4.5 Strains (*10^6), Stresses (σ-psi) and Moments (M-lb in.) for Pipe 17
Load Applied(M)=5600 lb

DAYS	HOURS	ε_c 45^0	E	σ	M	ε_L 135^0	σ	M	ε_L 270^0	σ	M
1	24	0	109892	0.00	0.00	0	0.00	0.00	0	0.00	0.00
6	144	112	109352	12.25	1.26	145	15.86	226.51	35	3.83	54.68
9	216	245	109028	26.71	2.75	215	23.44	334.87	113	12.32	176.00
16	384	347	108272	37.57	3.87	290	31.40	448.56	77	8.34	119.10
19	456	475	107948	51.28	5.28	375	40.48	578.29	101	10.90	155.75
24	576	584	107408	62.73	6.45	471	50.59	722.70	142	15.25	217.88
27	648	624	107084	66.82	6.88	517	55.36	790.89	168	17.99	257.00
39	936	718	105788	75.96	7.82	672	71.09	1015.56	201	21.26	303.76
41	984	774	105572	81.71	8.41	768	81.08	1158.28	232	24.49	349.90
48	1152	845	104816	88.57	9.11	814	85.32	1218.86	273	28.61	408.78
56	1344	915	103952	95.12	9.79	934	97.09	1387.02	301	31.29	446.99
63	1512	998	103196	102.99	10.60	984	101.54	1450.64	365	37.67	538.09
72	1728	1085	102224	110.91	11.41	1004	102.63	1466.18	428	43.75	625.03
80	1920	1580	101360	160.15	16.48	1047	106.12	1516.06	468	47.44	677.66
88	2112	1840	100496	184.91	19.03	1074	107.93	1541.90	501	50.35	719.26
97	2328	2220	99524	220.94	22.73	1180	117.44	1677.69	531	52.85	754.96
103	2472	2420	98876	239.28	24.62	1220	120.63	1723.27	568	56.16	802.31
119	2856	2645	97148	256.96	26.44	1286	124.93	1784.75	637	61.88	884.05
126	3024	2874	96392	277.03	28.50	1310	126.27	1803.91	678	65.35	933.63
134	3216	3100	95528	296.14	30.47	1385	132.31	1890.09	731	69.83	997.59
149	3576	3245	93908	304.73	31.36	1485	139.45	1992.19	798	74.94	1070.55
159	3816	3480	92828	323.04	33.24	1578	146.48	2092.61	851	79.00	1128.52
185	4440	3740	90020	336.67	34.64	1674	150.69	2152.76	901	81.11	1158.69
214	5136	3878	86888	336.95	34.67	1678	145.80	2082.83	1003	87.15	1244.98
225	5400	3945	85700	338.09	34.79	1785	152.97	2185.35	1065	91.27	1303.86
248	5952	3978	83216	331.03	34.06	1810	150.62	2151.73	1142	95.03	1357.61
260	6240	4020	81920	329.32	33.88	1887	154.58	2208.33	1198	98.14	1402.00
270	6480	4123	80840	333.30	34.29	1945	157.23	2246.20	1305	105.50	1507.09
317	7608	4150	75764	314.42	32.35	1978	149.86	2140.87	1336	101.22	1446.01
368	8832	4200	70256	295.08	30.36	2010	141.21	2017.35	1193	83.82	1197.36

Un-notched - continued

Type II, 20^{0}C

Table 4.6 Strains (*10^6), Stresses (σ-psi) and Moments (M-lb in.) for Pipe 18
Load Applied(M)=5600 lb

DAYS	HOURS	ε_c 45^0	E	σ	M	ε_L 135^0	σ	M	ε_L 270^0	σ	M
1	24	0	109892	0	0	0	0	0	0	0	0
6	144	88	109352	9.62	0.99	97	10.607	151.53	10	1.0935	15.62
9	216	221	109028	24.1	2.479	167	18.208	260.11	15	1.6354	23.36
16	384	323	108272	34.97	3.598	242	26.202	374.31	18	1.9489	27.84
19	456	451	107948	48.68	5.009	327	35.299	504.27	26	2.8066	40.09
24	576	560	107408	60.15	6.189	423	45.434	649.05	33	3.5445	50.64
27	648	600	107084	64.25	6.611	469	50.222	717.46	59	6.318	90.26
39	936	694	105788	73.42	7.554	624	66.012	943.02	92	9.7325	139
41	984	750	105572	79.18	8.147	720	76.012	1085.9	123	12.985	185.5
48	1152	821	104816	86.05	8.854	766	80.289	1147	164	17.19	245.6
56	1344	891	103952	92.62	9.53	886	92.101	1315.7	192	19.959	285.1
63	1512	974	103196	100.5	10.34	936	96.591	1379.9	256	26.418	377.4
72	1728	1061	102224	108.5	11.16	956	97.726	1396.1	319	32.609	465.8
80	1920	1556	101360	157.7	16.23	999	101.26	1446.6	359	36.388	519.8
88	2112	1816	100496	182.5	18.78	1026	103.11	1473	392	39.394	562.8
97	2328	2196	99524	218.6	22.49	1132	112.66	1609.4	422	41.999	600
103	2472	2396	98876	236.9	24.38	1172	115.88	1655.5	459	45.384	648.3
119	2856	2621	97148	254.6	26.2	1238	120.27	1718.1	528	51.294	732.8
126	3024	2850	96392	274.7	28.27	1262	121.65	1737.8	569	54.847	783.5
134	3216	3076	95528	293.8	30.23	1337	127.72	1824.6	622	59.418	848.8
149	3576	3221	93908	302.5	31.12	1437	134.95	1927.8	689	64.703	924.3
159	3816	3456	92828	320.8	33.01	1530	142.03	2029	742	68.878	984
185	4440	3716	90020	334.5	34.42	1626	146.37	2091	792	71.296	1019
214	5136	3854	86888	334.9	34.46	1630	141.63	2023.2	894	77.678	1110
225	5400	3921	85700	336	34.58	1737	148.86	2126.6	956	81.929	1170
248	5952	3954	83216	329	33.86	1762	146.63	2094.7	1033	85.962	1228
260	6240	3996	81920	327.4	33.68	1839	150.65	2152.2	1089	89.211	1274
270	6480	4099	80840	331.4	34.1	1897	153.35	2190.8	1196	96.685	1381
317	7608	4226	75764	320.2	32.94	1930	146.22	2088.9	1227	92.962	1328
368	8832	4479	70256	314.7	32.38	1962	137.84	1969.2	1084	76.158	1088

Un-notched - continued

Type II, 50^{0}C

Table 4.7 Strains (*10^6), Stresses (σ, psi) and Moments (M, lb in.) for Pipe 1
Load Applied(M)=1900 lb

DAYS	HOURS	ε_c 45^0	E	σ	M	ε_L 135^0	σ	M	ε_L 270^0	σ	M
1	24	0	109892	0	0	0	0	0	0	0	0
3	72	14	109676	1.53	0.15	14	1.53	21.93	73	8.00	114.37
5	120	43	109460	4.70	0.48	84	9.19	131.35	120	13.13	187.64
13	312	276	108596	29.97	3.08	254	27.58	394.04	130	14.11	201.67
28	672	383	106976	40.97	4.21	294	31.45	449.29	137	14.65	209.36
38	912	517	105896	54.74	5.63	516	54.64	780.60	140	14.82	211.79
45	1080	600	105140	63.08	6.49	393	41.32	590.28	207	21.76	310.91
56	1344	750	103952	77.96	8.02	413	42.93	613.31	220	22.86	326.70
79	1896	817	101468	82.89	8.52	456	46.26	660.99	247	25.06	358.03
87	2088	920	100604	92.55	9.52	477	47.98	685.54	290	29.17	416.78
91	2184	993	100172	99.47	10.23	513	51.38	734.11	317	31.75	453.63
101	2424	1140	99092	112.96	11.62	546	54.10	772.91	360	35.67	509.61
148	3552	1253	94016	117.80	12.12	606	56.97	813.90	427	40.14	573.49
162	3888	1326	92504	122.66	12.62	663	61.33	876.14	450	41.62	594.66
188	4512	1340	89696	120.19	12.36	720	64.58	922.58	458	41.08	586.86

Type II, 50^{0}C

Table 4.8 Strains (*10^6), Stresses (σ, psi) and Moments (M, lb in.) for Pipe 7
Load Applied(M)=5600 lb

DAYS	HOURS	ε_c 45^0	E	σ	M	ε_L 135^0	σ	M	ε_L 270^0	σ	M
1	24	0	109892	0.00	0.00	0	0.00	0.00	0	0.00	0.00
3	72	19	109676	2.08	0.21	52	5.70	81.47	32	3.51	50.14
5	120	91	109460	9.96	1.02	124	13.57	193.90	84	9.19	131.35
13	312	125	108596	13.57	1.40	168	18.24	260.63	158	17.16	245.12
28	672	561	106976	60.01	6.18	214	22.89	327.04	268	28.67	409.57
38	912	831	105896	88.00	9.05	345	36.53	521.92	345	36.53	521.92
45	1080	996	105140	104.72	10.77	421	44.26	632.34	490	51.52	735.98
56	1344	1651	103952	171.62	17.66	587	61.02	871.71	501	52.08	744.00
79	1896	2421	101468	245.65	25.28	758	76.91	1098.75	521	52.86	755.21
87	2088	3091	100604	310.97	32.00	925	93.06	1329.41	585	58.85	840.76
91	2184	3520	100172	352.61	36.28	1005	100.67	1438.18	660	66.11	944.48
101	2424	3851	99092	381.60	39.26	1250	123.87	1769.50	785	77.79	1111.25
148	3552	4121	96068	395.90	40.74	1420	136.42	1948.81	870	83.58	1193.99
162	3888	4341	94016	408.12	41.99	1620	152.31	2175.80	980	92.14	1316.22
188	4512	4841	89696	434.22	44.68	1680	150.69	2152.70	1020	91.49	1307.00

The effective stresses at the midsection were evaluated as follows:

$$\sigma_e = \frac{1}{\sqrt{2}}[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2)]^{1/2} \quad \text{---- (4.5)}$$

The maximum stresses (from Table 4.4) were 436.82 and 192.73 psi for circumferential and longitudinal stresses, respectively. Therefore, the maximum effective stress was 379.17 psi, based on equation 4.5 (i.e. 7.5% deflection of the diameter), which is much less than 3000 psi (CPPA yield stress). The change of diameter is the governing factor and the CPPA limit is not reasonable for the general failure criterion of the buried HDPE pipe subjected to live loading.

5.1.1.1 Arrhenius Plot for Type I-Notched Maximum Loading (NM)

Type I-NM

Temperature T(°K)	1/(T)	*Time (hours) to reach 7.5% deflection*	*1/Time*
323	*0.003096*	*3360 (see Appendix A Pipe #9)*	*0.0002976*
313	*0.003195*	*12000 (see Fig. 4.11)*	*8.333E-5*

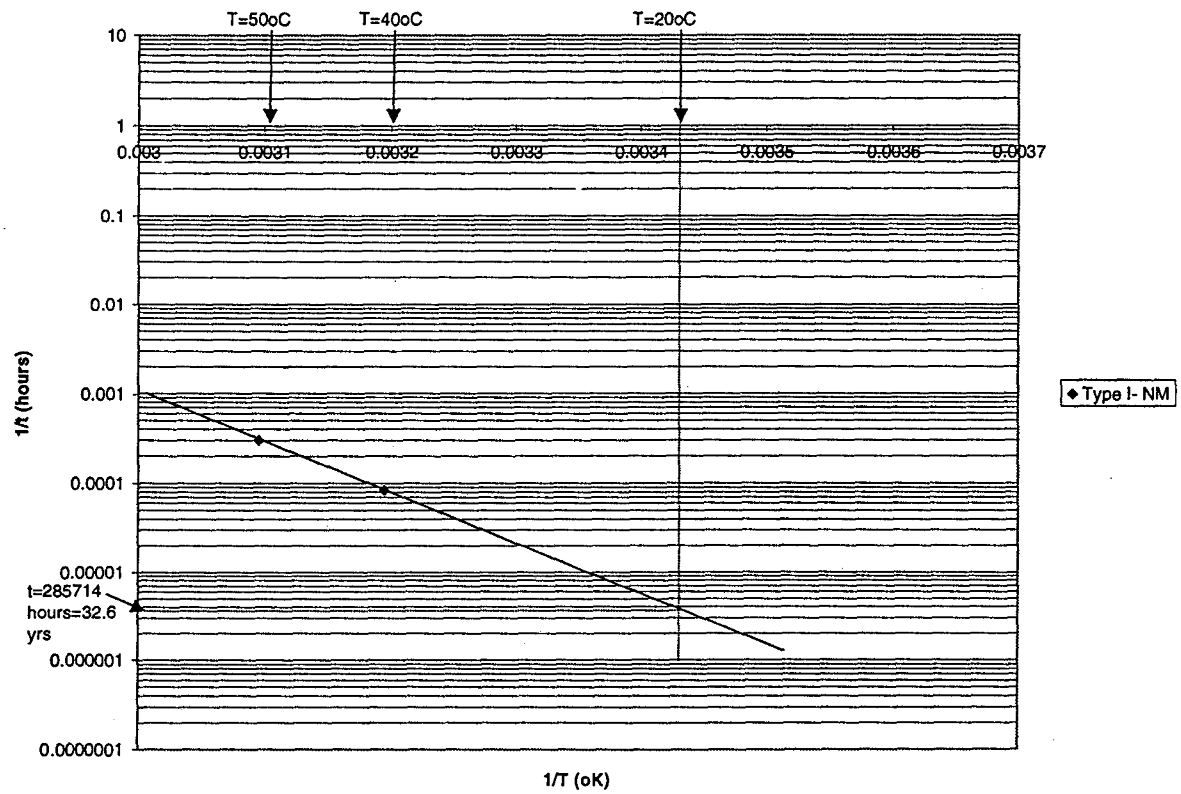


Fig. 5.1 Arrhenius plot for Type I- NM corresponding to 7.5% vertical change of diameter

Assuming proper installation conditions, the life prediction for Type I specimen, notched at valley, under the maximum loading (5,600lb), is 32.6 years.

5.1.1.2 Arrhenius Plot for Type I- Un-Notched Maximum Loading UM

Type I- UM

Temperature T(°K)	1/(T)	*Time (hours) to reach 7.5% deflection*	*1/Time*
323°	*0.003096*	*2976 (see Appendix A Pipe # 8)*	*0.000336*
313°	*0.003195*	*14000 (see Fig. 4.17)*	*7.14E-5*

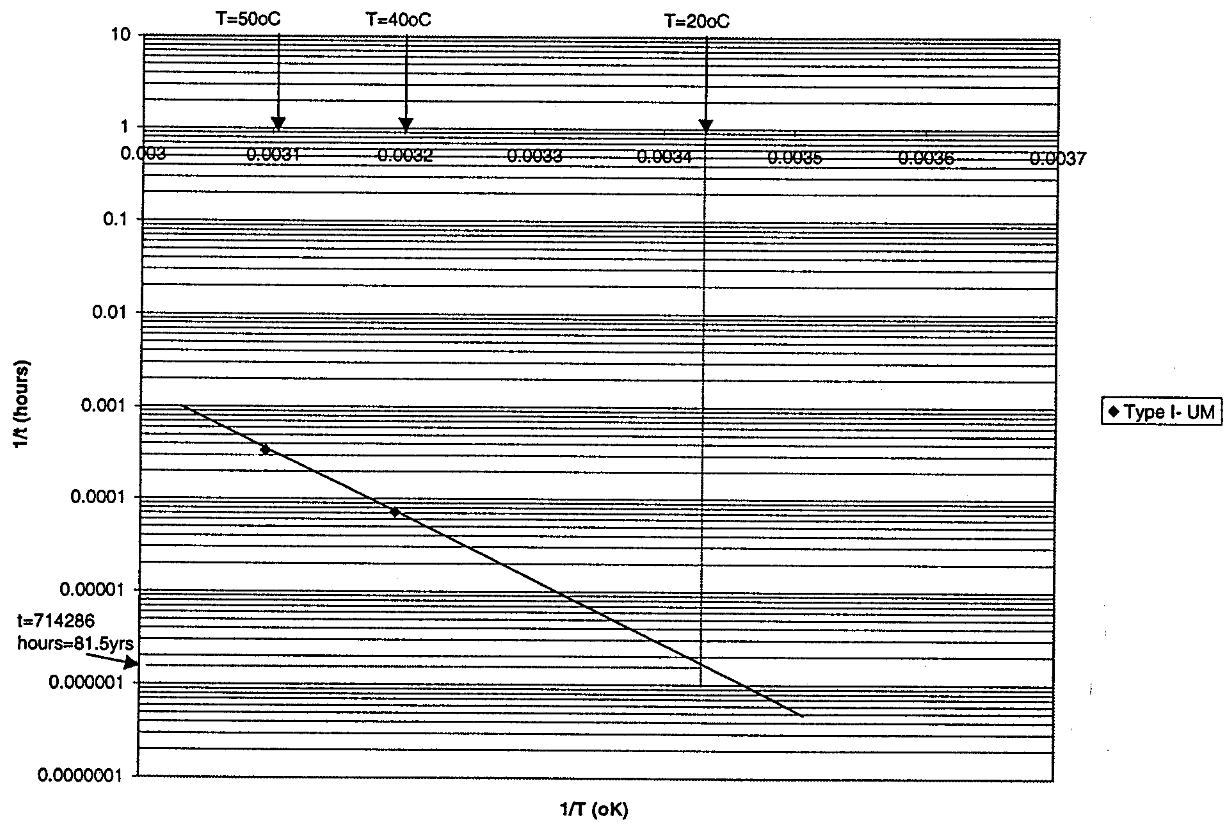


Fig. 5.2 Arrhenius plot for Type I- UM corresponding to 7.5% vertical change of diameter

Assuming proper installation conditions, the life prediction for Type I specimen, unnotched, under the maximum loading (5,600 lb), is 81.5 years.

5.1.1.3 Arrhenius Plot for Type I- Un-Notched,1/3 Maximum Loading U 1/3

Type I- U1/3

Temperature T(°K)	1/(T)	*Time (hours) to reach 7.5% deflection*	*1/Time*
323°	*0.003096*	*65000 (see Fig. 4.6)*	*1.54E-05*
313°	*0.003195*	*300000 (see Fig. 4.12)*	*3.33E-06*

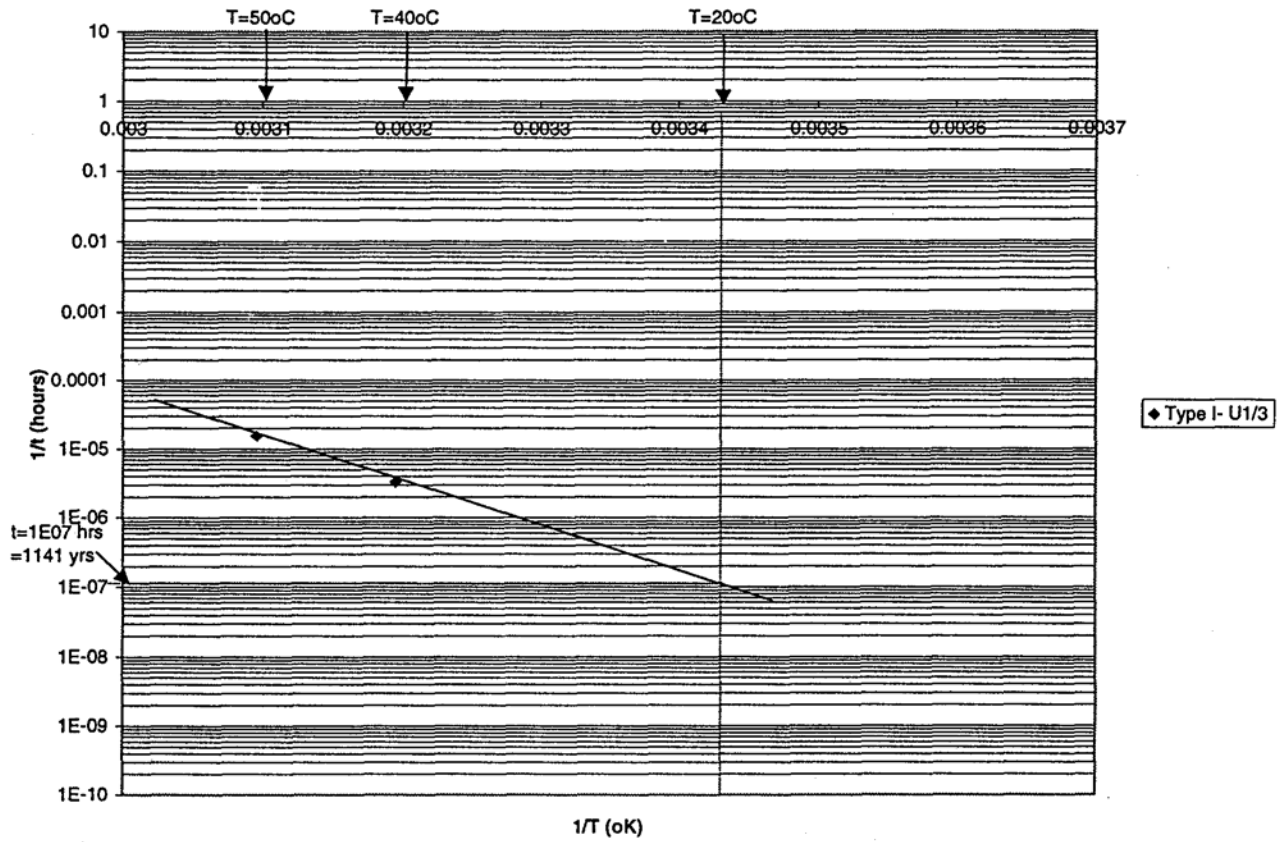


Fig. 5.3 Arrhenius plot for Type I- U1/3 corresponding to 7.5% vertical change of diameter

Assuming proper installation conditions, the life prediction for Type I specimen, unnotched, under the 1/3 of the maximum loading (1,900 lb), is 1,141 years.

5.1.1.4 Arrhenius Plot for Type II-NM

Type II- NM

Temperature T(°K)	1/(T)	*Time (hours) to reach 7.5% deflection*	*1/Time*
323°	*0.003096*	*3096 (see Appendix A Pipe # 7)*	*0.000323*
313°	*0.003195*	*10500 (see Fig. 4.18)*	*9.52E-05*

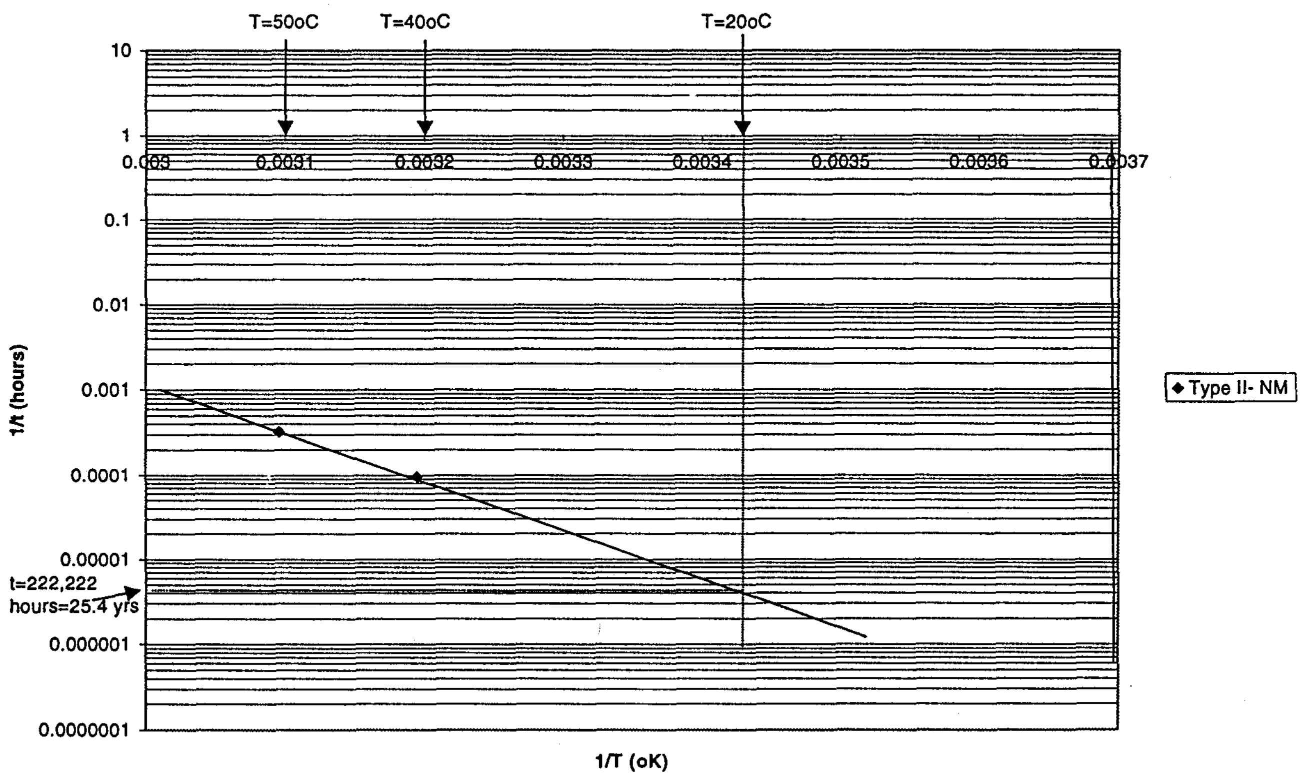


Fig. 5.4 Arrhenius plot for Type II-NM corresponding to 7.5% vertical change of diameter

Assuming proper installation conditions, the life prediction for Type II specimen, notched at valley, under the maximum loading (5,600 lb), is 25.4 years.

5.1.1.5 Arrhenius Plot for Type II-UM

Type II- UM

Temperature T(°K)	1/(T)	*Time (hours) to reach 7.5% deflection*	*1/Time*
323°	*0.003096*	*2904 (see Appendix A Pipe #10)*	*0.000344*
313°	*0.003195*	*16000 (see Fig. 4.8)*	*6.25E-05*

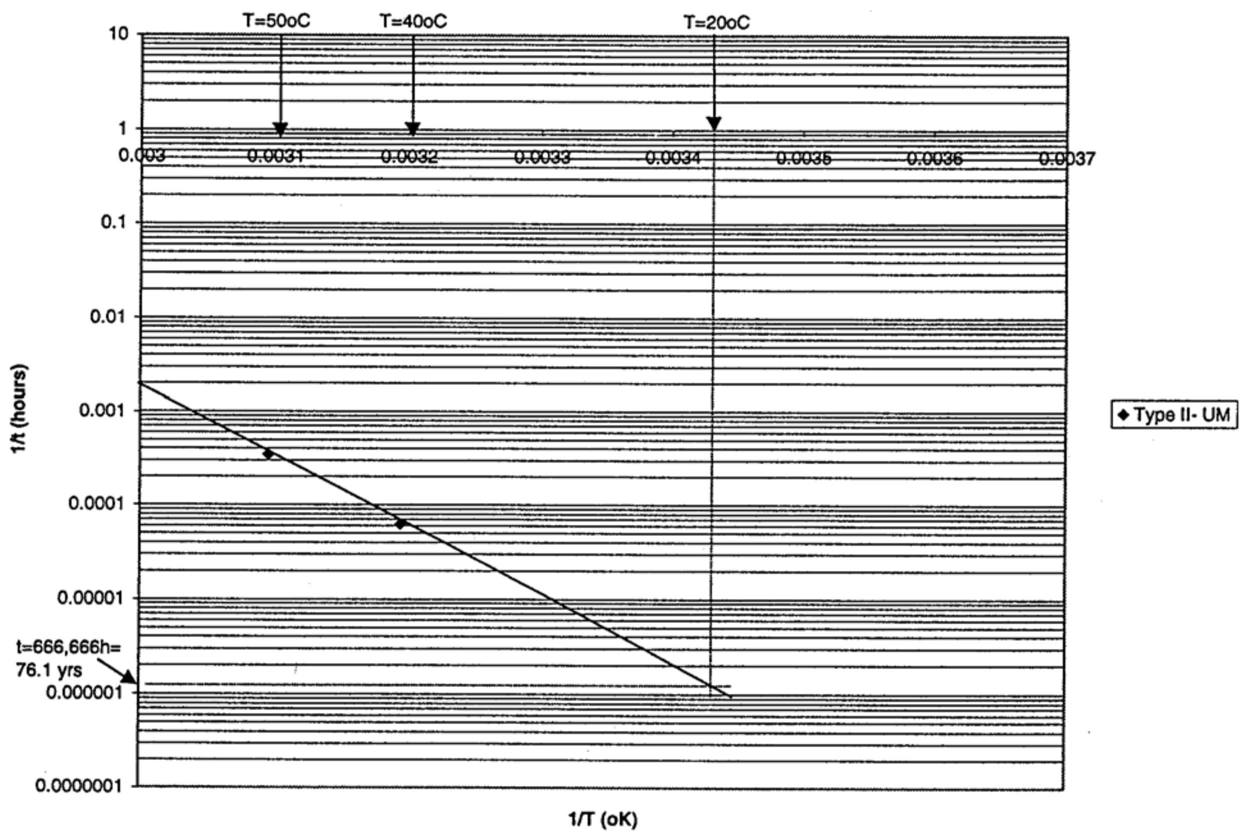


Fig. 5.5 Arrhenius plot for Type II-UM corresponding to 7.5% vertical change of diameter

Assuming proper installation conditions, the life prediction for Type II specimen, unnotched, under the maximum loading (5,600 lb), is 76.1 years.

5.1.1.6 Arrhenius Plot for Type II-U1/3

Type II- U1/3

Temperature T(°K)	1/(T)	*Time (hours) to reach 7.5% deflection*	*1/Time*
323°	*0.003096*	*70000 (see Fig. 4.5)*	*1.42E-05*
313°	*0.003195*	*290000 (see Fig. 4.7)*	*3.45E-06*

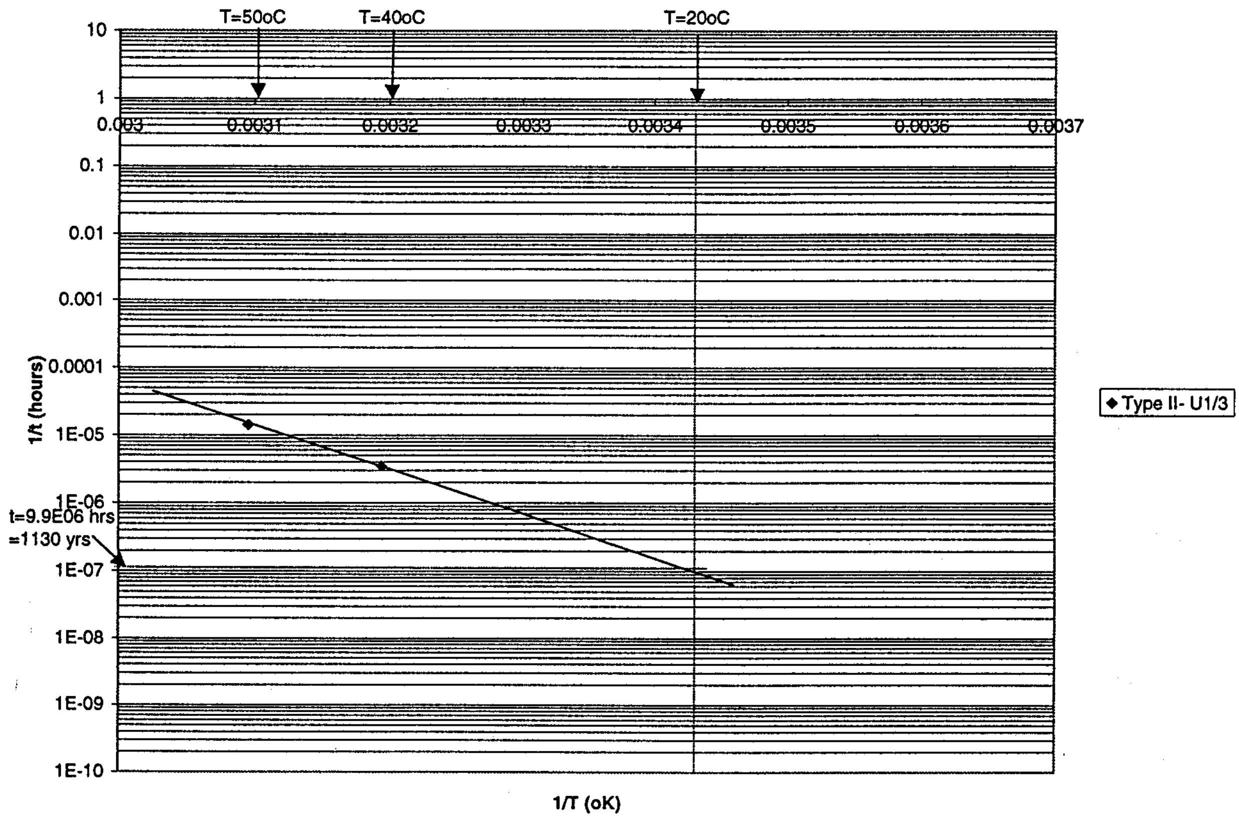


Fig. 5.6 Arrhenius plot for Type II-U1/3 corresponding to 7.5% vertical change of diameter

Assuming proper installation conditions, the life prediction for Type II specimen, unnotched, less than 1/3 of the maximum loading (1,900 lb), is 1,130 years.

5.1.2. Evaluation of the long-term vertical change of diameter using Bi-directional shifting method

The Bi-directional Shifting Function Method, Popelar et al. [1990]. It enables the construction of master curves for nonpressurized HDPE sewer pipe material using creep test data. In this procedure, no curve fitting is needed, which enables even a single data point, representing any viscoelastic phenomenon determined at a given test temperature, to be shifted to another temperature. Based on the time-temperature superposition principle, the horizontal and vertical shift functions, aT and bT, respectively, are given by:

aT = exp [-0.109 (T-Tr)]-------------------------------------- (5

.2) bT= exp [0.0116 (T-Tr)]-------------------------------------

(5.3)

The master curves, based on the Bi-directional method are shown in Figs. 5.7 to 5.12. The data used for the Bi-directional plots are Appendix B.

APPENDIX B

The values are for the Bi-directional method, which are shown in Figs. 5.7 to 5.12.
Deflections (1/1000 in.)

Un-notched

Type I, 40^{0}C

Load applied = 1, 900 lb (pipe 13)

			Vertical top		Vertical bottom		Total	
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	24	212.311	25	1	465	1	2	2.52
6	144	1273.87	186	161	458	-6	155	195.47
9	216	1910.8	190	165	456	-8	157	198.00
16	384	3396.98	210	185	456	-8	177	223.22
19	456	4033.92	211	186	454	-10	176	221.96
24	576	5095.47	212	187	446	-18	169	213.13
27	648	5732.41	217	192	443	-21	171	215.65
39	936	8280.14	232	207	447	-17	190	239.61
41	984	8704.77	233	208	444	-20	188	237.09
48	1152	10190.9	238	213	441	-23	190	239.61
56	1344	11889.4	258	233	439	-25	208	262.31
63	1512	13375.6	262	237	438	-26	211	266.10
72	1728	15286.4	262	237	437	-27	210	264.84
80	1920	16984.9	265	240	433	-31	209	263.57
88	2112	18683.4	271	246	432	-32	214	269.88
97	2328	20594.2	276	251	430	-34	217	273.66
103	2472	21868.1	280	255	428	-36	219	276.19
119	2856	25265.1	281	256	426	-38	218	274.92
126	3024	26751.2	283	258	424	-40	218	274.92
134	3216	28449.7	284	259	424	-40	219	276.19
149	3576	31634.4	285	260	422	-42	218	274.92
159	3816	33757.5	285	260	422	-42	218	274.92
185	4440	39277.6	286	261	422	-42	219	276.19
214	5136	45434.6	289	264	422	-42	222	279.97
225	5400	47770.1	289	264	422	-42	222	279.97
248	5952	52653.2	289	264	422	-42	222	279.97
260	6240	55201	290	265	422	-42	223	281.23
270	6480	57324.1	290	265	422	-42	223	281.23
317	7608	67302.7	290	265	422	-42	223	281.23
368	8832	78130.6	295	270	418	-46	224	282.49

Type I, 40⁰C

Load applied = 5, 600 lb (pipe 23)

			Vertical top		Vertical bottom		Total	
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	24	212.3114	130	1	254	1	2	2.52
6	144	1273.868	390	260	247	-6	254	320.32
9	216	1910.802	455	325	245	-8	317	399.77
16	384	3396.982	538	408	245	-8	400	504.45
19	456	4033.916	542	412	243	-10	402	506.97
24	576	5095.472	558	428	235	-18	410	517.06
27	648	5732.406	565	435	232	-21	414	522.10
39	936	8280.143	595	465	236	-17	448	564.98
41	984	8704.765	600	470	233	-20	450	567.50
48	1152	10190.94	616	486	230	-23	463	583.90
56	1344	11889.44	645	515	228	-25	490	617.95
63	1512	13375.62	657	527	227	-26	501	631.82
72	1728	15286.42	674	544	226	-27	517	652.00
80	1920	16984.91	680	550	222	-31	519	654.52
88	2112	18683.4	683	553	221	-32	521	657.04
97	2328	20594.2	695	565	219	-34	531	669.65
103	2472	21868.07	695	565	217	-36	529	667.13
119	2856	25265.05	725	595	215	-38	557	702.44
126	3024	26751.23	732	602	213	-40	562	708.75
134	3216	28449.72	735	605	213	-40	565	712.53
149	3576	31634.39	740	610	211	-42	568	716.32
159	3816	33757.5	747	617	211	-42	575	725.14
185	4440	39277.6	830	700	211	-42	658	829.82
214	5136	45434.63	855	725	211	-42	683	861.34
225	5400	47770.05	878	748	211	-42	706	890.35
248	5952	52653.21	897	767	211	-42	725	914.31
260	6240	55200.95	920	790	211	-42	748	943.32
270	6480	57324.06	930	800	211	-42	758	955.93
317	7608	67302.7	935	805	211	-42	763	962.23
368	8832	78130.58	949	815	207	-46	769	969.80

Type I, 50⁰C

Load applied = 1, 900 lb (pipe 2)

			Vertical top		Vertical bottom		Total	
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	137	3604.65	345	1	660	1	2	1.41
3	140	3683.59	461	43	658	-2	41	28.95
5	207	5446.45	489	52	653	-7	45	31.77
13	220	5788.49	538	79	650	-10	69	48.72
28	247	6498.9	814	142	650	-10	132	93.21
38	290	7630.29	847	168	650	-10	158	111.56
45	317	8340.69	886	178	642	-18	160	112.98
56	360	9472.08	905	192	640	-20	172	121.45
79	427	11234.9	925	202	638	-22	180	127.10
87	450	11840.1	986	212	632	-28	184	129.92
91	458	12050.6	1020	222	632	-28	194	136.98
101	2424	63778.7	1070	248	632	-28	220	155.34
148	3552	93457.9	1140	286	632	-28	258	182.17
162	3888	102298	1275	302	630	-30	272	192.06
188	4512	118717	1312	316	630	-30	286	201.94

Type I, 50⁰C

Load applied = 5, 600 lb (pipe 8)

			Vertical top		Vertical bottom		Total	
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	24	631.4721	238	1	190	1	2	1.41
3	72	1894.416	388	150	205	16	166	117.21
5	120	3157.361	425	187	214	25	212	149.69
13	312	8209.138	489	251	236	47	298	210.42
28	672	17681.22	512	274	243	54	328	231.60
38	912	23995.94	575	337	245	56	393	277.50
45	1080	28416.25	616	378	250	61	439	309.98
56	1344	35362.44	694	456	252	63	519	366.47
79	1896	49886.3	754	516	252	63	579	408.83
87	2088	54938.08	825	587	250	61	648	457.55
91	2184	57463.97	912	674	250	61	735	518.98
124	2976	78302.55	1057	819	268	79	898	634.08
148	3552	93457.88	1087	849	268	79	928	655.26
188	4512	118716.8	1148	910	278	89	999	705.39

Type II, 20⁰C

Load applied = 1, 900 lb (pipe 22)

		Vertical top		Vertical bottom		Total	
Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
24	24	55	1	372	1	2	2.00
144	144	340	285	235	138	423	423.00
216	216	460	405	224	149	554	554.00
384	384	490	435	218	155	590	590.00
456	456	492	437	208	165	602	602.00
576	576	498	443	198	175	618	618.00
648	648	503	448	195	178	626	626.00
936	936	532	477	191	182	659	659.00
984	984	536	481	187	186	667	667.00
1152	1152	545	490	181	192	682	682.00
1344	1344	570	515	174	199	714	714.00
1512	1512	577	522	168	205	727	727.00
1728	1728	581	526	164	209	735	735.00
1920	1920	588	533	158	215	748	748.00
2112	2112	595	540	152	221	761	761.00
2328	2328	608	553	144	229	782	782.00
2472	2472	620	565	142	231	796	796.00
2856	2856	628	573	140	233	806	806.00
3024	3024	635	580	140	233	813	813.00
3216	3216	635	580	137	236	816	816.00
3576	3576	635	580	136	237	817	817.00
3816	3816	645	590	132	241	831	831.00
4440	4440	647	592	130	243	835	835.00
5136	5136	651	596	128	245	841	841.00
5400	5400	655	600	128	245	845	845.00
5952	5952	658	603	126	247	850	850.00
6240	6240	660	605	126	247	852	852.00
6480	6480	690	635	124	249	884	884.00
7608	7608	710	655	124	249	904	904.00
8832	8832	728	673	120	253	926	926.00

Type II, 20^{0}C

Load applied = 3, 700 lb (pipe 19)

		Vertical top		Vertical bottom		Total	
Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
24	24	420	1	375	1	2	2.00
144	144	480	60	360	-15	45	45.00
216	216	586	166	359	-16	150	150.00
384	384	642	222	359	-16	206	206.00
456	456	646	226	357	-18	208	208.00
576	576	654	234	357	-18	216	216.00
648	648	655	235	356	-19	216	216.00
936	936	683	263	356	-19	244	244.00
984	984	684	264	355	-20	244	244.00
1152	1152	693	273	355	-20	253	253.00
1344	1344	719	299	355	-20	279	279.00
1512	1512	727	307	354	-21	286	286.00
1728	1728	735	315	354	-21	294	294.00
1920	1920	734	314	353	-22	292	292.00
2112	2112	740	320	352	-23	297	297.00
2328	2328	748	328	352	-23	305	305.00
2472	2472	757	337	351	-24	313	313.00
2856	2856	763	343	351	-24	319	319.00
3024	3024	770	350	350	-25	325	325.00
3216	3216	778	358	350	-25	333	333.00
3576	3576	791	371	350	-25	346	346.00
3816	3816	796	376	348	-27	349	349.00
4440	4440	812	392	348	-27	365	365.00
5136	5136	818	398	348	-27	371	371.00
5400	5400	890	470	346	-29	441	441.00
5952	5952	910	490	344	-31	459	459.00
6240	6240	925	505	342	-33	472	472.00
6480	6480	945	525	335	-40	485	485.00
7608	7608	965	545	325	-50	495	495.00
8832	8832	984	564	321	-54	510	510.00

Un-notched – continued

Type II, 20⁰C

Load applied = 5, 600 lb (pipe 18)

		Vertical top		Vertical bottom		Total	
Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
24	24	130	1	232	-16	-15	-15.00
144	144	330	201	225	-23	178	178.00
216	216	416	287	223	-25	262	262.00
384	384	416	287	223	-25	262	262.00
456	456	418	289	221	-27	262	262.00
576	576	422	293	213	-35	258	258.00
648	648	426	297	210	-38	259	259.00
936	936	445	316	214	-34	282	282.00
984	984	450	321	211	-37	284	284.00
1152	1152	453	324	208	-40	284	284.00
1344	1344	472	343	206	-42	301	301.00
1512	1512	474	345	205	-43	302	302.00
1728	1728	478	349	204	-44	305	305.00
1920	1920	478	349	200	-48	301	301.00
2112	2112	481	352	199	-49	303	303.00
2328	2328	484	355	197	-51	304	304.00
2472	2472	492	363	195	-53	310	310.00
2856	2856	492	363	193	-55	308	308.00
3024	3024	493	364	191	-57	307	307.00
3216	3216	503	374	191	-57	317	317.00
3576	3576	508	379	189	-59	320	320.00
3816	3816	510	381	189	-59	322	322.00
4440	4440	524	395	189	-59	336	336.00
5136	5136	524	395	189	-59	336	336.00
5400	5400	536	407	189	-59	348	348.00
5952	5952	590	461	189	-59	402	402.00
6240	6240	605	476	189	-59	417	417.00
6480	6480	650	521	189	-59	462	462.00
7608	7608	845	716	189	-59	657	657.00
8832	8832	945	816	185	-63	753	753.00

Un-notched – continued

Type II, 40⁰C

Load applied = 5, 600 lb (pipe 5)

Vertical top			Vertical bottom			Total		
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Defl.*b_T
1	24	212.311	425	1	205	1	2	2.52
2	48	424.623	505	80	195	-10	70	88.28
3	72	636.934	508	83	190	-15	68	85.76
4	96	849.245	510	85	188	-17	68	85.76
5	120	1061.56	512	87	186	-19	68	85.76
9	216	1910.8	520	95	86	-19	76	95.85
13	312	2760.05	630	205	186	-19	186	234.57
17	408	3609.29	658	233	175	-30	203	256.01
22	528	4670.85	665	240	172	-33	207	261.05
26	624	5520.1	673	248	168	-37	211	266.10
30	720	6369.34	689	264	164	-41	223	281.23
36	864	7643.21	710	285	142	-63	222	279.97
40	960	8492.45	765	340	137	-68	272	343.02
44	1056	9341.7	788	363	135	-70	293	369.51
48	1152	10190.9	790	365	125	-80	285	359.42
54	1296	11464.8	805	380	108	-97	283	356.90
57	1368	12101.7	800	375	108	-97	278	350.59
64	1536	13587.9	808	383	105	-100	283	356.90
67	1608	14224.9	811	386	103	-102	284	358.16
72	1728	15286.4	812	387	103	-102	285	359.42
75	1800	15923.4	816	391	102	-103	288	363.20
87	2088	18471.1	826	401	100	-105	296	373.29
89	2136	18895.7	830	405	100	-105	300	378.34
96	2304	20381.9	830	405	100	-105	300	378.34
104	2496	22080.4	848	423	100	-105	318	401.04
111	2664	23566.6	850	425	100	-105	320	403.56
120	2880	25477.4	852	427	98	-107	320	403.56
128	3072	27175.9	855	430	98	-107	323	407.34
136	3264	28874.3	860	435	95	-110	325	409.86
145	3480	30785.1	866	441	95	-110	331	417.43
151	3624	32059	868	443	93	-112	331	417.43
167	4008	35456	881	456	86	-119	337	425.00
174	4176	36942.2	880	455	64	-141	314	395.99
182	4368	38640.7	888	463	82	-123	340	428.78
197	4728	41825.3	900	475	80	-125	350	441.39
207	4968	43948.4	904	479	72	-133	346	436.35
214	5136	45434.6	907	482	70	-135	347	437.61
225	5400	47770.1	912	487	70	-135	352	443.91
248	5952	52653.2	925	500	70	-135	365	460.31
260	6240	55201	930	505	65	-140	365	460.31
270	6480	57324.1	937	512	65	-140	372	469.14
317	7608	67302.7	957	532	55	-150	382	481.75
368	8832	78130.6	978	553	52	-153	400	504.45

Un-notched – continued

Type II, 50^{0}C

Load applied = 1, 900 lb (pipe 1)

Vertical top			Vertical bottom			Total		
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	137	3604.65	275	1	217	1	2	1.41
3	140	3683.59	290	15	214	-3	12	8.47
5	207	5446.45	308	33	213	-4	29	20.48
13	220	5788.49	331	56	210	-7	49	34.60
28	247	6498.9	350	75	208	-9	66	46.60
38	290	7630.29	365	90	208	-9	81	57.19
45	317	8340.69	383	108	207	-10	98	69.20
56	360	9472.08	400	125	210	-7	118	83.32
79	427	11234.9	408	133	217	0	133	93.91
87	450	11840.1	434	159	217	0	159	112.27
91	458	12050.6	467	192	216	-1	191	134.86
101	2424	63778.7	485	210	215	-2	208	146.87
148	3552	93457.9	527	252	215	-2	250	176.52
162	3888	102298	578	303	217	0	303	213.95
188	4512	118717	603	328	218	1	329	232.31

Type II, 50^{0}C

Load applied = 5, 600 lb (pipe 7)

Vertical top			Vertical bottom			Total		
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	24	631.472	340	1	192	1	2	1.41
3	72	1894.42	540	201	205	14	215	151.81
5	120	3157.36	627	288	210	19	307	216.77
13	312	8209.14	709	370	212	21	391	276.08
28	672	17681.2	798	459	215	24	483	341.05
38	912	23995.9	878	539	220	29	568	401.06
45	1080	28416.2	924	585	222	31	616	434.96
56	1344	35362.4	979	640	224	33	673	475.20
79	1896	49886.3	1024	685	230	39	724	511.22
87	2088	54938.1	1069	730	235	44	774	546.52
91	2184	57464	1120	781	235	44	825	582.53
101	2424	63778.7	1150	811	240	49	860	607.25
129	3096	81459.9	1187	848	245	54	902	636.90
148	3552	93457.9	1240	901	257	66	967	682.80
188	4512	118717	1310	971	263	72	1043	736.46

Notched

Type I, 40⁰C

Load applied = 5, 600 lb (pipe 11)

Vertical top			Vertical bottom			Total		
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	24	212.311	250	1	245	1	2	2.52
6	144	1273.87	382	132	228	-16	116	146.29
9	216	1910.8	395	145	217	-27	118	148.81
16	384	3396.98	470	220	215	-29	191	240.87
19	456	4033.92	472	222	212	-32	190	239.61
24	576	5095.47	485	235	204	-40	195	245.92
27	648	5732.41	495	245	202	-42	203	256.01
39	936	8280.14	535	285	195	-49	236	297.62
41	984	8704.77	538	288	192	-52	236	297.62
48	1152	10190.9	549	299	189	-55	244	307.71
56	1344	11889.4	589	339	183	-61	278	350.59
63	1512	13375.6	596	346	177	-67	279	351.85
72	1728	15286.4	607	357	170	-74	283	356.90
80	1920	16984.9	608	358	128	-116	242	305.19
88	2112	18683.4	617	367	122	-122	245	308.97
97	2328	20594.2	623	373	122	-122	251	316.54
103	2472	21868.1	633	383	121	-123	260	327.89
119	2856	25265.1	642	392	118	-126	266	335.46
126	3024	26751.2	648	398	118	-126	272	343.02
134	3216	28449.7	665	415	117	-127	288	363.20
149	3576	31634.4	672	422	116	-128	294	370.77
159	3816	33757.5	676	426	116	-128	298	375.81
185	4440	39277.6	704	454	116	-128	326	411.13
214	5136	45434.6	710	460	116	-128	332	418.69
225	5400	47770.1	710	460	115	-129	331	417.43
248	5952	52653.2	796	546	108	-136	410	517.06
260	6240	55201	840	590	108	-136	454	572.55
270	6480	57324.1	850	600	105	-139	461	581.38
317	7608	67302.7	860	610	103	-141	469	591.47
368	8832	78130.6	865	615	100	-144	471	593.99

Notched -continued

Type I, 50^{0}C

Load applied = 5, 600 lb (pipe 9)

Vertical top			Vertical bottom			Total		
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	24	631.472	185	1	792	1	2	1.41
3	72	1894.42	320	135	793	2	137	96.74
5	120	3157.36	380	195	794	3	198	139.81
13	312	8209.14	420	235	794	3	238	168.05
28	672	17681.2	475	290	798	7	297	209.71
38	912	23995.9	525	340	798	7	347	245.02
45	1080	28416.2	578	393	800	9	402	283.85
56	1344	35362.4	625	440	802	11	451	318.45
79	1896	49886.3	685	500	802	11	511	360.82
87	2088	54938.1	725	540	804	13	553	390.47
91	2184	57464	780	595	804	13	608	429.31
101	2424	63778.7	840	655	806	15	670	473.09
140	3360	88406.1	1071	886	807	16	902	636.90
148	3552	93457.9	1180	995	810	19	1014	715.98
188	4512	118717	1220	1035	815	24	1059	747.76

Type II, 20⁰C

Load applied = 5, 600 lb (pipe 15)

		Vertical top		Vertical bottom		Total	
Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
24	24	215	1	287	0	1	1.00
144	144	520	305	278	-9	296	296.00
216	216	538	323	277	-10	313	313.00
384	384	560	345	270	-17	328	328.00
456	456	562	347	268	-19	328	328.00
576	576	568	353	267	-20	333	333.00
648	648	573	358	262	-25	333	333.00
936	936	605	390	260	-27	363	363.00
984	984	608	393	260	-27	366	366.00
1152	1152	620	405	259	-28	377	377.00
1344	1344	646	431	251	-36	395	395.00
1512	1512	654	439	249	-38	401	401.00
1728	1728	660	445	249	-38	407	407.00
1920	1920	667	452	247	-40	412	412.00
2112	2112	677	462	247	-40	422	422.00
2328	2328	690	475	244	-43	432	432.00
2472	2472	704	489	244	-43	446	446.00
2856	2856	718	503	239	-48	455	455.00
3024	3024	728	513	237	-50	463	463.00
3216	3216	728	513	237	-50	463	463.00
3576	3576	737	522	237	-50	472	472.00
3816	3816	750	535	237	-50	485	485.00
4440	4440	750	535	237	-50	485	485.00
5136	5136	766	551	237	-50	501	501.00
5400	5400	790	575	235	-52	523	523.00
5952	5952	830	615	234	-53	562	562.00
6240	6240	830	615	232	-55	560	560.00
6480	6480	850	635	229	-58	577	577.00
7608	7608	1087	872	227	-60	812	812.00
8832	8832	1110	895	224	-63	832	832.00

Notched -continued

Type II, 20⁰C

Load applied = 5, 600 lb (pipe 16)

		Vertical top		Vertical bottom		Total	
Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
24	24	55	1	373	1	2	2.00
144	144	340	285	228	-144	141	274.00
216	216	460	405	224	-148	257	381.00
384	384	490	435	218	-154	281	405.00
456	456	492	437	208	-164	273	397.00
576	576	498	443	198	-174	269	393.00
648	648	503	448	195	-177	271	395.00
936	936	532	477	191	-181	296	420.00
984	984	536	481	187	-185	296	420.00
1152	1152	545	490	181	-191	299	423.00
1344	1344	570	515	174	-198	317	441.00
1512	1512	577	522	168	-204	318	442.00
1728	1728	581	526	164	-208	318	442.00
1920	1920	588	533	158	-214	319	443.00
2112	2112	595	540	152	-220	320	444.00
2328	2328	608	553	144	-228	325	449.00
2472	2472	620	565	142	-230	335	459.00
2856	2856	628	573	140	-232	341	465.00
3024	3024	635	580	140	-232	348	472.00
3216	3216	635	580	137	-235	345	469.00
3576	3576	635	580	136	-236	344	468.00
3816	3816	645	590	132	-240	350	474.00
4440	4440	647	592	130	-242	350	474.00
5136	5136	651	596	128	-244	352	476.00
5400	5400	655	600	128	-244	356	480.00
5952	5952	658	603	126	-246	357	481.00
6240	6240	660	605	126	-246	359	483.00
6480	6480	690	635	124	-248	387	511.00
7608	7608	861	806	124	-248	558	682.00
8832	8832	928	873	120	-252	621	745.00

Notched -continued

Type II, 40^0C

Load applied = 5, 600 lb (pipe 25)

Vertical top			Vertical bottom			Total		
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	24	212.311	190	1	330	1	2	2.52
6	144	1273.87	328	138	315	-30	108	136.20
9	216	1910.8	365	175	319	-26	149	187.91
16	384	3396.98	435	245	319	-26	219	276.19
19	456	4033.92	440	250	317	-28	222	279.97
24	576	5095.47	462	272	317	-28	244	307.71
27	648	5732.41	470	280	316	-29	251	316.54
39	936	8280.14	525	335	316	-29	306	385.90
41	984	8704.77	530	340	315	-30	310	390.95
48	1152	10190.9	553	363	315	-30	333	419.95
56	1344	11889.4	594	404	315	-30	374	471.66
63	1512	13375.6	608	418	314	-31	387	488.05
72	1728	15286.4	624	434	314	-31	403	508.23
80	1920	16984.9	639	449	313	-32	417	525.89
88	2112	18683.4	656	466	312	-33	433	546.06
97	2328	20594.2	682	492	312	-33	459	578.85
103	2472	21868.1	700	510	311	-34	476	600.29
119	2856	25265.1	735	545	311	-34	511	644.43
126	3024	26751.2	752	562	310	-35	527	664.61
134	3216	28449.7	768	578	310	-35	543	684.79
149	3576	31634.4	794	604	310	-35	569	717.58
159	3816	33757.5	794	604	308	-37	567	715.05
185	4440	39277.6	794	604	308	-37	567	715.05
214	5136	45434.6	820	630	308	-37	593	747.84
225	5400	47770.1	840	650	306	-39	611	770.54
248	5952	52653.2	865	675	304	-41	634	799.55
260	6240	55201	910	720	302	-43	677	853.78
270	6480	57324.1	915	725	295	-50	675	851.26
317	7608	67302.7	940	750	285	-60	690	870.17
368	8832	78130.6	960	770	281	-64	706	890.35

Notched -continued

Type II, 50⁰C

Load applied = 5, 600 lb (pipe 10)

Vertical top			Vertical bottom			Total		
Days	Hours	Time*a_T	Dial gage	Value	Dial gage	Value	Vert. Defl.	Deflection*b_T
1	24	631.472	340	1	192	1	2	1.41
3	72	1894.42	540	200	205	14	214	151.11
5	120	3157.36	627	287	210	19	306	216.07
13	312	8209.14	709	369	212	21	390	275.38
28	672	17681.2	798	458	215	24	482	340.34
38	912	23995.9	878	538	220	29	567	400.36
45	1080	28416.2	924	584	222	31	615	434.25
56	1344	35362.4	979	639	224	33	672	474.50
79	1896	49886.3	1024	684	230	39	723	510.51
87	2088	54938.1	1069	729	235	44	773	545.81
91	2184	57464	1120	780	235	44	824	581.83
101	2424	63778.7	1150	810	240	49	859	606.54
129	3096	81459.9	1187	847	245	54	901	636.20
148	3552	93457.9	1240	900	257	66	966	682.09
188	4512	118717	1310	970	263	72	1042	735.76

5.1.2.1 Bi-directional plot for Type I-NM

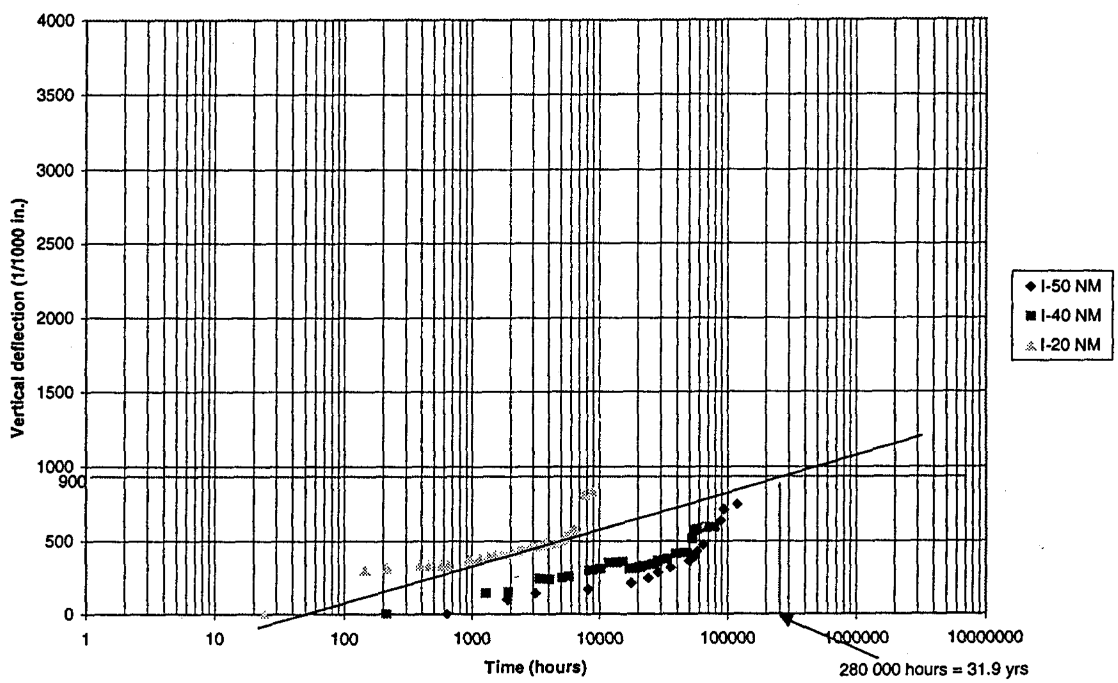


Fig. 5.7 Master curve, based on the Bi-directional method for Type I- Notched-

M=5,600lb.

Assuming proper installation conditions, the life prediction for Type I specimen, notched, under the maximum loading (5,600 lb), is 31.9 years.

5.1.2.2 Bi-directional plot for Type I-UM

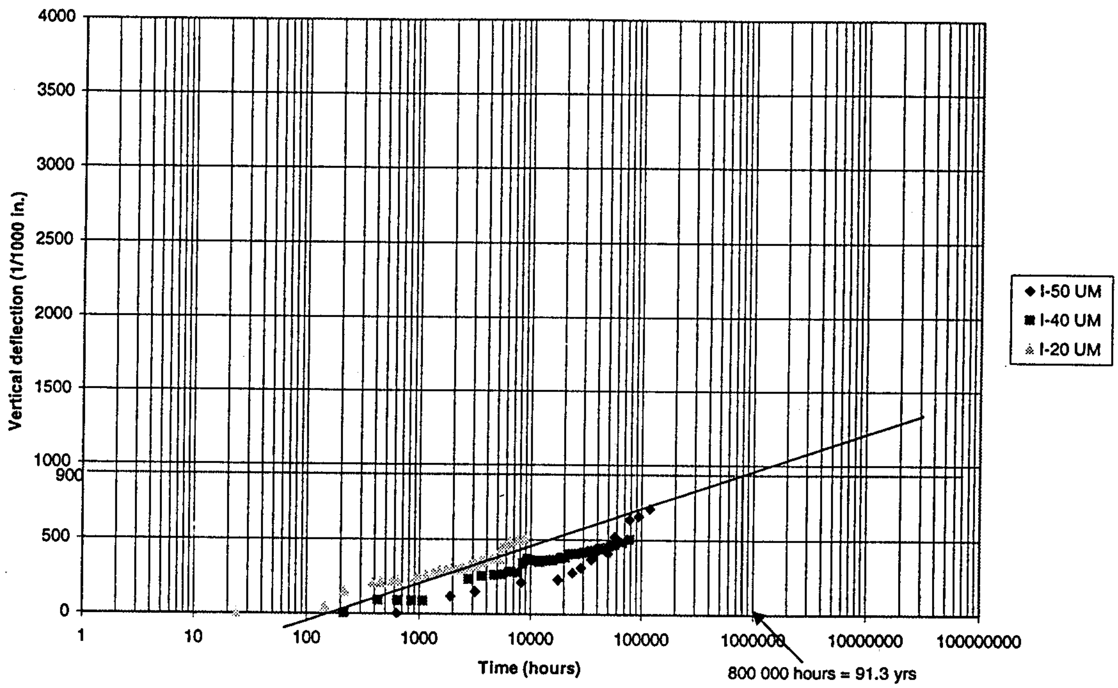


Fig. 5.8 Master curve, based on the Bi-directional method for Type I- Unnotched-M=5,600lb.

Assuming proper installation conditions, the life prediction for Type I specimen, unnotched, under the maximum loading (5,600 lb), is 91.3 years.

5.1.2.3 Bi-directional plot for Type I-U1/3

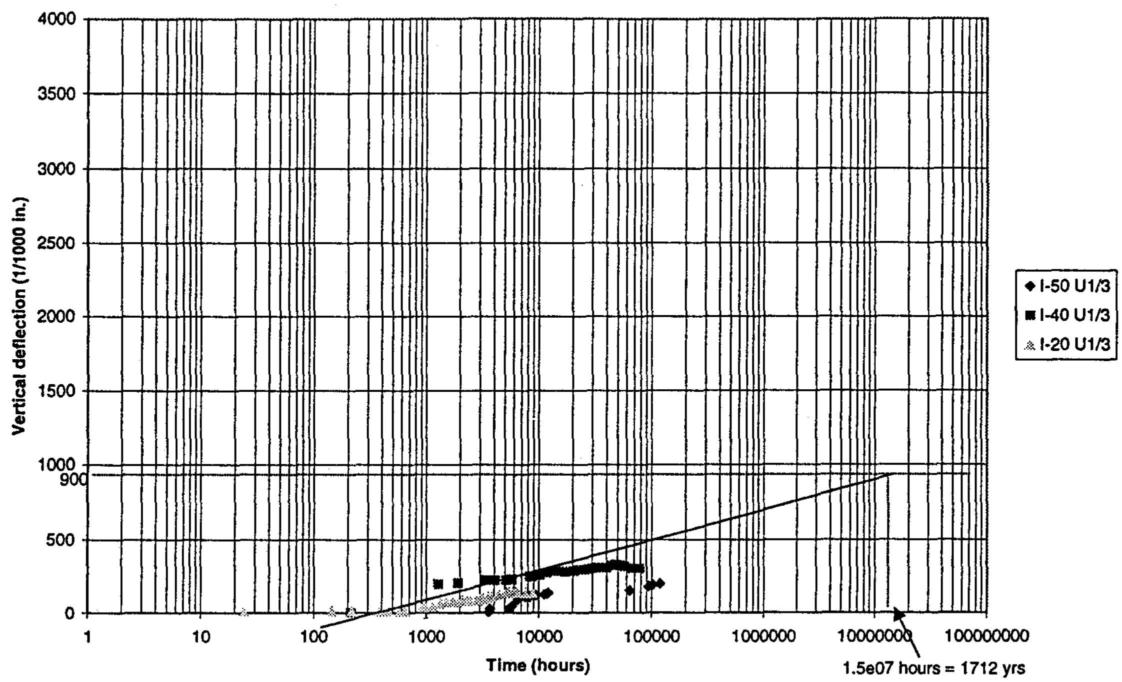


Fig. 5.9 Master curve, based on the Bi-directional method for Type I- Notched-M=1,900lb.

Assuming proper installation conditions, the life prediction for Type I specimen, unnotched, less than 1/3 of the maximum loading (1,900 lb), is 1,712 years.

5.1.2.4 Bi-directional plot for Type II-NM

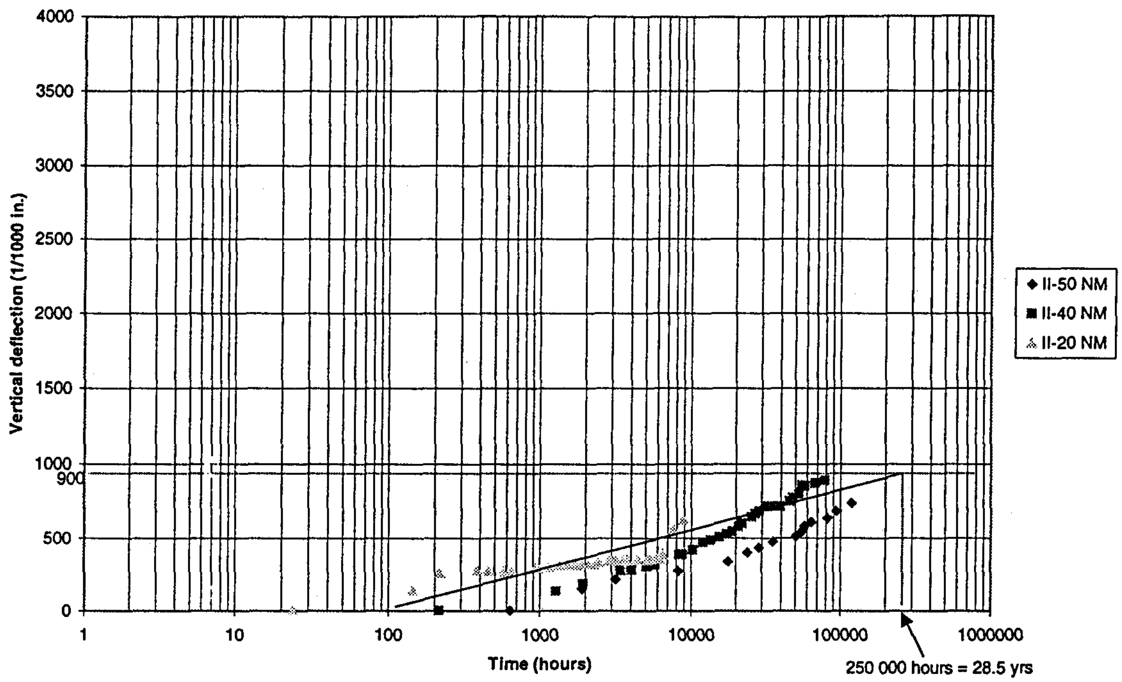


Fig. 5.10 Master curve, based on the Bi-directional method for Type II- Notched-M=5,600lb.

Assuming proper installation conditions, the life prediction for Type II specimen, notched, under the maximum loading (5,600 lb), is 28.5 years.

5.1.2.5 Bi-directional plot for Type II-UM

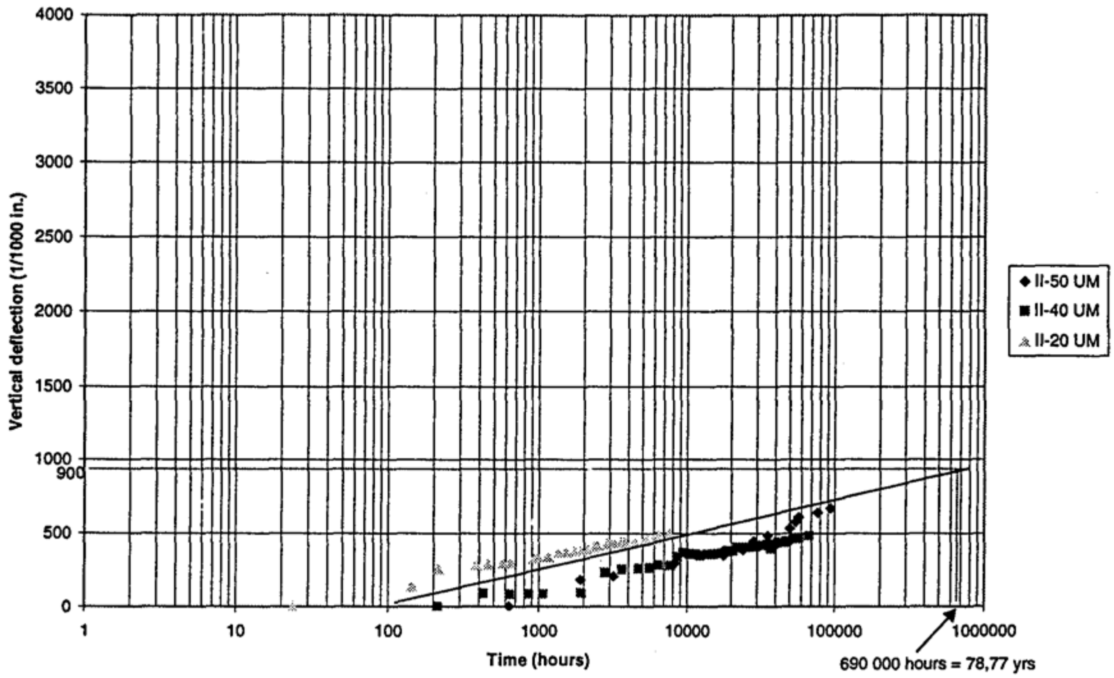


Fig. 5.11 Master curve, based on the Bi-directional method for Type II- Unnotched-M=5,600lb.

Assuming proper installation conditions, the life prediction for Type II specimen, unnotched, under the maximum loading (1,900 lb), is 78.7 years.

5.1.2.6 Bi-directional plot for Type II-U1/3

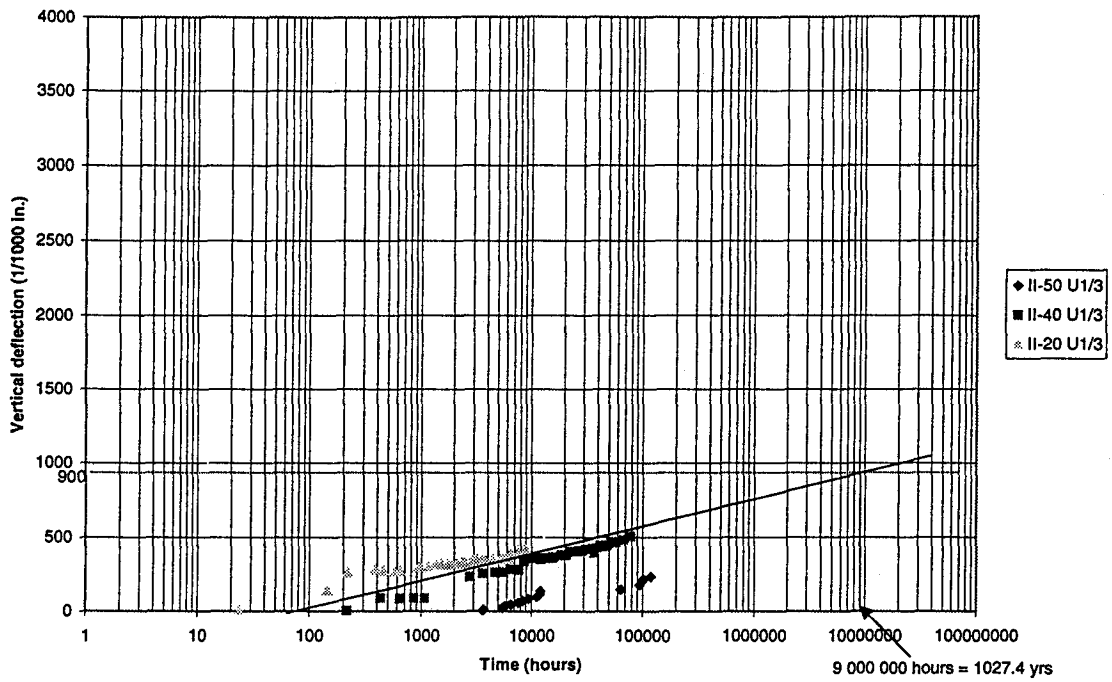


Fig. 5.12 Master curve, based on the Bi-directional method for Type II- Unnotched-

M=1,900lb.

Assuming proper installation conditions, the life prediction for Type II specimen, unnotched, less than 1/3 of the maximum loading (1,900 lb), is 1,027.4 years.

5.1.3. Comparison of the Arrhenius and the Bi-directional Methods

Type of specimen	Life prediction with Arrhenius equation	Life prediction with Bi-directional method
I-NM	32.6 yrs.	31.9 yrs.
I-UM	81.5 yrs.	91.3 yrs.
I-U1/3	1,141 yrs.	1,712 yrs.
II-NM	25.4 yrs.	28.5 yrs.
II-UM	76.1 yrs.	78.7 yrs.
II-U1/3	1,130 yrs.	1,027.4 yrs.

Both the Arrhenius and the Bi-directional methods provide similar results, with the Arrhenius equation being more conservative.

5.2. CANDE Analysis

5.2.1. General information

The finite-element program CANDE, a proven software for soil-structure interaction analyses of buried conducts, is used with established design criteria to achieve the design objective, which are the minimum cover requirements for corrugated plastic pipe.

CANDE, an acronym for culvert analysis and design, was developed especially for the structural design and analysis of buried conduits. Both the pipe and the surrounding soil envelope are incorporated into an incremental, static, plane strain formulation. The pipe was modeled with a connected sequence of beam-column elements, and the soil was modeled with continuum elements by using a revised linear viscoelastic soil model. The fundamental analysis assumptions are small deformation theory, linear elastic polyethylene properties (short-term) and a bonded pipe-soil interface.

The gravity loading of the soil is applied in the first load step for the analysis of each pipe-soil system with a specified minimum cover. Next, the H-truck rear wheel loading, as defined in Table 5.1, is simulated by applying increments of pressure to the soil surface over a 10 in. segment (i.e. footprint width) centered directly above the pipe. Only one rear wheel of the H-truck vehicle needs to be considered, because the other wheels are too far away (at least 6 feet, Fig.3.4) to add to the local deformation of the pipe under the wheel considered.

Table 5.1 H-Truck Loading on Rear Tire

Truck Type	Gross Wt. (kips)	Rear Tire Wt. (kips)	Tire length (in.)	Tire width (in.)
H10	20	8	10	8
H15	30	12	10	12
H20	40	16	10	16
H25	50	20	10	20
H30	60	24	10	24

Tire (single or dual) pressure = 100 psi

H-Truck load representation

Since CANDE is a two-dimensional plane strain formulation, the footprint length in Fig. 5.13 can be modeled exactly. However, plane strain analysis infers that the footprint width is infinitely deep, as illustrated on the right side of the Fig. 5.13. To reasonably simulate a finite footprint width as pictured in the left side of Fig. 5.13, the plane strain pressure P_S should be appropriately reduced from that of the actual tire footprint pressure P_t, that is,

$$P_S = {}_r Pt \text{---} (5.1)$$

where r is a reduction factor (less than 1.0). This reduction is required because the soil stress associated with Pt diminishes more rapidly with depth than does the soil stress associated with PS (i.e. two-dimensional load spreading versus one-dimensional load spreading).

To compute the reduction factor, use is made of an exact elasticity solution for a homogenous half space (no pipe) loaded by the pressure P_t acting on a rectangular footing with dimensions 2L by 2b.

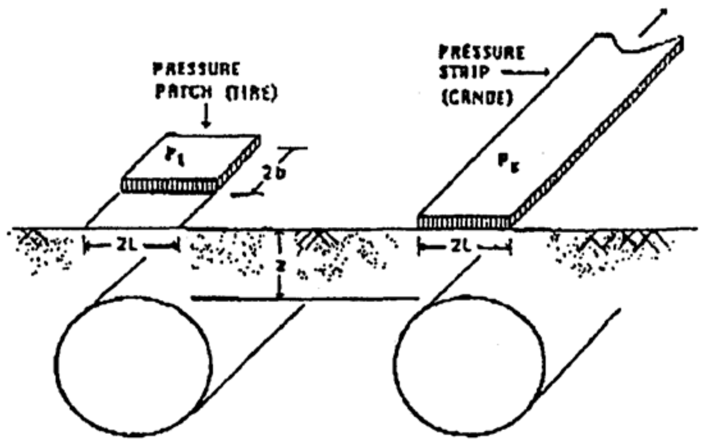


Fig. 5.13 H-truck loading and tire pressure distribution

<u>Soil model</u>

All design cases are analyzed for two soil conditions generically called "fair" and "good" quality soils. Specifically, those two cases are represented by some linear elastic soil models for silty clayey sand at 85 percent compaction (fair=SC85) and silty clayey sand at 100 percent compaction (good=SC100).

The details of node numbering for the pipe modeling are presented in Fig. 5.14.

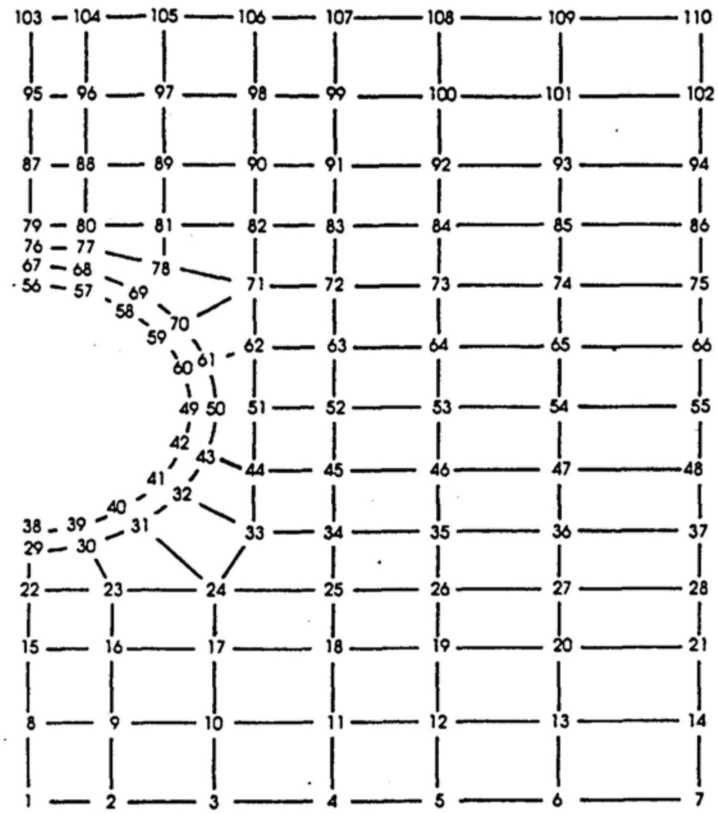


Fig. 5.14 Details of node numbering

5.2.2. CANDE results

CANDE cannot take account of non-uniform longitudinal soil properties and compaction. The backfill modulus can vary along the pipe because the degree of saturation and the density of backfill soil change with time [Drumm et al., 1997].

The distribution loading is expressed as a Fourier's series, Appendix C for the CANDE solution and along the tank is as shown in Figure 5.15.

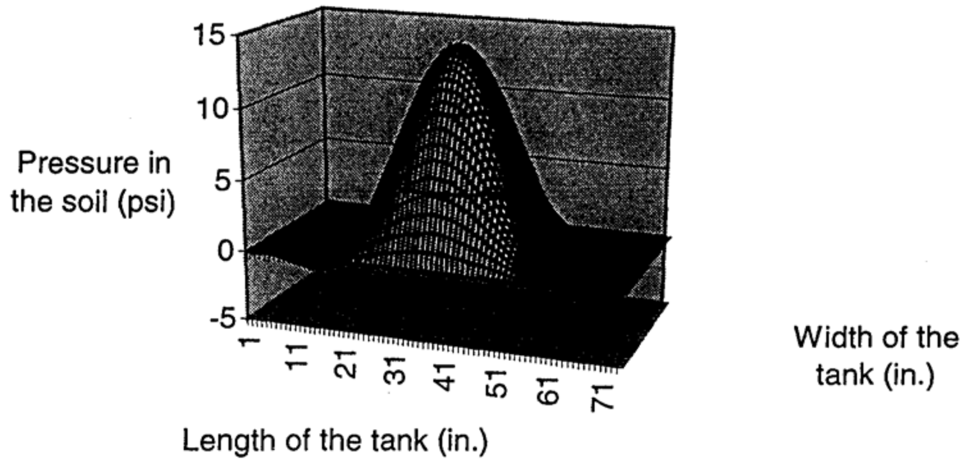


Figure 5.15 Representation of the distribution loading

For each abscissa (x-axis, length of the pipe) and ordinate (y-axis, diameter of the pipe) the loading pressure on the pipe through the soil is defined. The precision can be increased by using more terms in the Fourier series but the number of terms used is adequate for realistic simulation of the loading. The CANDE methodology incorporates the soil mass along with the structure into an incremental, static, plane-strain boundary value problem, which is solved by a user selected solution level. CANDE has three solution levels corresponding to successive increases in analytical power and modeling detail.

Level 1 is the most restrictive but simplest to use. It is based on a closed form, plane strain solution fort a circular conduit in elastic half-space. Levels 2 and 3 are much more versatile. These levels are based in a two-dimensional setting. Level 2 contains a completely automated mesh generation routine suitable for most of the typical culvert installations and pipe shapes. Included are generators for circular, elliptical, rectangular and arch geometry. Thus, no special knowledge of finite element mesh is required by user for this level. Level 3, which is applicable to arbitrary soil-structure configurations such as non-symmetric installations and miscellaneous shapes, can provide a more general solution than the other levels. However, it requires the user to have knowledge of finite techniques in order to prepare and input the mesh topology of the soil-structure system. The solution level concept permits the user to choose the degree of rigor and effort commensurate with the worth of a particular project and the confidence in the system input variables. For a designer, this means CANDE is not only available to perform a quick, approximate design for input into a feasibility study. It can also be used as a rigorous analytical tool in the detail design phase. For the analyst, it offers extended flexibility in performing parametric studies and comparative research.

One of the main problems in the use of this software is that CANDE 89 is twodimensional software. In this way, we cannot get the deflections along the length of the pipe directly. CANDE 89 gives the deflection of a ring of the pipe at a given abscissa. Typically if a pipe is 80 inches long, CANDE89 needs to be run at 80 successive longitudinal locations at one inch spacing to get a realistic deflected profile.

Finally in CANDE 89, the loading is selected across the cross-section for a given abscissa above the soil on the nodes from 103 to 110 as shown in Fig.5.16. A uniform loading is defined for each element by taking the averages for the CANDE 89 input.

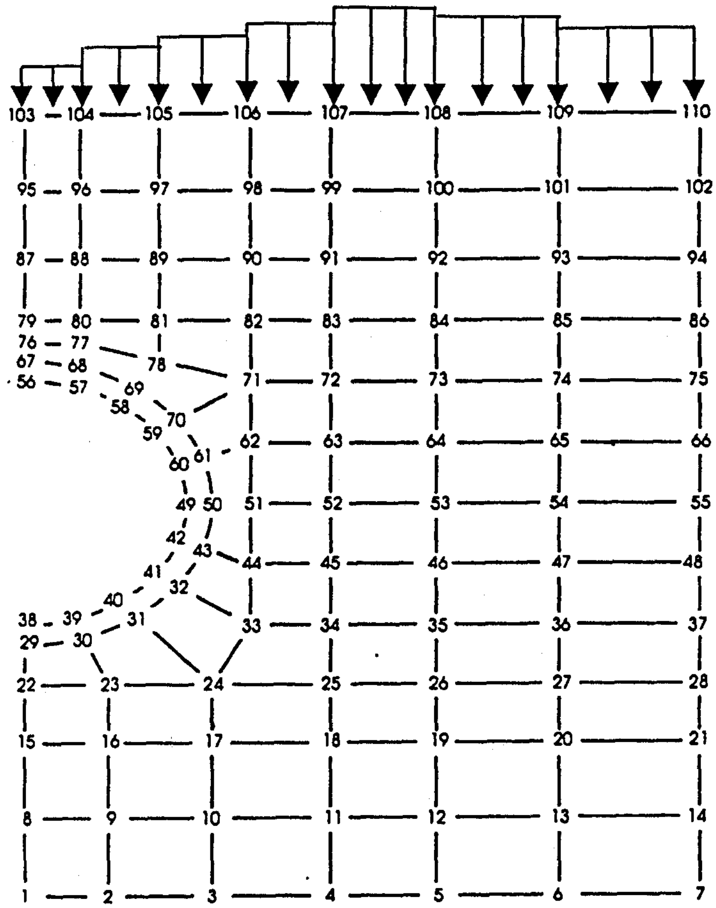


Figure 5.16 The distribution loading

The deflection value of 5600 lb is compared with the experimental value in Table 5.2 by using this approximation.

APPENDIX C

Fourier Simulation of Loading

The sinusoidal load distribution is given by the equation below.

$$q = q_0 \sin\frac{m\pi x}{a}\sin\frac{n\pi y}{b}$$

It can be seen in Fig. 5.17 the view of the footprint on the tank with the different parameters.

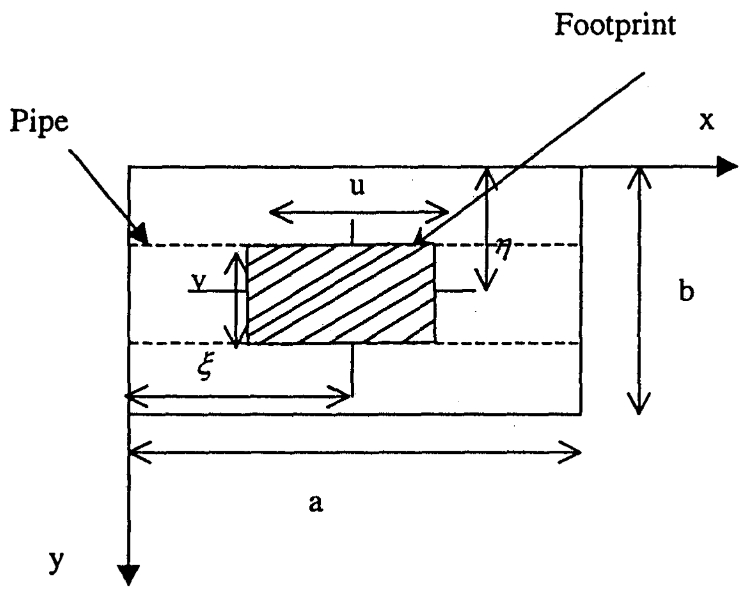


Figure 5.17. Parameters for the distribution loading calculus

Where:

$a = 72''$
$b = 36''$
$\xi = 36''$
$\eta = 18''$
$u = 24''$
$v = 10''$
$P = 5600 Lb$

$$q = f(x,y) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} a_{mn} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b}$$

$$\text{with } a_{mn} = \frac{16P}{\pi^2 mnuv}.\sin\frac{m\pi\zeta}{a}.\sin\frac{n\pi\eta}{b}.\sin\frac{m\pi u}{2a}.\sin\frac{n\pi v}{2b}$$

$$\int_S q = \int_S f(x,y) = \iint_S \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} a_{mn} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b} dxdy$$

$$q = f(x,y) = \sum_{m=1}^{\infty}\left[a_{m1} \sin\frac{m\pi y}{72}.\sin\frac{\pi y}{36} + a_{m2.}.\sin\frac{m\pi x}{144}.\sin\frac{\pi y}{36}\right]$$

$$q = f(x,y) = \underbrace{a_{11} \sin\frac{\pi y}{72}.\sin\frac{\pi y}{36}}_{I} + \underbrace{a_{12} \sin\frac{\pi y}{36}.\sin\frac{\pi y}{18}}_{II} + \underbrace{a_{21.}.\sin\frac{\pi x}{36}.\sin\frac{\pi y}{36}}_{III} + \underbrace{a_{22.}.\sin\frac{\pi x}{36}.\sin\frac{\pi y}{18}}_{IV}$$

$$+ \underbrace{a_{13} \sin\frac{\pi y}{72}.\sin\frac{\pi y}{12}}_{V} + \underbrace{a_{31} \sin\frac{\pi y}{24}.\sin\frac{\pi y}{36}}_{VI} + \underbrace{a_{23} \sin\frac{\pi y}{36}.\sin\frac{\pi y}{12}}_{VII} + \underbrace{a_{32} \sin\frac{\pi y}{24}.\sin\frac{\pi y}{18}}_{VIII} + \underbrace{a_{33} \sin\frac{\pi y}{24}.\sin\frac{\pi y}{12}}_{IX}$$

Let's calculate the different terms I to IX.

$$a_{11} = \frac{16*5600}{\pi^2*24*10*1*1}.\underbrace{\sin\frac{18\pi}{36}}_{1}.\underbrace{\sin\frac{36\pi}{72}}_{1}.\underbrace{\sin\frac{24\pi}{144}}_{\frac{1}{2}}.\underbrace{\sin\frac{10\pi}{72}}_{0.4226}$$

$$a_{11} = 7.99$$

$$a_{12} = \frac{16*5600}{\pi^2*24*10*2*1}.\underbrace{\sin\frac{36\pi}{72}}_{1}.\underbrace{\sin\frac{36\pi}{36}}_{0}.\underbrace{\sin\frac{24\pi}{144}}_{\frac{1}{2}}.\underbrace{\sin\frac{20\pi}{72}}_{0.766}$$

$$a_{12} = 0$$

$$a_{21} = \frac{16*5600}{\pi^2*24*10*1*2}.\underbrace{\sin\frac{72\pi}{72}}_{0}.\underbrace{\sin\frac{18\pi}{36}}_{1}.\underbrace{\sin\frac{48\pi}{144}}_{\frac{\sqrt{3}}{2}}.\underbrace{\sin\frac{10\pi}{72}}_{0.4226}$$

$a_{21} = 0$

$$a_{22} = \frac{16*5600}{\pi^2*24*10*2*2}.\underbrace{\sin\frac{72\pi}{72}}_{0}.\underbrace{\sin\frac{36\pi}{36}}_{0}.\underbrace{\sin\frac{48\pi}{144}}_{\frac{\sqrt{3}}{2}}.\underbrace{\sin\frac{20\pi}{72}}_{0.766}$$

$a_{22} = 0$

$$a_{13} = \frac{16*5600}{\pi^2*24*10*1*3}.\underbrace{\sin\frac{36\pi}{72}}_{1}.\underbrace{\sin\frac{54\pi}{36}}_{-1}.\underbrace{\sin\frac{24\pi}{144}}_{\frac{1}{2}}.\underbrace{\sin\frac{30\pi}{72}}_{0.966}$$

$a_{13} = -6.1$

$$a_{31} = \frac{16*5600}{\pi^2*24*10*3*1}.\underbrace{\sin\frac{108\pi}{72}}_{-1}.\underbrace{\sin\frac{18\pi}{36}}_{1}.\underbrace{\sin\frac{72\pi}{144}}_{1}.\underbrace{\sin\frac{10\pi}{72}}_{0.4226}$$

$a_{31} = -5.33$

$$a_{23} = \frac{16*5600}{\pi^2*24*10*2*3}.\underbrace{\sin\frac{72\pi}{72}}_{0}.\underbrace{\sin\frac{54\pi}{36}}_{-1}.\underbrace{\sin\frac{48\pi}{144}}_{\frac{\sqrt{3}}{2}}.\underbrace{\sin\frac{36\pi}{72}}_{1}$$

$a_{23} = 0$

$$a_{32} = \frac{16*5600}{\pi^2*24*10*3*2}.\underbrace{\sin\frac{108\pi}{72}}_{-1}.\underbrace{\sin\frac{36\pi}{36}}_{0}.\underbrace{\sin\frac{72\pi}{144}}_{1}.\underbrace{\sin\frac{20\pi}{72}}_{0.766}$$

$a_{32} = 0$

$$a_{33} = \frac{16*5600}{\pi^2*24*10*3*3}.\underbrace{\sin\frac{108\pi}{72}}_{-1}.\underbrace{\sin\frac{54\pi}{36}}_{-1}.\underbrace{\sin\frac{72\pi}{144}}_{1}.\underbrace{\sin\frac{30\pi}{72}}_{0.966}$$

$a_{33} = 4.06$

So, it can be written that:

$$q = \underbrace{a_{11}\sin\frac{\pi x}{36}.\sin\frac{\pi y}{72}}_{I} + \underbrace{a_{13}\sin\frac{\pi x}{36}.\sin\frac{3\pi y}{72}}_{V} + \underbrace{a_{31}\sin\frac{\pi x}{12}.\sin\frac{\pi y}{72}}_{VI} + \underbrace{a_{33}\sin\frac{\pi x}{12}.\sin\frac{3\pi y}{72}}_{ix}$$

$$\int_S q = LIVE \quad LOAD$$

$$I = \int_0^a\int_0^b a_{11}\sin.\frac{\pi x}{36}.\sin\frac{\pi y}{72}dxdy = a_{11}.\int_0^{36}\sin\frac{\pi x}{36}.\left[\frac{-\cos\frac{\pi y}{72}}{\frac{\pi}{72}}\right]_0^{72} dx$$

$$I = \frac{144.a_{11}}{\pi}.\left[\frac{-\cos\frac{\pi x}{36}}{\frac{\pi}{36}}\right]_0^{36} = \frac{144.a_{11}}{\pi} * \frac{2*36}{\pi}$$

$$I = 8397Lb$$

$$II = 0$$

$$III = 0$$

$$IV = 0$$

$$VII = 0$$

$$VIII = 0$$

$$V = \int_0^a\int_0^b a_{13}\sin.\frac{\pi x}{36}.\sin\frac{3\pi y}{72}dxdy = a_{13}.\int_0^{36}\sin\frac{\pi x}{36}.\left[\frac{-\cos\frac{3\pi y}{72}}{\frac{3\pi}{72}}\right]_0^{72} dx$$

$$V = \frac{48.a_{13}}{\pi}.\left[\frac{-\cos\frac{\pi x}{36}}{\frac{\pi}{36}}\right]_0^{36} = \frac{48.a_{13}}{\pi} * \frac{2*36}{\pi}$$

$$V = -2132Lb$$

$$VI = \int_0^a \int_0^b a_{31} \sin .\frac{\pi x}{12} .\sin \frac{\pi y}{72} dxdy = a_{31} . \int_0^{72} \sin \frac{\pi x}{12} . \underbrace{\left[\frac{-\cos \frac{\pi y}{72}}{\frac{\pi}{72}} \right]_0^{36}}_{0} dx$$

$$VI = 0$$

$$IX = \int_0^a \int_0^b a_{33} \sin .\frac{\pi x}{12} .\sin \frac{3\pi y}{72} dxdy = a_{33} . \int_0^{36} \sin \frac{3\pi x}{72} . \underbrace{\left[\frac{-\cos \frac{\pi y}{12}}{\frac{\pi}{12}} \right]_0^{72}}_{0} dx$$

$$IX = 0$$

$$\int_S q = 6265Lb$$

The integration of the sinusoidal function we found gives 6265lb for a live load given of 5600lb (11200lb on two footprints). It means an error of 11.8%.

CHAPTER 6

INVESTIGATION of JOINTED PIPE

In this chapter, jointed pipes were investigated both experimentally and numerically to determine the deflection, stress and bending moment values. The pipes used in the experiment and the mounted dial gages are shown in Figs. 6.1 and 6.2, and the strain gages in Figs. 6.3 and 6.4.

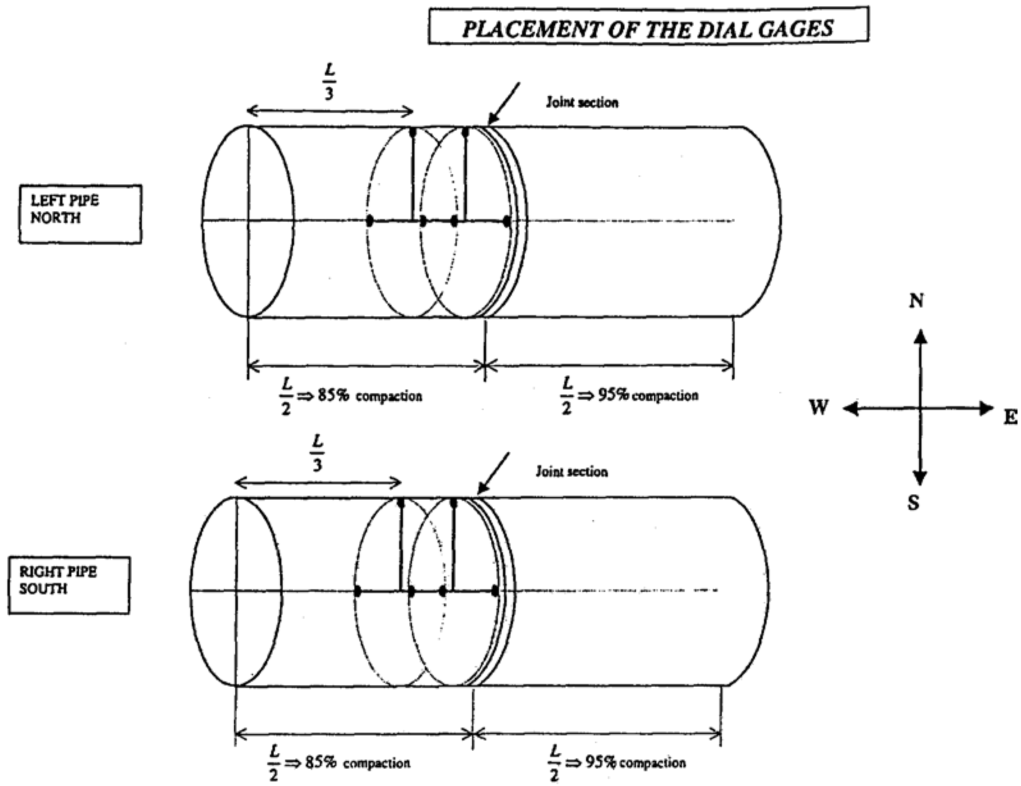


Figure 6.1 Position of dial gages

There are two series of three dial gages. One set of three was placed at the third of the pipe, and the other set at the mid-section of the pipe. Each series was composed three dial gages. Two were placed horizontally (diametrically opposed) and the other vertically (orientated to the top).

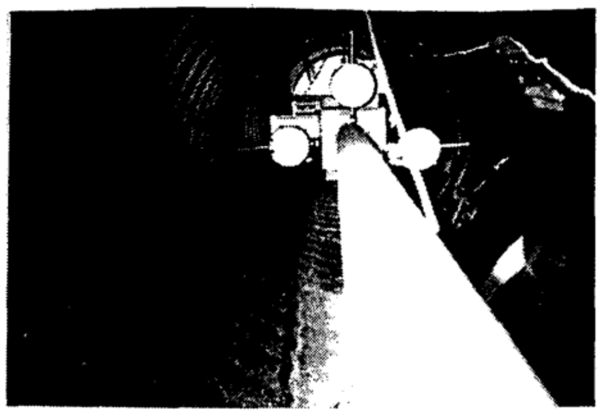


Figure 6.2 Dial gages inside a pipe

The top dial gage measures the vertical deflection and the side dial gages the lateral deflections of the pipe.

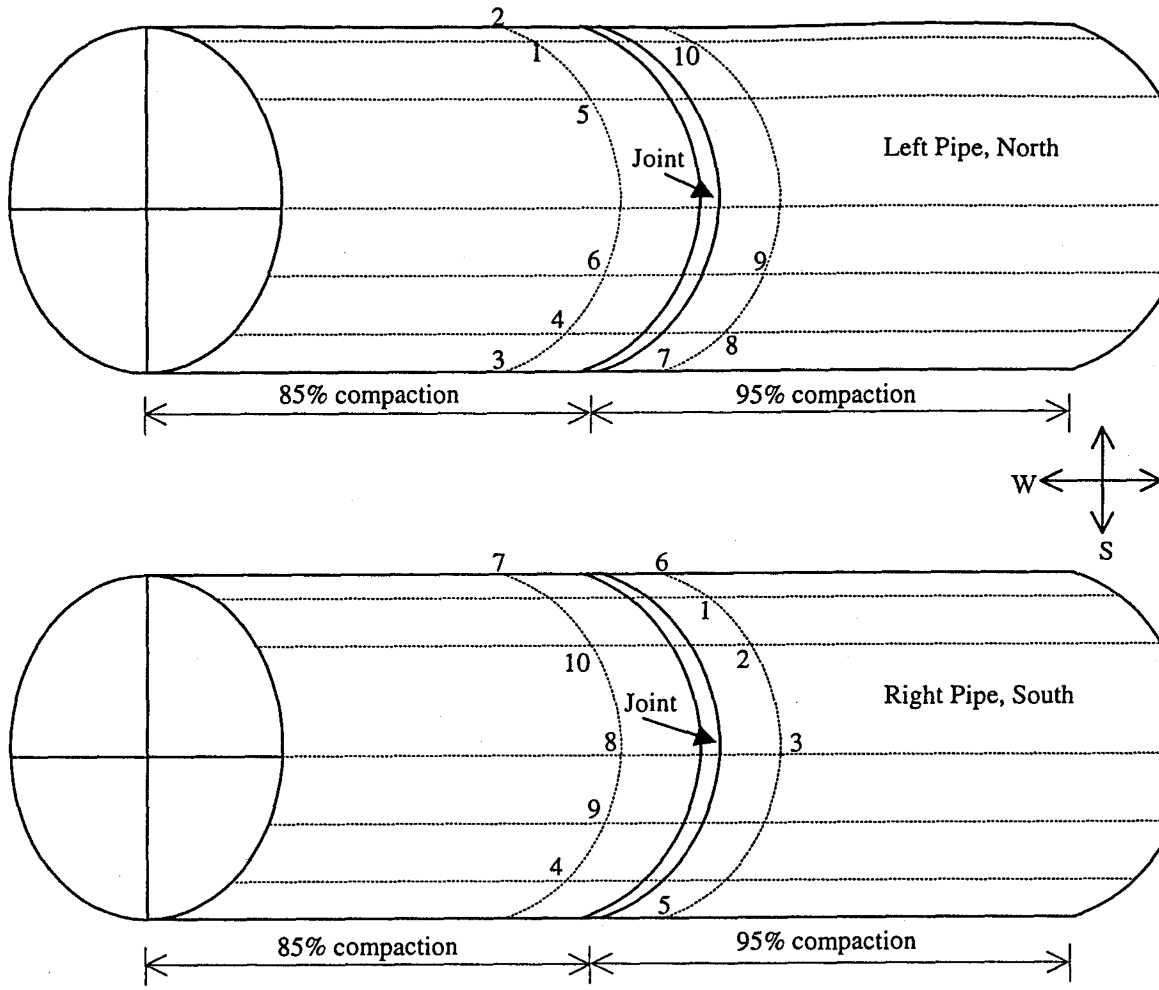


Figure 6.3 Position of the strain gages on the pipe

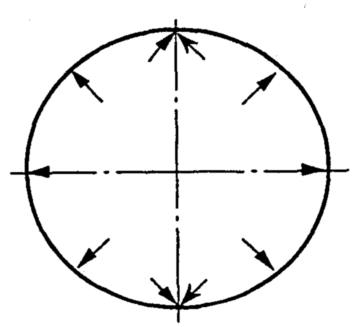


Figure 6.4 Position of the strain gages on the section

Node points, which correspond to the strain-gages are given below.

	Left Pipe	
No	**Node**	**Type**
1	58	Longitudinally
2	56	Circumferentially
3	38	Circumferentially
4	39	Longitudinally
5	59	Longitudinally
6	41	Circumferentially
7	38	Circumferentially
8	39	Longitudinally
9	41	Circumferentially
10	58	Longitudinally

	Right Pipe	
No	**Node**	**Type**
1	58	Longitudinally
2	59	Longitudinally
3	49	Circumferentially
4	39	Longitudinally
5	38	Longitudinally
6	56	Circumferentially
7	56	Circumferentially
8	49	Longitudinally
9	41	Circumferentially
10	59	Circumferentially

The data are given in Appendix D.

APPENDIX D

Deflection and strain values for jointed pipe

Deflections(1/1000in.)

JOINTED PIPE – 20^0C – Left pipe (North) – load 5600 lb

Date	Days	Hours	Top deflection	Right deflection	Left deflection	Top deflection	Right deflection	Left deflection
8/12	0	12	320	220	305	30	341	517
10/12	2	48	320	233	303	223	314	507
14/12	6	144	335	228	295	330	314	503
17/12	9	216	345	228	295	340	308	506
22/12	14	336	355	232	294	352	304	506
25/12	17	408	338	225	288	338	308	511
28/12	20	480	355	218	285	402	305	507
2/1	25	600	368	209	274	418	302	500
7/1	30	720	377	210	268	423	298	500
11/1	34	816	378	209	265	419	295	501
13/01	36	864	380	209	266	410	294	503
20/01	43	1032	391	205	266	426	291	504
1/22	45	1080	391	208	266	410	291	505
1/25	48	1152	393	210	267	410	291	505
1/28	51	1224	390	205	262	408	289	505
2/1	55	1320	413	203	258	452	289	500
2/3	57	1368	418	203	256	460	288	500
2/10	64	1536	406	204	258	419	286	505
2/12	66	1584	415	202	256	440	286	502
2/15	69	1656	425	198	250	473	284	498
2/17	71	1704	412	198	248	435	282	500
2/22	76	1824	412	199	248	435	282	500
2/24	78	1872	410	192	248	438	282	499
2/29	83	1992	418	192	246	435	282	499
3/2	85	2040	415	192	246	436	281	500
3/8	91	2184	407	190	245	410	277	500
3/9	92	2208	410	186	250	390	277	500
3/14	97	2328	415	188	257	397	277	500
3/16	99	2376	432	186	240	444	276	498
3/21	104	2496	460	178	232	427	285	505
3/23	106	2544	450	178	232	498	285	507
3/29	112	2688	465	171	232	540	288	505
3/30	113	2712	475	171	225	555	310	505
4/4	118	2832	470	166	221	523	310	505
4/6	120	2880	469	165	220	587	308	507
4/12	126	3024	505	162	216	575	308	501
4/13	127	3048	511	165	216	584	307	500
4/18	132	3168	520	160	210	568	291	497
4/20	134	3216	516	160	209	561	295	495
4/25	139	3336	520	154	205	554	290	495
4/27	141	3384	514	155	205	534	290	498
5/1	145	3480	508	152	205	521	291	498
5/4	148	3552	515	154	203	535	290	498
5/9	153	3672	519	150	200	535	289	498

JOINTED PIPE – 20^0C – Left pipe (North) – load 5600 lb - continued

5/11	155	3720	529	149	200	556	289	496
5/16	160	3840	537	148	197	560	295	496
5/18	162	3888	531	148	198	548	286	496
5/23	167	4008	534	147	195	551	285	495
5/25	169	4056	538	145	195	550	285	495
5/30	174	4176	540	145	192	552	285	495
6/1	176	4224	545	145	192	565	285	495
6/6	181	4344	553	145	191	570	284	495
6/8	183	4392	555	145	190	575	283	495
6/13	188	4512	566	146	190	595	282	494
6/15	190	4560	558	142	190	570	282	495
6/20	195	4680	565	137	187	561	282	495
6/22	197	4728	565	137	185	555	282	495
6/27	202	4848	579	138	182	590	281	492
6/29	204	4896	582	138	183	586	281	493
7/4	209	5016	587	138	182	592	280	490
7/10	215	5160	590	135	180	594	280	494
8/1	237	5688	592	131	178	585	273	496
8/3	239	5736	606	135	178	610	275	495
8/14	250	6000	600	133	174	598	276	493
8/16	252	6048	603	132	175	603	275	494
8/22	258	6192	600	127	174	586	274	495
8/24	260	6240	595	129	172	589	273	495
8/29	265	6360	618	133	173	612	274	93
8/31	267	6408	612	130	173	610	273	94
9/8	275	6600	620	129	171	615	274	93
9/14	281	6744	602	125	169	594	274	93
9/21	288	6912	625	122	168	523	270	94
9/26	293	7032	618	125	167	591	267	98
10/5	302	7248	560	130	163	573	267	108
10/10	307	7368	545	102	191	571	300	138
10/12	309	7416	541	95	192	568	310	142
10/17	314	7536	539	106	198	553	310	137
10/19	316	7584	541	99	196	579	311	135
10/26	323	7752	540	95	196	564	309	138
11/6	334	8016	546	95	194	551	308	137
12/4	362	8688	562	98	190	585	304	136

JOINTED PIPE – 20^0C – Left pipe (North) – load 5600 lb - continued

Date	Days	Hours	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5	Gage 6	Gage 7	Gage 8	Gage 9	Gage 10
8/12	0	12	-2773	-1990	-436	-1920	-420	-515	-580	550	-950	-620
10/12	2	48	-2850	-1960	-580	-1940	-500	-660	-700	860	-1115	-750
14/12	6	144	-2585	-1600	-210	-1720	-270	-430	-470	1300	-910	-520
17/12	9	216	-2585	-1620	-470	-1720	-260	-443	-435	1860	-940	-520
22/12	14	336	-2310	-1280	60	-1520	120	-50	10	2200	-240	-270
25/12	17	408	-3790	-2810	-1770	-2730	-1160	-1370	-1090	970	-2080	-2130
28/12	20	480	-3000	-1690	-1220	-1950	-610	-1300	-560	2400	1110	-1080
2/1	25	600	-2800	-1870	-630	-2120	-570	-850	-100	3060	-650	-900
7/1	30	720	-2620	-1920	-430	-2160	-410	-380	-90	3190	353	-960
11/1	34	816	-2643	-1825	-410	-2100	-310	-240	-45	4275		-919
13/01	36	864	-2715	-1780	-550	-2050	-330	-380	-50	6075		-999
20/01	43	1032	-2767	-1730	-700	-1995	-320	-600	20	1411		-1050
1/22	45	1080	-3250	-2172	-850	-2297	-700	-970	-550	1350	-1390	-1683
1/25	48	1152	-3609	-2500	-1000	-2411	-872	-1289	-900	6150	-950	-2000
1/28	51	1224	-3700	-1931	-1150	-2140	-700	-1300	-140		760	-1460
2/1	55	1320	-2691	-1767	-1300	-2040	-410	-675	920		540	-1015
2/3	57	1368	-2505	-1534	-1450	-1883	-270	-520	679		1420	-770
2/10	64	1536	-3348	-2240	-1600	-2270	-870	-1200	-120		450	-1880
2/12	66	1584	-2910	-1725	-1750	-2190	-610	-485	210		520	-1495
2/15	69	1656	-2712	-2047	-1900	-2142	-515	-400	520		650	-1209
2/17	71	1704	-2822	-2100	-2050	-2256	-600	-340	823		729	-1285
2/22	76	1824	-2840	-2000	-2200	-2175	-575	-310	840			-1210
2/24	78	1872	-2728	-1926	185	-2100	-530	-290	850			-1197
2/29	83	1992	-2779	-2100	50	-2240	-550	-102	1010			-1241
3/2	85	2040	-2827	-1997	-150	-2190	-600	-260	940			-1250
3/8	91	2184	-2780	-2037	-20	-2257	-582	-41	992			-1217
3/9	92	2208	-2757	-2085	-127	-2380	-589	8	700			-1330
3/14	97	2328	-2920	-2227	128	-2280	-634	-67	886	5373		-1300
3/16	99	2376	-2488	-1720	416	-2136	-383	210	240	3820		-909
3/21	104	2496	-1972	-1430	980	-1064	-300	1320	1710			-370
3/23	106	2544	-2510	-1985	279	-1645	-285	993	1068	6261		-1005
3/29	112	2688	-2945	-2293	-510	-2780	-962	433	614			-1500
3/30	113	2712	-2661	-2023	361	-1892	-520	550	612			-1142
4/4	118	2832	-2747	-2333		-2270	-860	2468	797			-3484
4/6	120	2880	-3100	-2460	-440	-2200	-728	774	152			-1852
4/12	126	3024	-1269	-620	-524	-2597	-803	2592	574			-1654
4/13	127	3048	-2121	-1347	654	-1282	42	1508	1127			-824
4/18	132	3168	-2977	-2454	75	-1907	-252	1314	97			-1812
4/20	134	3216	-2789	-1928	-102	-1792	-317	1189	-1109			-1414

JOINTED PIPE – 20^0C – Left pipe (North) – load 5600 - continued

4/25	139	3336		-2514	-28	-2340	-629	1215	1919			-977
4/27	141	3384	-2907	-2249	-156	-2103	-495	1274	1107			-1642
5/1	145	3480	-2962	-2284	-153	-2126	-595	1237	6587			-1630
5/4	148	3552	-2996	-2531	-131	-2022	-521	1291	9860			-1554
5/9	153	3672	-2556	-1979	-410	-2794	-660	3253	9590			-3288
5/11	155	3720	-2577	-2000	-490	-1841	-170	1649	8471			-1061
5/16	160	3840	-2435	-1795	636	-1780	-138	1731	15825	15972		-1036
5/18	162	3888	-2670	-2052	786	-1857	-267	1609	4452			-1190
5/23	167	4008	-2354	-1640	2502	-1649	-56	1867	4195			-940
5/25	169	4056	-3160	-2034	2344	-2034	-401	1511	11624			-1130
5/30	174	4176	-2379	-1873	2518	-1858	-152	1918	3915			-965
6/1	176	4224	-2219	-1581	2779	-1569	44	1950	4340			-902
6/6	181	4344	-2242	-1734	398	-1665	5	1941	4424			-903
6/8	183	4392	-2354	-1691	600	-1644	-63	1857	5459			-1002
6/13	188	4512	-2193	-1510		-1357	734	1890	6312			-786
6/15	190	4560	-2276	-1727	1011	-1700	-46	1880	5396			-956
6/20	195	4680	-2403	-1957	940	-1907	-168	2073	4866			-1099
6/22	197	4728	-2360	-1910	1017	-1882	-140	2134	5543			-1021
6/27	202	4848	-2078	-1418	1328	-1429	190	2357	11330			-702
6/29	204	4896	-2225	-1612	1235	-1600	50	2237	12000			-835
7/4	209	5016	-2215	-1612	-255	-1538	84	2182	2674		-588	-831
7/10	215	5160	-2181	-1554	456	-1547	115	2266	3563		401	-864
8/1	237	5688	-2322	-1890	2296	-1745	32	2340	9226			-967
8/3	239	5736	-300	5400	3600	500	2200	4300				1500
8/14	250	6000	-600	-85	3300	100	2200	4800				
8/16	252	6048	-760	-170	2600	-30	1630	3620			12740	220
8/22	258	6192	-2050	-1690	1020	-1620	155	2425			16840	-765
8/24	260	6240	-2120	-1630	1080	-1500	200	2490	8450			-760
8/29	265	6360	-1600	-680	1560	-600	960	3150	17310			
8/31	267	6408	-2000	-1225	1100	-1070	490	2550				-465
9/8	275	6600	-1890	-1405	1150	-1260	405	2560	14530			-550
9/14	281	6744	-2250	-1740	750	-1600	50	2420	13690			-890
9/21	288	6912	-1975	-1395	-138	-1255	410	2499	7940			-545
9/26	293	7032	-2109	-1699	-46	-1559	219	2500	6990			-507
10/5	302	7248	-1773	-961	214	-616	969	2722	12145		19884	159
10/10	307	7368	-2952	-2392	-2055	-2757	-528	1707				-1377
10/12	309	7416	-2805	-2110	-1806	-2588	-698	1723				-3145
10/17	314	7536	-1404	-931	-2105	-2868	-881	1406				-2468
10/19	316	7584	-2656	-1910	-864	-1600	-176	1789	-9562		19240	-1200
10/26	323	7752	-2712	-1642	-404	-996	320	2437	300			-
11/6	334	8016	-1026	-583	-1643	-2457	-622	3445	945			-3200
12/4	362	8688	-1595	-1038	-2207	-2865	-1139	1888	537			-3802

JOINTED PIPE – 20^0C – Right pipe (South) – load 5600 lb

Date	Days	Hours	Top deflection	Right deflection	Left deflection	Top deflection	Right deflection	Left deflection
8/12	0	12	110	347	160	346	116	232
10/12	2	48	119	342	174	346	104	232
14/12	6	144	123	341	172	347	106	231
17/12	9	216	128	343	171	350	114	232
22/12	14	336	130	343	171	352	148	232
25/12	17	408	131	341	169	350	90	226
28/12	20	480	136	343	170	354	100	240
2/1	25	600	136	341	167	350	97	234
7/1	30	720	138	337	166	349	101	231
11/1	34	816	138	338	167	350	101	234
13/01	36	864	138	338	167	350	93	234
20/01	43	1032	140	340	168	350	99	240
1/22	45	1080	140	340	168	350	99	240
1/25	48	1152	146	342	168	359	99	240
1/28	51	1224	150	342	168	359	93	240
2/1	55	1320	151	343	166	360	102	238
2/3	57	1368	151	344	166	361	102	239
2/10	64	1536	153	346	166	361	91	240
2/12	66	1584	152	349	165	361	96	234
2/15	69	1656	154	362	146	360	108	234
2/17	71	1704	152	341	162	358	85	232
2/22	76	1824	151	341	162	357	86	232
2/24	78	1872	151	342	162	356	87	236
2/29	83	1992	151	341	160	356	86	231
3/2	85	2040	150	341	160	356	86	240
3/8	91	2184	149	342	155	351	75	231
3/9	92	2208	149	340	154	352	74	230
3/14	97	2328	149	340	144	355	79	231
3/16	99	2376	150	340	155	357	89	230
3/21	104	2496	153	310	168	355	92	226
3/23	106	2544	195	290	172	360	77	225
3/29	112	2688	202	290	125	365	90	230
3/30	113	2712	204	290	125	365	97	230
4/4	118	2832	202	293	125	361	81	232
4/6	120	2880	204	288	121	360	72	231
4/12	126	3024	210	291	125	366	73	240
4/13	127	3048	210	293	126	370	6	237
4/18	132	3168	235	283	116	378	96	230
4/20	134	3216	230	280	110	374	82	235
4/25	139	3336	231	280	106	373	85	231

JOINTED PIPE – 20⁰C – Right pipe (South) – load 5600 lb - continued

4/27	141	3384	230	280	105	372	76	233
5/1	145	3480	229	279	101	369	70	230
5/4	148	3552	230	279	103	370	73	235
5/9	153	3672	230	277	100	369	74	231
5/11	155	3720	231	276	101	371	81	234
5/16	160	3840	231	276	100	375	85	235
5/18	162	3888	231	276	100	373	76	233
5/23	167	4008	230	275	100	373	80	233
5/25	169	4056	231	275	100	374	80	230
5/30	174	4176	229	272	98	370	76	232
6/1	176	4224	232	275	99	375	82	235
6/6	181	4344	234	276	98	377	86	234
6/8	183	4392	235	277	99	379	86	234
6/13	188	4512	236	279	102	383	85	2358
6/15	190	4560	235	274	101	378	84	237
6/20	195	4680	231	272	96	375	79	230
6/22	197	4728	231	271	97	374	77	230
6/27	202	4848	234	274	97	377	87	236
6/29	204	4896	236	275	98	380	87	235
7/4	209	5016	238	275	100	38/2	90	232
7/10	215	5160	238	275	97	380	89	234
8/1	237	5688	238	274	95	380	85	232
8/3	239	5736	241	261	98	386	100	235
8/14	250	6000	238	275	94	383	90	237
8/16	252	6048	241	278	95	385	91	238
8/22	258	6192	237	272	94	379	81	230
8/24	260	6240	236	272	93	377	82	233
8/29	265	6360	241	279	95	387	92	239
8/31	267	6408	241	278	95	386	95	235
9/8	275	6600	243	276	95	388	96	232
9/14	281	6744	238	271	91	378	78	233
9/21	288	6912	246	279	96	388	98	234
9/26	293	7032	219	264	70	383	85	283
10/5	302	7248	237	285	93	400		238
10/10	307	7368	242	310	124	394	94	228
10/12	309	7416	239	308	115	394	100	226
10/17	314	7536	236	308	108	390	95	266
10/19	316	7584	238	310	108	393	107	230
10/26	324	7776	239	308	109	392	103	224
11/6	335	8040	240	309	108	394	103	229
12/4	363	8712	256	314	112	402	111	230

JOINTED PIPE – 20^0C – Right pipe (South) – load 5600 lb - continued

Date	Days	Hours	Gage 1	Gage 2	Gage 3	Gage 4	Gage 5	Gage 6	Gage 7	Gage 8	Gage 9	Gage 10
8/12	0	12	380	1302	-2200	-1430	-910	-2900	-70	-620	-2600	-5880
10/12	2	48	250	1325	-2380	-1550	-1000	-3130	-70	-560	-2700	-6105
14/12	6	144	360	1600	-2220	-1360	-830	-3000	140	-270	-2600	-6050
17/12	9	216	290	1480	-2360	-1490	-880	-3160	-30	-380	-2750	-6260
22/12	14	336	390	1740	-2260	-1280	-750	-3080	180	20	-2620	-6110
25/12	17	408	-880	580	-3480	-2700	-2260	-4220	-970	-750	-3570	-6855
28/12	20	480	-160	1060	-2810	-1880	-1190	-3790	-310	-620	-3260	-6990
2/1	25	600	180	1700	-2450	-1470	-880	-3160	170	130	-2880	-6510
7/1	30	720	190	1900	-2420	-1410	-890	-3370	340	435	-2750	-6320
11/1	34	816	165	1965	-2412	-1420	-900	-3350	370	515	-2700	-6290
13/01	36	864	85	1830	-2513	-1543	-965	-3488	352	315	-2870	-6550
20/01	43	1032	-60	1652	-2594	-1620	-1010	-3660	220	221	-3060	-6760
1/22	45	1080	-550	1240	-3080	-2150	-1540	-4100	-290	-130	-3450	-7045
1/25	48	1152	-875	775	-3475	-2511	-1901	-4411	-859	-450	-3780	-7361
1/28	51	1224	-490	1060	-3150	-2100	-1380	-4240	-500	-310	-3610	-7412
2/1	55	1320	-130	1690	-2728	-1610	-940	-3750	50	220	-3200	-7000
2/3	57	1368	-70	1910	-2520	-1419	-760	-3620	160	300	-3040	-6950
2/10	64	1536	-807	940	-3421	-2401	-1650	-4000	-388	-358	-3700	-7500
2/12	66	1584	-911	1722	-3100	-2610	-1810	-3990	390	515	-3500	-6900
2/15	69	1656	-140	1880	-2700	-1575	-975	-3785	390	620	-3120	-6840
2/17	71	1704	-280	1920	-2800	-1690	-1070	-3800	390	650	-3094	-6785
2/22	76	1824	-242	1920	-2790	-1800	-1100	-3700	390	630	-2841	-6625
2/24	78	1872	-206	1920	-2765	-1640	-990	-3750	410	600	-3092	-6900
2/29	83	1992	-300	2020	-2757	-1635	-1050	-3728	470	800	-3050	-6745
3/2	85	2040	-345	1850	-2868	-1750	-1120	-3820	350	520	-3160	-6970
3/8	91	2184	-330	2030	-2824	-1747	-1080	-3745	480	830	-3055	-6810
3/9	92	2208	-335	2187	-2780	-1886	-1072	-3632	584	996	-3260	-6696
3/14	97	2328	-382	2067	-2780	-2241	-1048	-3730	473	867	-3380	-6800
3/16	99	2376	-40	2400	-2390	-1820	-709	-3450	377	1187	-3130	-6555
3/21	104	2496	-147	3581	-2300	-2030	-652	-4740	1140	1437	-3168	-6670
3/23	106	2544	-534	3311	-2804	-2628	-1064	-5140	800	1247	-3451	-6893
3/29	112	2688	-21	3760	-2270	-1928	-383	-4750	1293	1585	-3144	-6815
3/30	113	2712	8	3894	-1965	-1534	-335	-4673	1396	1717	-3080	-6750
4/4	118	2832	-269	3690	-2675	-2385	-677	-5034	1204	1722	-3270	-6921
4/6	120	2880	-404	3574	-2878	-2632	-915	-5242	1027	1750	-3394	-7034
4/12	126	3024	72	3995	-1979	-1540	-188	-4828	1562	2018	-3110	-6933
4/13	127	3048	72	3987	-1949	-1534	-220	-4916	1535	1966	-3189	-7039
4/18	132	3168	-377	3992	-2755	-2401	-670	-5497	1309	2179	-3423	-7000
4/20	134	3216	-611	3640	-2948	-2646	-940	-5734	992	1552	-3756	-7466
4/25	139	3336	-161	4303	-2496	-2109	-455	-5284	1548	2509	-3262	-6831
4/27	141	3384	-623	3806	-3031	-2747	-1010	-5703	1035	1977	-3665	-7194

JOINTED PIPE – 20^0C – Right pipe (South) – load 5600 lb - continued

5/1	145	3480	-510	3922	-2877	-2581	-833	-5588	1200	2169	-3593	-7152
5/4	148	3552	-593	3749	-2926	-2660	-965	-5695	1091	2060	-3655	-7200
5/9	153	3672	-317	4023	-2646	-2296	-643	-5391	1403	2418	-3397	-6967
5/11	155	3720	-15	4221	-2384	-1998	-379	-5184	1641	2574	-3256	-6882
5/16	160	3840	-51	4236	-2361	-1977	-382	-5128	1647	2641	-3177	-6811
5/18	162	3888	-27	4077	-2618	-2271	-627	-5357	1427	2467	-3352	-6956
5/23	167	4008	55	4190	-2422	-2602	-428	-5200	1597	2660	-3244	-6883
5/25	169	4056	-35	4364	-2324	-1925	-291	-5062	1721	2861	-3126	-6726
5/30	174	4176	-55	4360	-2411	-2019	-422	-5133	1666	2903	-3126	-6712
6/1	176	4224	-187	‘4163	-2567	-2229	-465	-5240	1466	2636	-3294	-6953
6/6	181	4344	-19	4322	-2357	-1990	-330	-5122	1625	2818	-3756	-6810
6/8	183	4392	-175	4231	-2547	-2218	-441	-5217	1482	2734	-3251	-6910
6/13	188	4512	-191	4236	-2484	-2152	-474	-5357	1364	2513	-3429	-7156
6/15	190	4560	-186	4289	-2534	-2165	-452	-5287	1504	2866	-3271	-6899
6/20	195	4680	-93	4576	-2514	-2120	-397	-5172	1675	3145	-3149	-6860
6/22	197	4728	-92	4582	-2487	-2105	-384	-5135	1680	3231	-3114	-6837
6/27	202	4848	47	4429	-2278	-1898	-209	-5301	1792	3133	-3078	-6922
6/29	204	4896	-54	4461	-2373	-2011	-295	-5157	1681	3144	-3162	-6940
7/4	209	5016	-200	4811	-2439	-2105	-364	-5273	1222	3341	-3112	-6677
7/10	215	5160	-6	4873	-2278	-1950	-234	-5123	1434	3547	-2878	-6545
8/1	237	5688	-32	5901	-2262	-1915	-222	-5105	1397	3877	-2811	-6398
8/3	239	5736	-24	5340	-2241	-1919	-223	-5179	495	3578		-6596
8/14	250	6000	-70	5300	-2281	1964	-285	-5155	-360	3728		-6491
8/16	252	6048	-194	7030	-2410	-2117	-420	-5321	-622	3507		-6680
8/22	258	6192	15	7970	-2250	-1920	-185	-5105	-270	4060		-6360
8/24	260	6240	-80	7421	-2342	-2018	-293	-5156	31	3847		-6457
8/29	265	6360	-60	6602	-2225	-1926	-258	-5173	-35	3567		-6672
8/31	267	6408	-70	7704	-2250	-1969	-242	-5214	-42	3600		-6710
9/8	275	6600	9	5700	-2207	-1882	-153	-5151	49	3938		-6559
9/14	281	6744	-157	5783	-2417	-2115	-392	-5336	-1990	3830	13630	-6578
9/21	288	6912	5	6320	-2135	-1815	-144	-5149	-1246	3967	18735	-6583
9/26	293	7032	-70	6858	-2289	-1944	-245	-5160	-8479	439	10461	-6474
10/5	302	7248	-115	5200	-2330	-1928	-310	-5495	-6850	3572	7880	-7040
10/10	307	7368	-1205	4463	-3518	-3302	-1400	-6413	-8873	3201		-7431
10/12	309	7416	-936	7470	-3165	-2874	-1020	-6165	-6533	3433		-7318
10/17	314	7536	-1096	5652	-3426	-3206	-1246	-6377	-10333	3290		-7443
10/19	316	7584	-714	6070	-2550	-2628	-829	-6081	-5994	3538		-7284
10/26	324	7776	-653	7041	-2855	-2536	-766	-5927	-7769	3813		-7094
11/6	335	8040	-519	7320	-2724	-2383	-569	-5883	-1805	3855		-7181

Experimental and CANDE Deflection and Stress Values for the jointed-pipe subjected to 5600 lb loading at the commencement of testing are given in Tables 6.1 and 6.2 for the nodal points are shown in Fig. 5.14, respectively.

Table 6.1 Comparisons of Experimental and CANDE Deflection Values for the Jointed-Pipe Subjected to 5600 lb loading at the Commencement of Testing

	Experimental values	CANDE values
Deflection value on the top of the pipe (in.)	0.346 (Right pipe), 0.030 (Left pipe)	0.08 (85% compaction), 0.025 (95% compaction)

Table 6.2 Comparisons of Experimental and CANDE Stress Values for Jointed-Pipe Subjected to 5600 lb Loading at the Commencement of Testing

			Experimental Stress Values	CANDE Stress Values
Pipe	Node	Compaction (%)		T (Thrust Stress), M (Moment Stress)
Right	38	95	-100	T=-8.1
Left	38	95	-64	M=14.1
Left	38	85	-48	T=-5.4; M=43
Left	39	95	60.5	T=-8.66; M=11
Left	39	85	-211	T=-6.64; M=32.3
Left	41	85	-56.65	T=-12.8
Right	41	85	-286	M=-21
Left	41	95	-104.5	T=-11.7; M=-60
Right	49	95	-242	T=-12.3; M=-11.6
Right	49	85	-68.2	T=-14.6; M=-27.4
Left	56	85	-219	T=-27.3
Right	56	85	-7.7	M=26.3
Right	56	95	-319	T=-5.24; M=8.8
Left	58	85	-305	T=-6.22; M=11.5
Right	58	95	-211	T=-7.1; M=44.1
Left	59	85	-46	T=-9.45; M=-6.75

It is not possible to obtain the bending moment values directly from CANDE 89. The moment that CANDE.89 gives us is a circumferential moment due to the fact that it is two-dimensional software. The simple way of calculating the longitudinal bending moment is by curve fitting the deflection values given by

CANDE 89. The values of deflection at the joint section and the adjacent left and right section are input used to define the curve for the longitudinal deflection, y. The deflection values can be expressed as a second order polynomial. The simple flexural equation below will enable the determination of the moment at the joint.

$$M = E.I.\frac{d^2 y}{dx^2} \tag{6.1}$$

The moment of inertia used is the overall pipe value at the valley section. The bending moment values are given in Table 6.3 and 6.4.

Table 6.3 Bending Moment Value for the Jointed-Pipe Subjected to 5600 lb Loading at Commencement of Testing

	Experimental Value	CANDE Value
Longitudinal Bending Moment (lb in.) at the 38 node	1429	10587

One reason for the large discrepancies in the moment values is that'strain gages are much more sensitive than dial gages because of the second derivative based on small differences in the deflections at adjacent location. The values are really dependent on the outside temperature. Therefore the values should be checked at the same hour during the day. Another source of error can be due to the subjectivity of the monitoring person. Another source of error can be due to lizards or rats that can move inside the pipes and touch the gages which changes the reference each time a gage is touched. The results would have been much more precise, if another strain gage had been placed on the outer diameter at each location. The stresses on the both sides of the pipe wall would enable the separation of the thrust and bending effects.

The principal purpose of these experiments and analytical studies were to verify if the joint was adequate to avoid leakage. As the two compactions of the sand interface at the joint, the shear stress is max at this location. Experimental study shows 143.22 and -646.8psi, at gage 2 and 10 in the south pipe at the commencement of testing, respectively. But these values reach 702.72 and -690psi during the experiment. Internal pressure of 74.5kPa(10.8psi) for initiation of leakage in the type of coupler with O-ring corresponds 707psi axial stress (ASTM D3212). It seems to be the governing failure criterion.

CHAPTER 7

THREE DIMENSIONAL FINITE ELEMENT ANALYSIS OF INTERACTION BETWEEN HDPE PIPELINE AND SOIL

This analysis describes the 3-dimensional finite element analysis of the response of HDPE pipeline buried in soil at some depth. The pipeline is of 1 feet internal diameter with a thickness of 0.129". The cover depth of soil above the pipeline is 1 feet. The length of the pipeline was taken as 6 feet. The schematic for the finite element analysis is shown below.

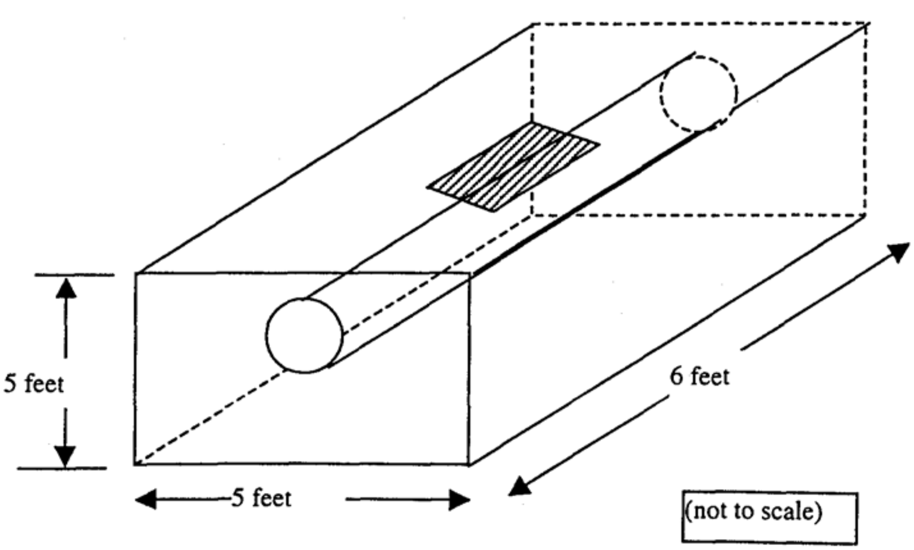


Figure 7.1. Schematic of the system considered for the FE analysis

The pipeline was subjected to a load of 5,600 lb load applied through a centrally located rigid steel channel 24" long (along the pipeline) and 10" wide (across the pipeline) as illustrated above. The analyses were performed with different Young's modulus values for the pipeline to represent its creep response with time. The long term flexural modulus values obtained based on the Bi-directional shifting method as described in the earlier sections are as follows:

Table 7.1. Flexural Modulus of HDPE at Different Times

Time (years)	Flexural modulus (psi)	
	Type I product	Type II product
0	110 psi	110 psi
25	75	78.5
50	71.9	74.5
100	69	71.8

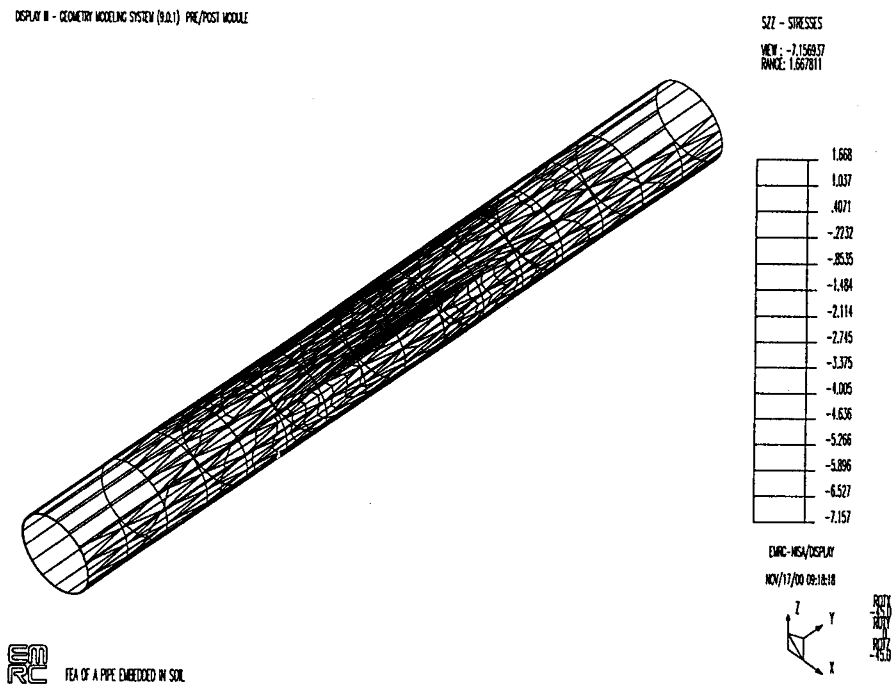
The creep response of the HDPE pipeline is approximately simulated in these analyses. The analyses were performed with the above flexural modulus values for the pipeline in the analyses to correspond to different times.

All the finite element analyses in this investigation were performed using the program Numerical Integrated Structural Analysis (NISA) developed by Engineering Mechanics Research Corporation (EMRC), Detroit, Michigan, USA. This is a commercially available general purpose finite element program for static and dynamic finite element analysis. This program has good pre and post-processors for displaying the results in a graphical form.

The analyses were performed using 20 node brick elements to represent the soil and pipeline. The 20 node brick element has quadratic variation for displacements and is a linear strain element and is suitable for simulation of problems with large variations of stresses and strains. The meshes had consisted of 2,936 number of nodes and 576 number of 20-node brick elements.

The Young's modulus and Poisson's ratio of the soil were 2000 psi and 0.30. The elastic-plastic behaviour of the soil was modelled **using Mohr-Coulomb yield condition with a friction angle (0)** of 35°. **The flexural modulus values of the pipeline material were taken as shown in Table 1. The loading of 5600 lb was applied as a uniform pressure of magnitude 23.33 psi spread over an area of 24" along the pipeline and 10" across the pipeline.**

The finite element results have not shown appreciable difference in the performance of the pipeline system with different modulus values for the pipeline. The maximum ground settlement was observed as 0.16 inches for all ,cases. The stress distribution in the pipeline was also found to be the same for all the cases of flexural modulus. This may be because of the small load intensity acting on a relatively strong foundation soil. The soil had remained in an elastic state even at the full load levels. The results from these analyses indicate that the creep response of the pipeline may not manifest as long as the soil is strong and is able to spread the loads over a wide area in the soil. Typical results are shown in the following.



DISPLAY III - GEOMETRY MODELING SYSTEM (9.0.1) PRE/POST MODULE
SZZ - STRESSES
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RANGE: 1.667811
1.668
1.037
.4071
-.2232
-.8535
-1.484
-2.114
-2.745
-3.375
-4.005
-4.636
-5.266
-5.896
-6.527
-7.157
EMRC-NISA/DISPLAY
NOV/17/00 09:18:18
Z
Y
X
ROTX
-45.0
ROTY
0
ROTZ
-45.0
FEA OF A PIPE EMBEDDED IN SOIL

DISPLAY III - GEOMETRY MODELING SYSTEM (7.0.0) PREIPOST MODULE

DISPLACED-SHAPE
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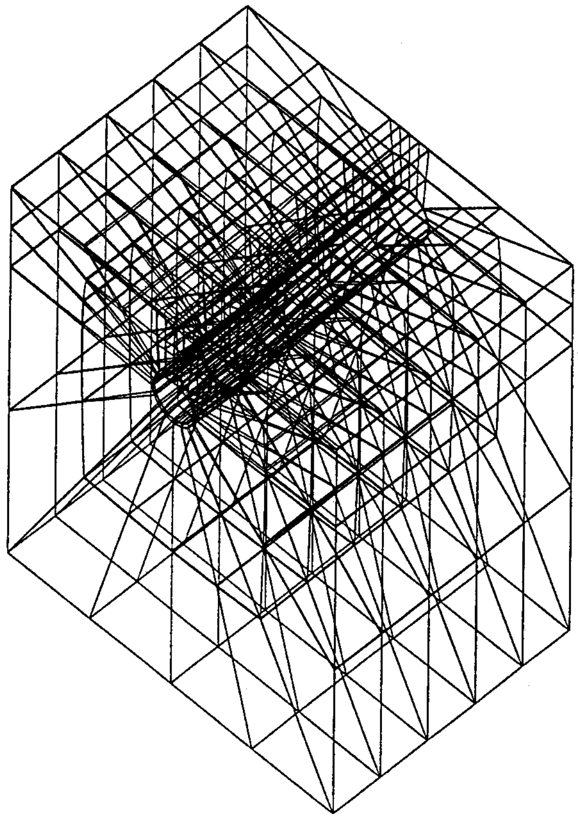
NODE NO.= 431
SCALE = 1.0 (MAPPED SCALING)



EMRC-NISA/DISPLAY
JAN/18/00 14:05:34

F3
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ROTY
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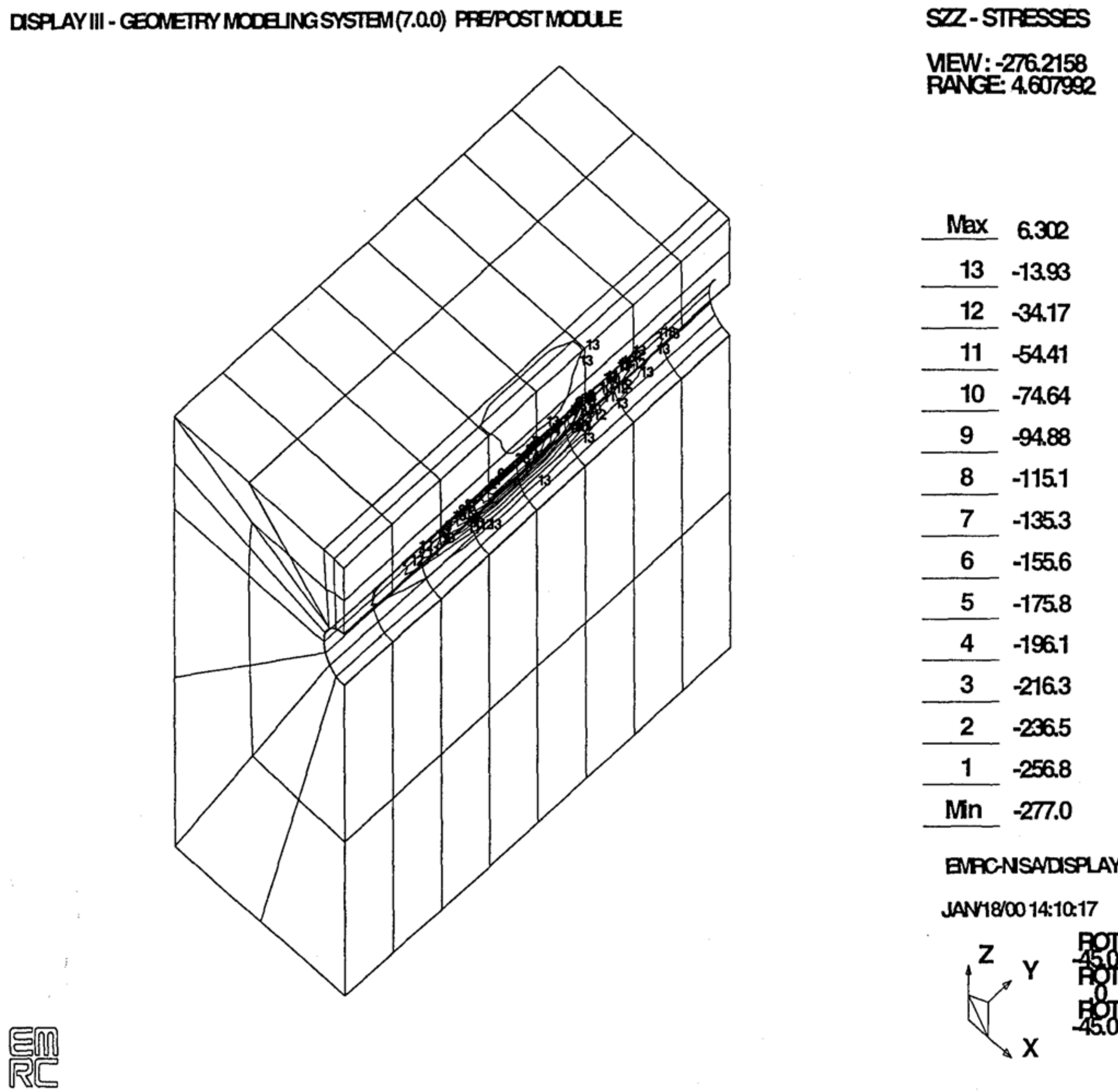
ROTZ
-45.0

RE:


DISPLAY III - GEOMETRY MODELING SYSTEM (7.0.0) PRE/POST MODULE
SZZ - STRESSES
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RANGE: 4.607992
Max 6.302
13 -13.93
12 -34.17
11 -54.41
10 -74.64
9 -94.88
8 -115.1
7 -135.3
6 -155.6
5 -175.8
4 -196.1
3 -216.3
2 -236.5
1 -256.8
Min -277.0
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Y
X
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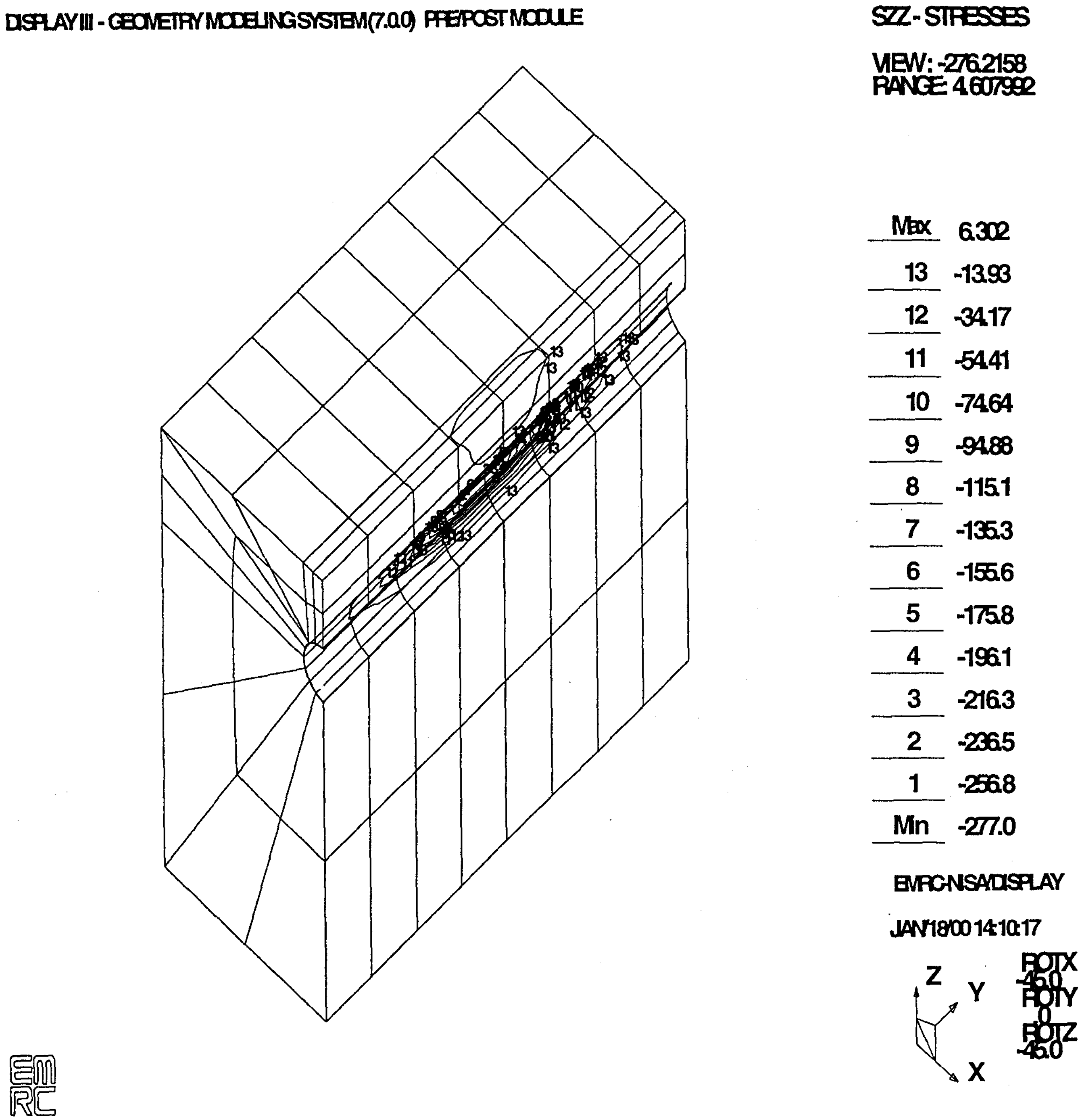
ROTY 0
ROTZ -45.0


DISPLAY III - GEOMETRY MODELING SYSTEM (7.0.0) PRE/POST MODULE
SZZ - STRESSES
VIEW: -276.2158
RANGE: 4.607992
Max 6.302
13 -13.93
12 -34.17
11 -54.41
10 -74.64
9 -94.88
8 -115.1
7 -135.3
6 -155.6
5 -175.8
4 -196.1
3 -216.3
2 -236.5
1 -256.8
Min -277.0
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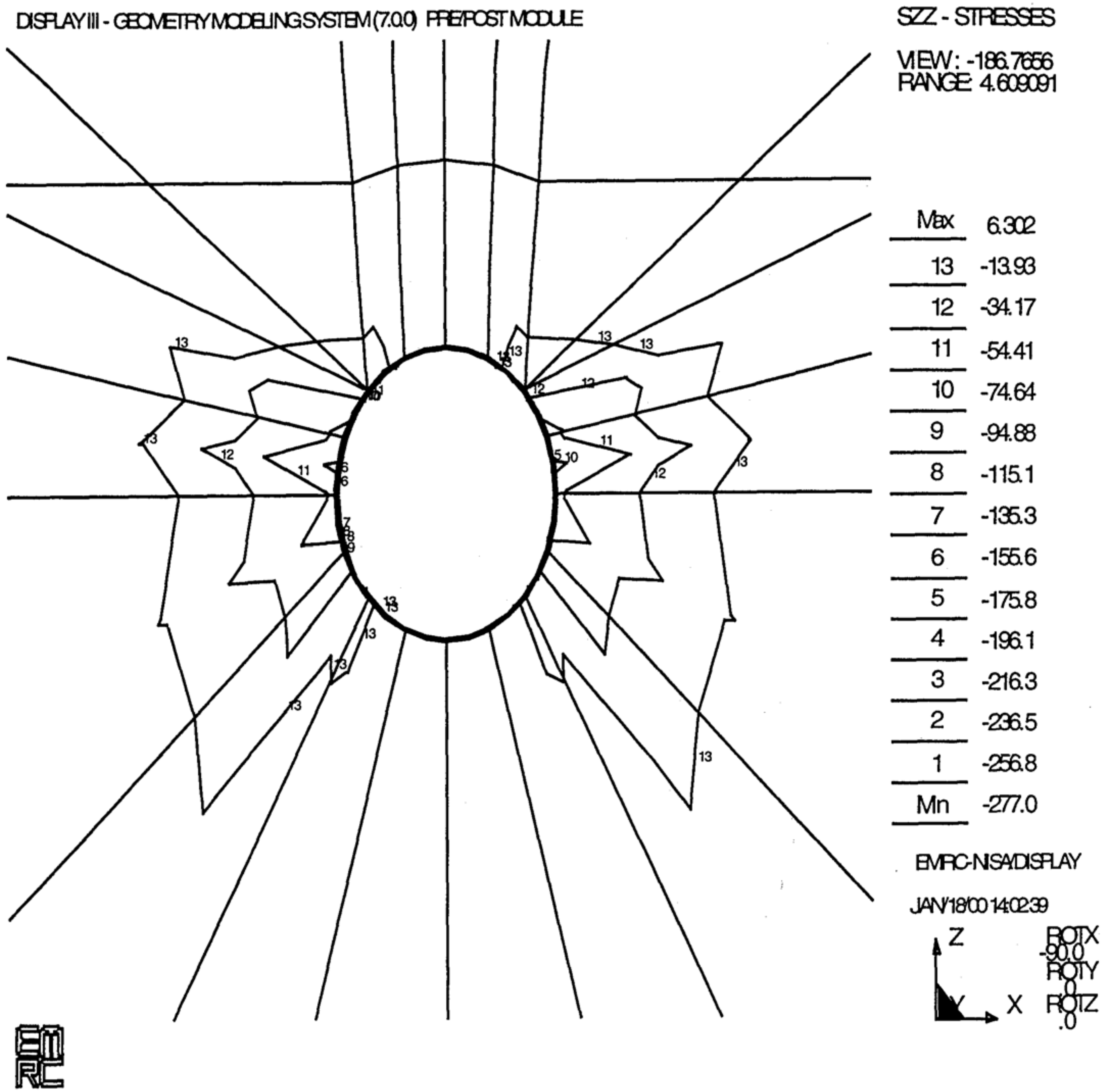
ROTY 0
ROTZ -45.0
Z
Y
X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10 -74.64
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8 -115.1
7 -135.3
6 -155.6
5 -175.8
4 -196.1
3 -216.3
2 -236.5
1 -256.8
Mn -277.0
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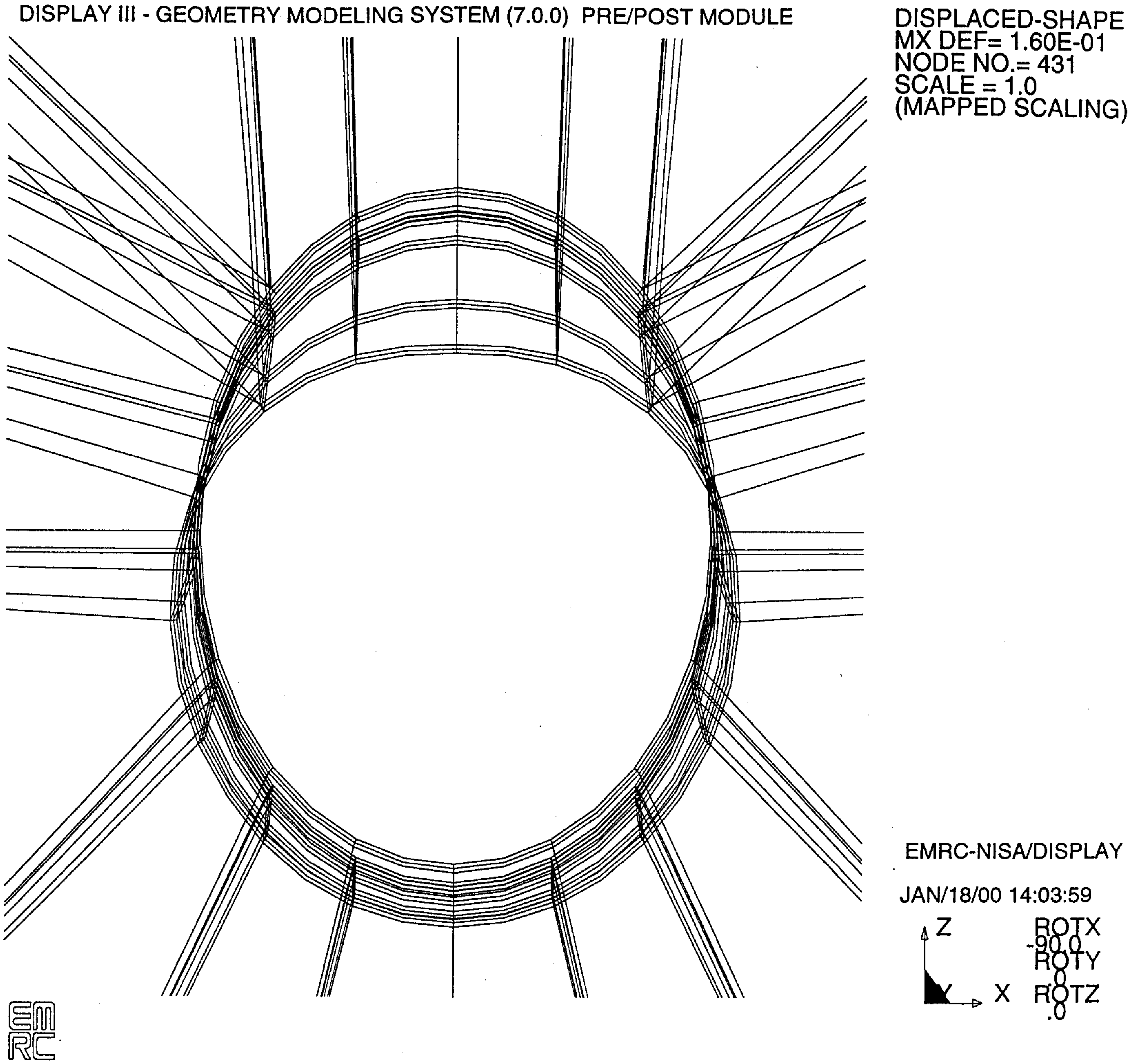
ROTZ .0



DISPLAY III - GEOMETRY MODELING SYSTEM (7.0.0) PRE/POST MODULE
DISPLACED-SHAPE
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NODE NO.= 431
SCALE = 1.0
(MAPPED SCALING)
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-90.0
ROTY
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ROTZ
.0
EMRC

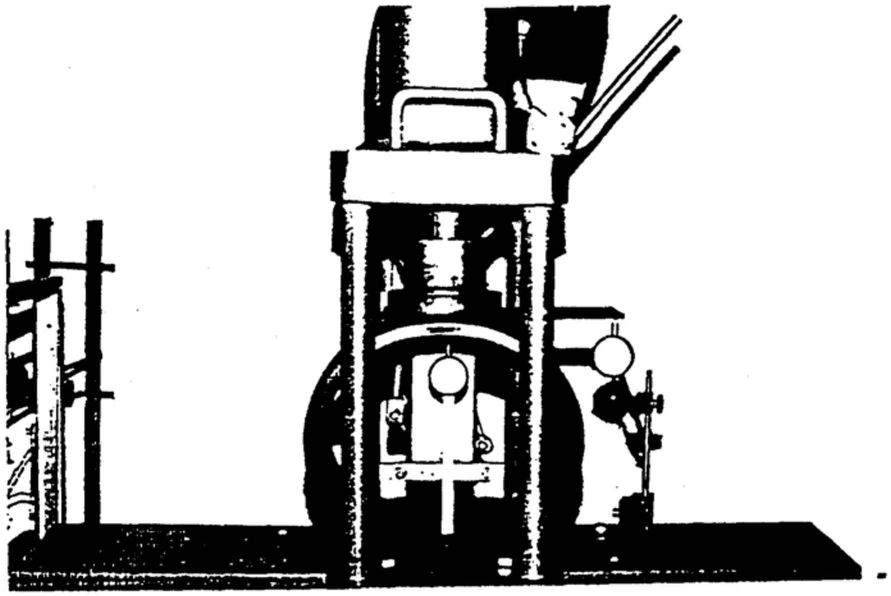

Figure 8.1 Parallel plate loading at ambient temperature

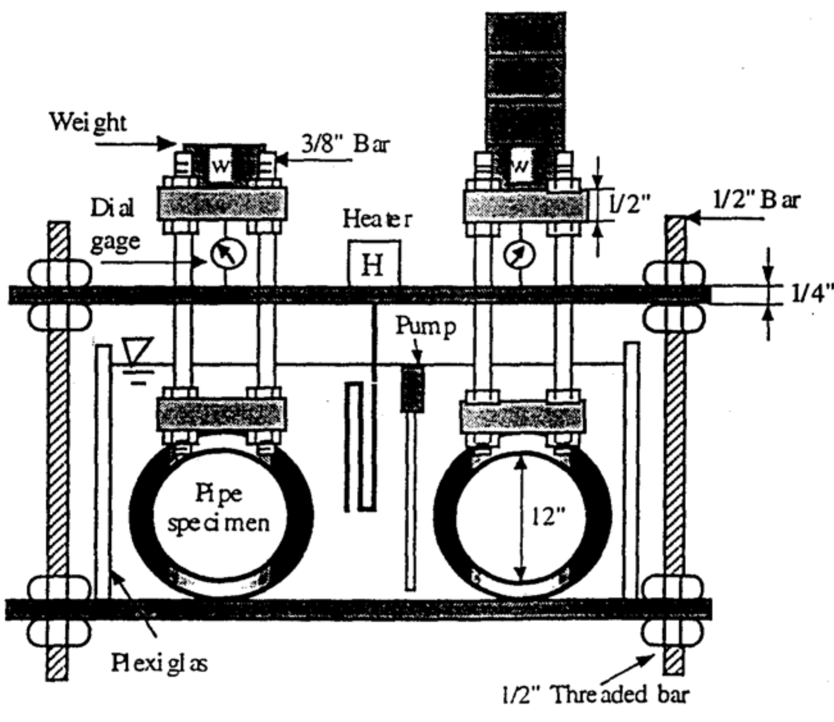

Figure 8.2 Parallel plate loading at super ambient temperature

8.3 CREEP

Short lengths of pipes, 12 in. (305 mm) diameter and 6 in. (152 mm) long, subjected to four different temperatures, 20, 30, 40 and 50°C, were loaded between two rigid parallel flat plates with constant loading to evaluate the time-temperature-dependent behavior of HDPE pipe, Fig. 8.3. Vertical changes of diameter were periodically measured by dial gages, accurate to the nearest 0.001 in. (0.0254 mm). The magnitude of the constant loading was based on equation (8.1).

$$EI=0.149Pr^3/Dy \tag{8.1}$$

Where

E=Flexural modulus, psi(MPa)

I=Moment of inertia,

P=Actual load applied

r--Mean radius, in.(mm)

Δy=Vertical deflection, in.(mm)

With the applied load (simulated service load) levels of 32 lb/in.(0.57 kg/mm) for type I specimens, and 26.5 lb/in.(0.47 kg/mm) for type II specimens, that cause the initial 2.5% of the change of inside diameter for the given pipe stiffness, [equation 8.1). Figs. 8. 4 and 8.5 show the arrangement of the test setups.

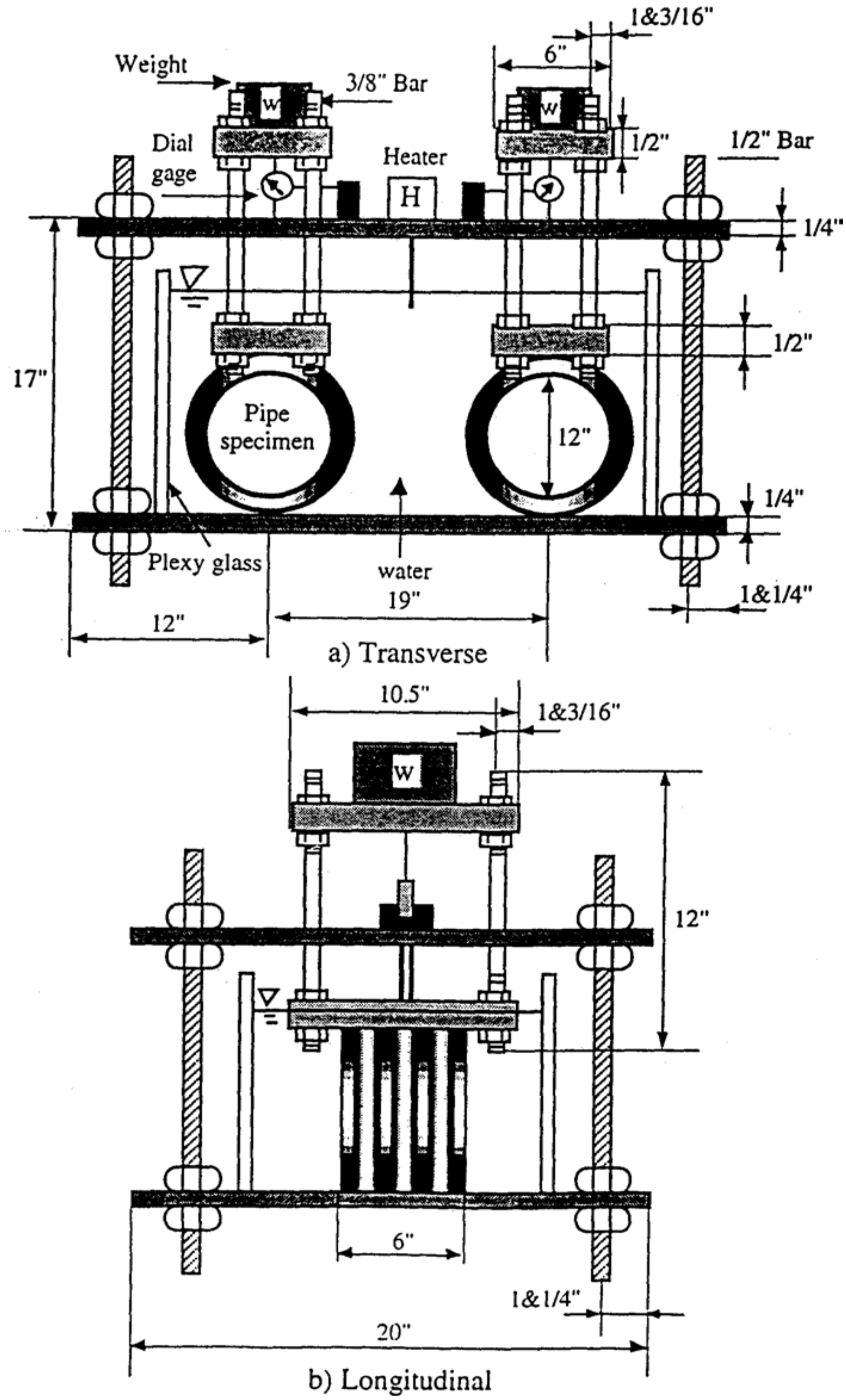

Figure 8.3 Schematic of creep test setup

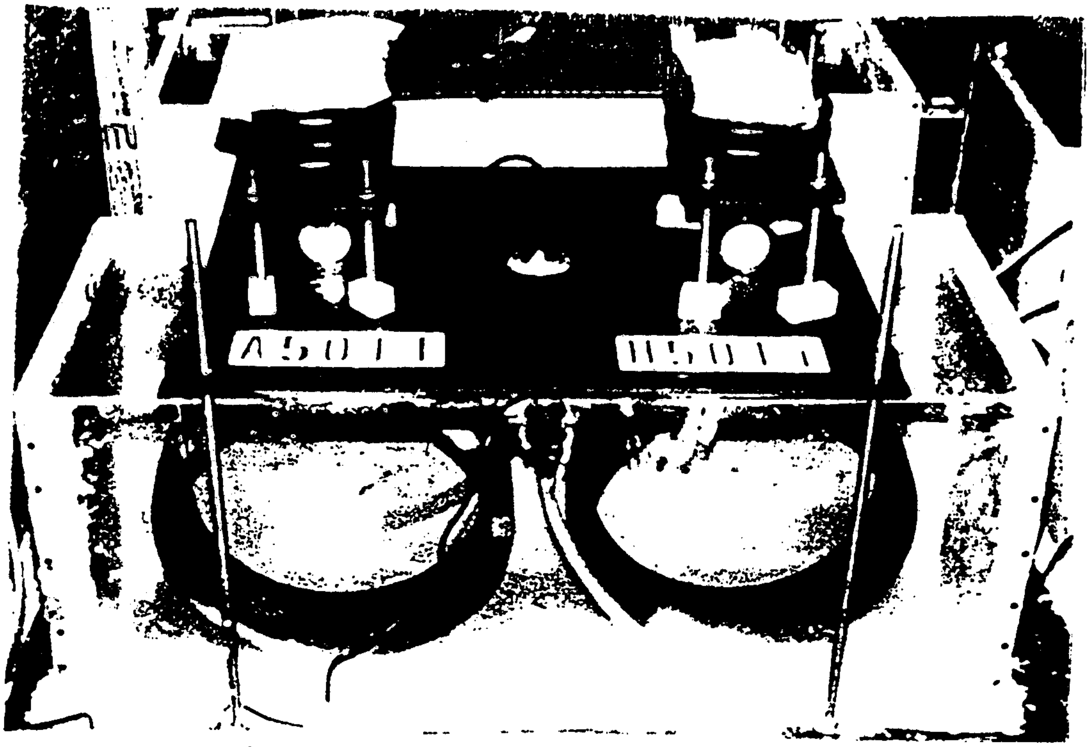

Figure 8.4 Creep test at constant temperature

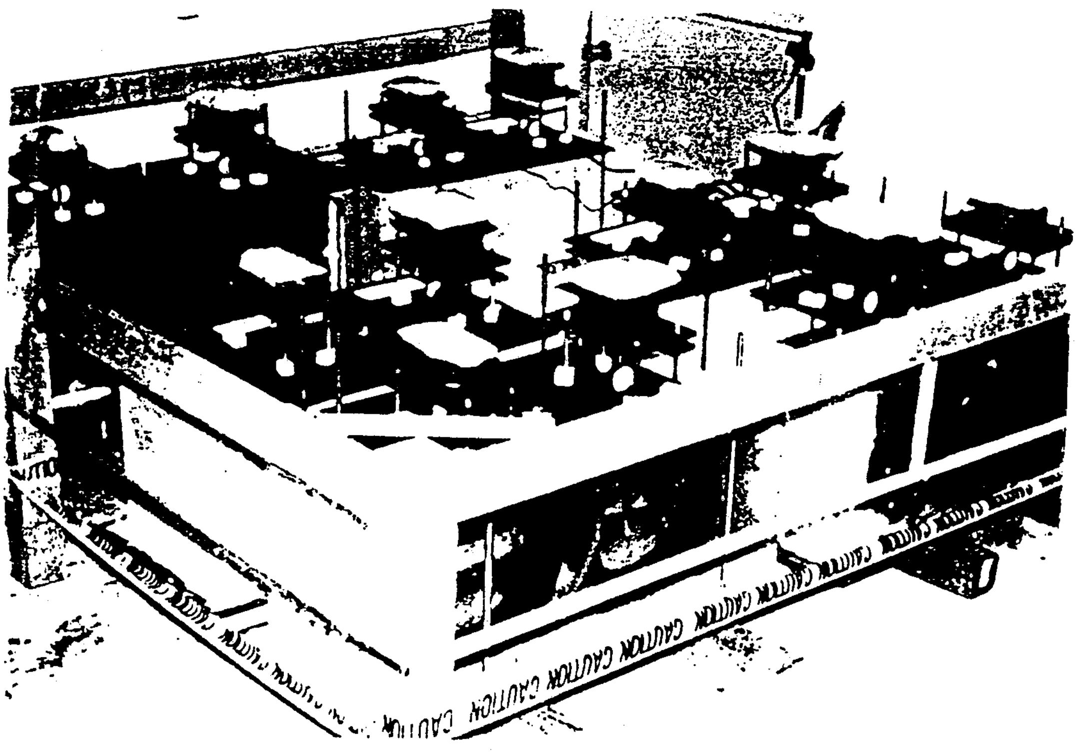

Figure 8.5 Arrangements of creep test setups

8.4 PREDICTION OF LONG-TERM PROPERTIES

The long-term properties are evaluated by the Bi-directional Shifting Method from Fig. 8.6 to 8.14 show the time scale master curves based on bi-directional shifting method for Type I and Type II notched pipe specimens tested at different temperature levels.

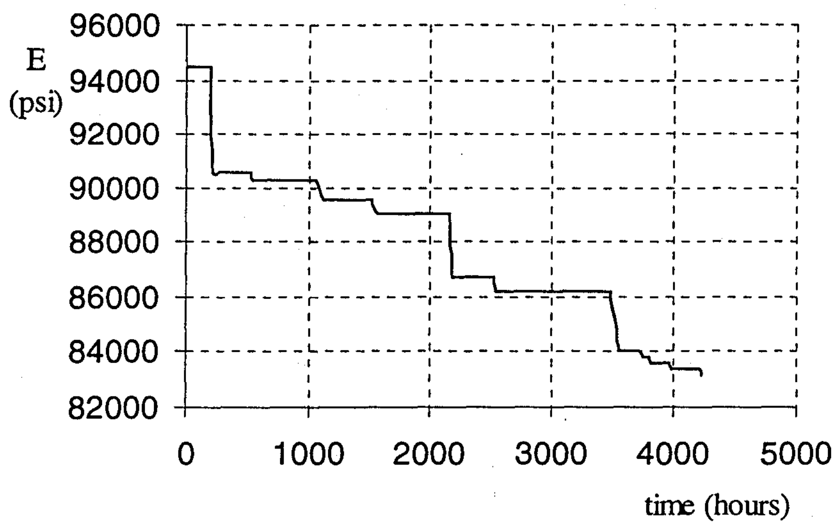

Figure 8.6 Master curve for Type I (20°C)

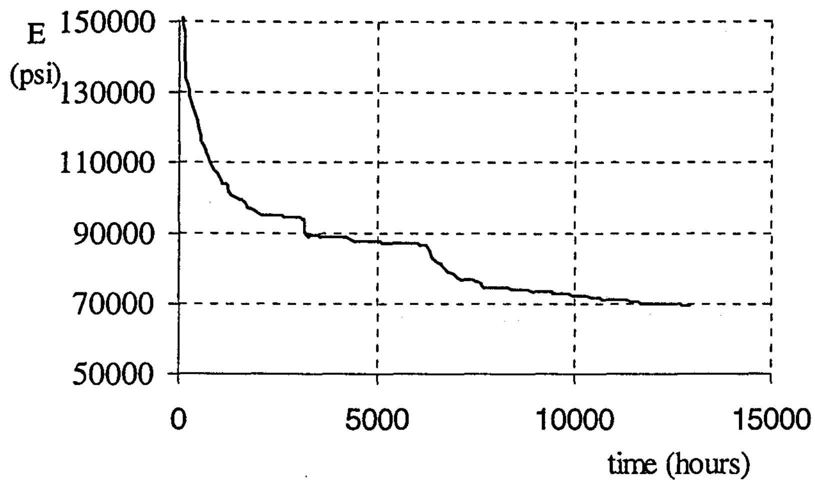

Figure 8.7 Master curve for Type II (30 ^{0}C)

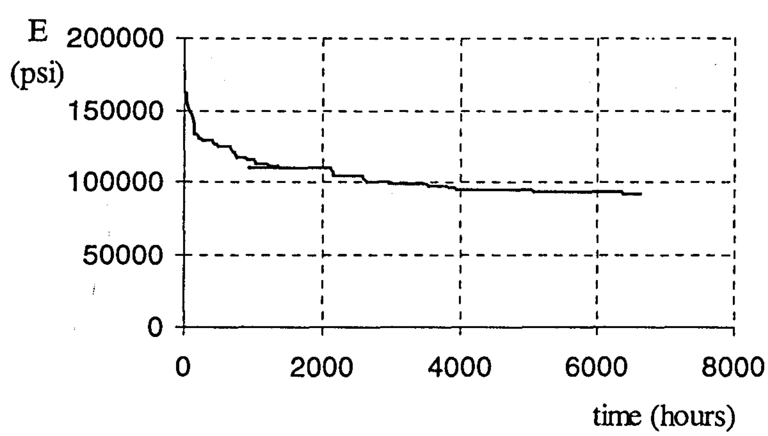

Figure 8.8 Master curve for type II (20^{0}C)

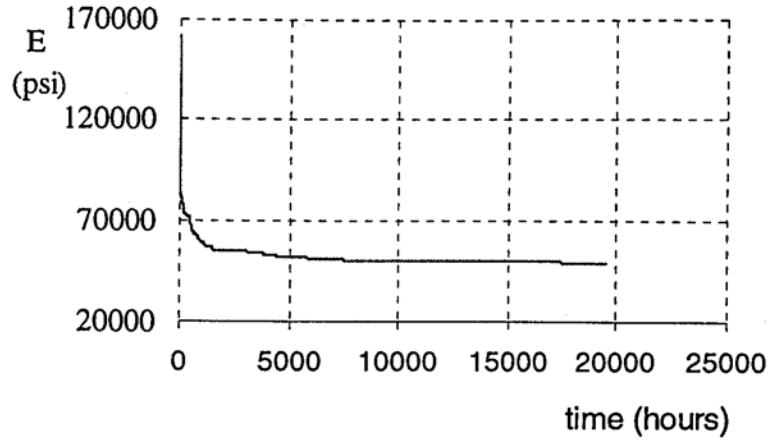

Figure 8.9 Master curve for type I (30 ^{0}C)

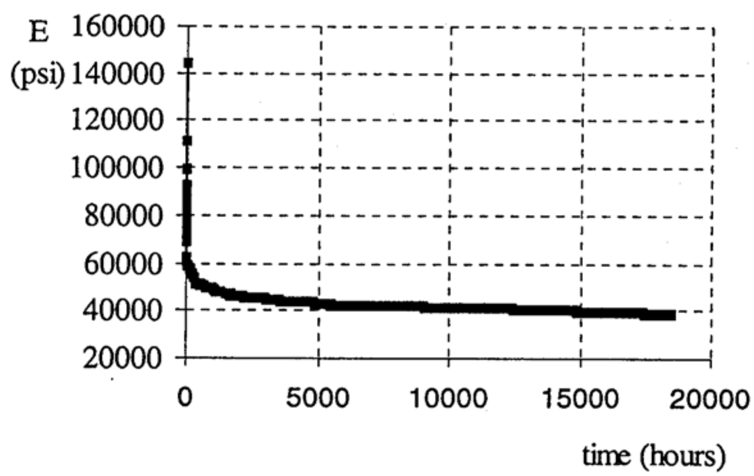

Figure 8.10 Master curve for type I (30 ^{0}C)

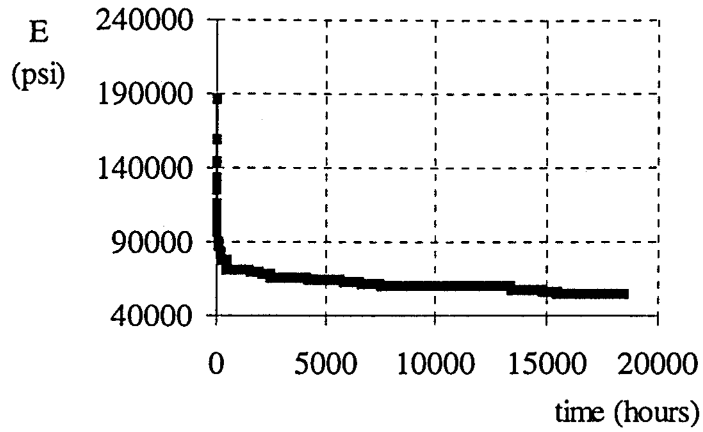

Figure 8.11 Master curve for type II (30 ^{0}C)

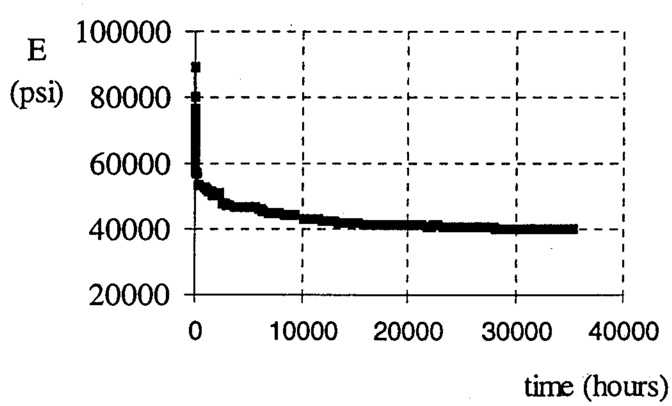

Figure 8.12 Master curve for type II (40 ^{0}C)

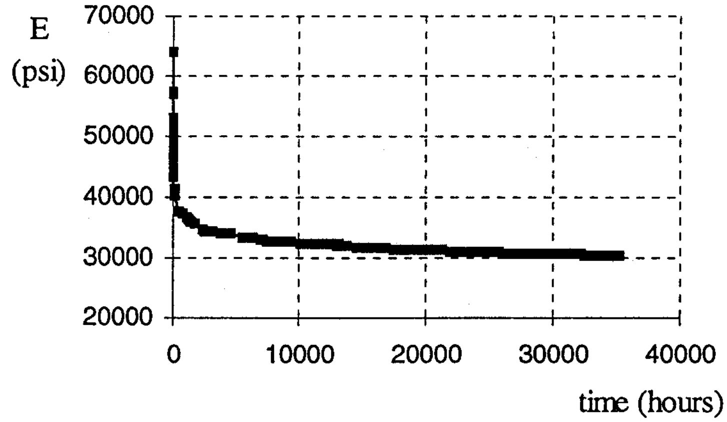

Figure 8.13 Master curve for type I (40 ^{0}C)

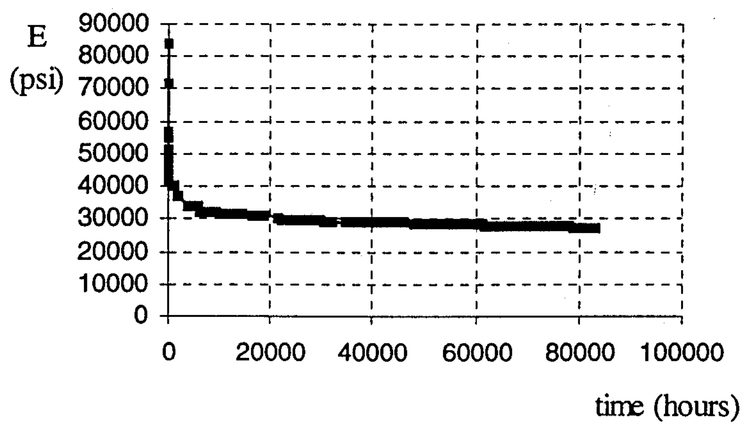

Figure 8.14 Master curve for type II (50 ^{0}C)

The rates of modulus decay were quite similar for both Type I and Type II unnotched specimens [Ahn, W., 1998]. The rates of modulus decay were quite similar for both Type I and Type II notched specimens but less than unnotched specimens. The experimental data in the figures is presented in Appendix D.

APPENDIX D

Data for Flexural Creep Testing of Notched and Un-Notched Pipe Rings for Enviromental Cracking Resistance

Tank 1

A-20 Type I 20^{0}C

Day	Hours:	Date:	Deflection (in.)
1	24	29-Apr	0.346
2	48	30-Apr	0.346
5	120	3-May	0.346
6	144	4-May	0.346
7	168	5-May	0.346
8	192	6-May	0.346
9	216	7-May	0.361
12	288	10-May	0.361
13	312	11-May	0.361
14	336	2-May	0.361
15	360	13-May	0.361
16	384	14-May	0.361
19	456	17-May	0.361
20	480	18-May	0.361
21	504	19-May	0.361
22	528	20-May	0.361
23	552	21-May	0.362
26	624	24-May	0.362
27	648	25-May	0.362
28	672	26-May	0.362
29	696	27-May	0.362
30	720	28-May	0.362
33	792	31-May	0.362
34	816	1-Jun	0.362
35	840	2-Jun	0.362
36	864	3-Jun	0.362
37	888	4-Jun	0.362
40	960	7-Jun	0.362
41	984	8-Jun	0.362
42	1008	9-Jun	0.362
43	1032	10-Jun	0.362
44	1056	11-Jun	0.362
47	1128	14-Jun	0.365
48	1152	15-Jun	0.365
49	1176	16-Jun	0.365
50	1200	17-Jun	0.365
51	1224	18-Jun	0.365
54	1296	21-Jun	0.365
55	1320	22-Jun	0.365
56	1344	23-Jun	0.365

57	1368	24-Jun	0.365
58	1392	25-Jun	0.365
61	1464	28-Jun	0.365
62	1488	29-Jun	0.365
63	1512	30-Jun	0.365
64	1536	1-Jul	0.366
65	1560	2-Jul	0.367
66	1584	3-Jul	0.367
67	1608	4-Jul	0.367
68	1632	5-Jul	0.367
69	1656	6-Jul	0.367
70	1680	7-Jul	0.367
71	1704	8-Jul	0.367
72	1728	9-Jul	0.367
73	1752	10-Jul	0.367
74	1776	11-Jul	0.367
75	1800	12-Jul	0.367
76	1824	13-Jul	0.367
77	1848	14-Jul	0.367
78	1872	15-Jul	0.367
79	1896	16-Jul	0.367
81	1944	18-Jul	0.367
82	1968	19-Jul	0.367
83	1992	20-Jul	0.367
84	2016	21-Jul	0.367
85	2040	22-Jul	0.367
86	2064	23-Jul	0.367
87	2088	24-Jul	0.367
88	2112	25-Jul	0.367
89	2136	26-Jul	0.367
90	2160	27-Jul	0.367
91	2184	28-Jul	0.377
92	2208	29-Jul	0.377
93	2232	30-Jul	0.377
94	2256	31-Jul	0.377
95	2280	1-Aug	0.377
96	2304	2-Aug	0.377
97	2328	3-Aug	0.377
98	2352	4-Aug	0.377
99	2376	5-Aug	0.377
100	2400	6-Aug	0.377
101	2424	7-Aug	0.377
102	2448	8-Aug	0.377
103	2472	9-Aug	0.377
104	2496	10-Aug	0.377
105	2520	11-Aug	0.377
106	2544	12-Aug	0.379

107	2568	13-Aug	0.379
108	2592	14-Aug	0.379
109	2616	15-Aug	0.379
110	2640	16-Aug	0.379
111	2664	17-Aug	0.379
112	2688	18-Aug	0.379
113	2712	19-Aug	0.379
114	2736	20-Aug	0.379
115	2760	21-Aug	0.379
116	2784	22-Aug	0.379
117	2808	23-Aug	0.379
118	2832	24-Aug	0.379
119	2856	25-Aug	0.379
120	2880	26-Aug	0.379
121	2904	27-Aug	0.379
122	2928	28-Aug	0.379
123	2952	29-Aug	0.379
124	2976	30-Aug	0.379
125	3000	31-Aug	0.379
126	3024	1-Sep	0.379
127	3048	2-Sep	0.379
128	3072	3-Sep	0.379
129	3096	4-Sep	0.379
130	3120	5-Sep	0.379
131	3144	6-Sep	0.379
132	3168	7-Sep	0.379
133	3192	8-Sep	0.379
134	3216	9-Sep	0.379
135	3240	10-Sep	0.379
136	3264	11-Sep	0.379
137	3288	12-Sep	0.379
138	3312	13-Sep	0.379
139	3336	14-Sep	0.379
140	3360	15-Sep	0.379
141	3384	16-Sep	0.379
142	3408	17-Sep	0.379
143	3432	18-Sep	0.379
144	3456	19-Sep	0.379
145	3480	20-Sep	0.382
146	3504	21-Sep	0.385
147	3528	22-Sep	0.389
148	3552	23-Sep	0.389
149	3576	24-Sep	0.389
150	3600	25-Sep	0.389
151	3624	26-Sep	0.389
152	3648	27-Sep	0.389
153	3672	28-Sep	

154	3696	29-Sep	0.389
155	3720	30-Sep	0.389
156	3744	1-Oct	0.39
157	3768	2-Oct	0.39
158	3792	3-Oct	0.39
159	3816	4-Oct	0.391
160	3840	5-Oct	0.391
161	3864	6-Oct	0.391
162	3888	7-Oct	0.391
163	3912	8-Oct	0.391
164	3936	9-Oct	0.391
165	3960	10-Oct	0.391
166	3984	11-Oct	0.392
167	4008	12-Oct	0.392
168	4032	13-Oct	0.392
169	4056	14-Oct	0.392
170	4080	15-Oct	0.392
171	4104	16-Oct	0.392
172	4128	17-Oct	0.392
173	4152	18-Oct	0.392
174	4176	19-Oct	0.392
175	4200	20-Oct	0.392
176	4224	21-Oct	0.393

Tank III
H-30 II Type II 30^{0}C

Date	Hours	Gage	Deflection (in.)
19-Jan	0	0.131	0
19-Jan	0.25	0.239	0.108
19-Jan	0.5	0.252	0.121
19-Jan	0.75	0.256	0.125
19-Jan	1	0.261	0.13
19-Jan	1.25	0.272	0.141
19-Jan	1.5	0.277	0.146
19-Jan	1.75	0.281	0.15
19-Jan	2	0.282	0.151
19-Jan	3	0.295	0.164
19-Jan	4	0.302	0.171
19-Jan	5	0.306	0.175
20-Jan	24	0.333	0.202
20-Jan	31	0.337	0.206
21-Jan	48	0.348	0.217
21-Jan	53	0.357	0.226
21-Jan	59	0.36	0.229
22-Jan	72	0.365	0.234
24-Jan	120	0.378	0.247
26-Jan	168	0.39	0.259
27-Jan	192	0.398	0.267
28-Jan	216	0.404	0.273
29-Jan	240	0.408	0.277
31-Jan	288	0.418	0.287
2-Feb	336	0.424	0.293
3-Feb	360	0.429	0.298
4-Feb	384	0.429	0.298
5-Feb	408	0.431	0.3
6-Feb	432	0.438	0.307
8-Feb	480	0.441	0.31
9-Feb	504	0.442	0.311
10-Feb	528	0.442	0.311
10-Feb	528	0.442	0.311
11-Feb	552	0.445	0.314
12-Feb	576	0.449	0.318
15-Feb	648	0.453	0.322

16-Feb	672	0.456	0.325
17-Feb	696	0.457	0.326
18-Feb	720	0.457	0.326
19-Feb	744	0.457	0.326
22-Feb	816	0.458	0.327
23-Feb	840	0.458	0.327
24-Feb	864	0.458	0.327
25-Feb	888	0.459	0.328
26-Feb	912	0.459	0.328
1-Mar	984	0.46	0.329
3-Mar	1032	0.461	0.33
4-Mar	1056	0.461	0.33
5-Mar	1080	0.479	0.348
8-Mar	1152	0.479	0.348
9-Mar	1176	0.479	0.348
10-Mar	1200	0.48	0.349
11-Mar	1224	0.48	0.349
12-Mar	1248	0.48	0.349
15-Mar	1320	0.48	0.349
16-Mar	1344	0.48	0.349
18-Mar	1392	0.481	0.35
19-Mar	1416	0.481	0.35
23-Mar	1488	0.484	0.353
24-Mar	1512	0.484	0.353
25-Mar	1536	0.484	0.353
26-Mar	1560	0.484	0.353
29-Mar	1632	0.484	0.353
30-Mar	1656	0.484	0.353
31-Mar	1680	0.485	0.354
1-Apr	1704	0.486	0.355
2-Apr	1728	0.487	0.356
5-Apr	1800	0.487	0.356
6-Apr	1824	0.487	0.356
7-Apr	1872	0.487	0.356
9-Apr	1920	0.487	0.356
13-Apr	2016	0.488	0.357
14-Apr	2040	0.49	0.359
15-Apr	2064	0.49	0.359
16-Apr	2088	0.49	0.359
19-Apr	2160	0.507	0.376
20-Apr	2184	0.509	0.378
21-Apr	2208	0.512	0.381
22-Apr	2232	0.512	0.381
23-Apr	2256	0.517	0.386
26-Apr	2328	0.526	0.395
27-Apr	2352	0.529	0.398
28-Apr	2376	0.531	0.4

29-Apr	2400	0.534	0.403
30-Apr	2424	0.535	0.404
3-May	2496	0.536	0.405
4-May	2520	0.539	0.408
5-May	2544	0.539	0.408
6-May	2568	0.542	0.411
7-May	2592	0.546	0.415
10-May	2664	0.546	0.415
11-May	2688	0.546	0.415
12-May	2712	0.546	0.415
13-May	2736	0.547	0.416
14-May	2760	0.548	0.417
17-May	2832	0.549	0.418
18-May	2856	0.549	0.418
19-May	2880	0.549	0.418
20-May	2904	0.549	0.418
21-May	2928	0.551	0.42
24-May	3000	0.553	0.422
25-May	3024	0.553	0.422
26-May	3048	0.553	0.422
27-May	3072	0.553	0.422
28-May	3144	0.554	0.423
31-May	3168	0.556	0.425
1-Jun	3192	0.556	0.425
2-Jun	3216	0.558	0.427
3-Jun	3240	0.558	0.427
4-Jun	3264	0.558	0.427
7-Jun	3336	0.559	0.428
8-Jun	3360	0.56	0.429
9-Jun	3384	0.56	0.429
10-Jun	3408	0.561	0.43
11-Jun	3432	0.561	0.43
14-Jun	3504	0.563	0.432
15-Jun	3528	0.564	0.433
16-Jun	3552	0.564	0.433
17-Jun	3576	0.564	0.433
18-Jun	3600	0.566	0.435
21-Jun	3672	0.567	0.436
23-Jun	3720	0.568	0.437
24-Jun	3744	0.568	0.437
25-Jun	3768	0.568	0.437
28-Jun	3840	0.571	0.44
29-Jun	3864	0.571	0.44
30-Jun	3888	0.571	0.44
1-Jul	3912	0.573	0.442
2-Jul	3936	0.573	0.442
3-Jul	3960	0.573	0.442

5-Jul	4008	0.573	0.442
6-Jul	4032	0.574	0.443
7-Jul	4056	0.574	0.443
8-Jul	4080	0.574	0.443
9-Jul	4104	0.575	0.444
10-Jul	4128	0.575	0.444
11-Jul	4152	0.575	0.444
12-Jul	4176	0.575	0.444
13-Jul	4200	0.575	0.444
14-Jul	4224	0.576	0.445
15-Jul	4248	0.576	0.445
16-Jul	4272	0.578	0.447
17-Jul	4296	0.578	0.447
18-Jul	4320	0.578	0.447
19-Jul	4344	0.579	0.448

Tank 1
H-20 Type II 20^{0}C

Date:	Time	Gage	Deflection (in.)
12-Jan	0	0.123	0
12-Jan	0.25	0.181	0.058
12-Jan	0.5	0.197	0.074
12-Jan	0.75	0.209	0.086
12-Jan	1	0.216	0.093
12-Jan	1.25	0.221	0.098
12-Jan	1.5	0.226	0.103
12-Jan	1.75	0.23	0.107
12-Jan	2	0.233	0.11
12-Jan	2.25	0.235	0.112
12-Jan	2.5	0.237	0.114
12-Jan	4	0.253	0.13
13-Jan	22.5	0.316	0.193
13-Jan	25.5	0.32	0.197
13-Jan	28.5	0.322	0.199
14-Jan	42.5	0.338	0.215
15-Jan	65.75	0.354	0.231
17-Jan	113.75	0.363	0.24
19-Jan	137.75	0.371	0.248
20-Jan	159.5	0.384	0.261
21-Jan	180.75	0.385	0.262
21-Jan	193.75	0.389	0.266
22-Jan	210.75	0.39	0.267
24-Jan	258.75	0.392	0.269
27-Jan	380.75	0.393	0.27
28-Jan	408.75	0.394	0.271
29-Jan	439	0.399	0.276
31-Jan	461.75	0.4	0.277
2-Feb	485.75	0.401	0.278
3-Feb	568	0.401	0.278
5-Feb	589	0.402	0.279
6-Feb	607	0.402	0.279
8-Feb	662	0.403	0.28

9-Feb	680	0.403	0.28
10-Feb	704	0.412	0.289
10-Feb	710.5	0.412	0.289
11-Feb	728	0.412	0.289
12-Feb	754	0.422	0.299
15-Feb	826.75	0.423	0.3
16-Feb	850.25	0.423	0.3
17-Feb	879.25	0.423	0.3
18-Feb	897.25	0.426	0.303
19-Feb	924.75	0.427	0.304
22-Feb	999.75	0.427	0.304
23-Feb	1016.75	0.431	0.308
24-Feb	1042.75	0.431	0.308
25-Feb	1067.25	0.434	0.311
26-Feb	1087.25	0.434	0.311
1-Mar	1167.25	0.434	0.311
3-Mar	1214.75	0.436	0.313
4-Mar	1231.75	0.436	0.313
5-Mar	1261.75	0.436	0.313
8-Mar	1327.75	0.436	0.313
9-Mar	1351.75	0.436	0.313
10-Mar	1378.75	0.44	0.317
11-Mar	1399.75	0.44	0.317
12-Mar	1429	0.44	0.317
15-Mar	1503.5	0.44	0.317
16-Mar	1524	0.441	0.318
18-Mar	1569	0.441	0.318
19-Mar	1598	0.441	0.318
23-Mar	1696	0.441	0.318
24-Mar	1720.25	0.441	0.318
25-Mar	1750.25	0.441	0.318
26-Mar	1778.25	0.441	0.318
29-Mar	1852	0.441	0.318
30-Mar	1869	0.441	0.318
31-Mar	1900.5	0.441	0.318
1-Apr	919.25	0.441	0.318
2-Apr	1947	0.441	0.318
5-Apr	2020.75	0.441	0.318
6-Apr	2038.5	0.441	0.318
7-Apr	2063.25	0.441	0.318
9-Apr	2115.25	0.441	0.318
13-Apr	2139.25	0.455	0.332
14-Apr	2163.25	0.457	0.334
15-Apr	2187.25	0.457	0.334
16-Apr	2211.25	0.457	0.334
19-Apr	2235.25	0.457	0.334
20-Apr	2259.25	0.457	0.334

21-Apr	2283.25	0.457	0.334
22-Apr	2307.25	0.457	0.334
23-Apr	2331.25	0.457	0.334
26-Apr	2355.25	0.457	0.334
27-Apr	2379.25	0.457	0.334
28-Apr	2403.25	0.457	0.334
29-Apr	2427.25	0.458	0.335
30-Apr	2451.25	0.458	0.335
3-May	2547.25	0.458	0.335
4-May	2571.25	0.458	0.335
5-May	2595.25	0.458	0.335
6-May	2619.25	0.467	0.344
7-May	2643.25	0.472	0.349
10-May	2715.25	0.472	0.349
11-May	2739.25	0.472	0.349
12-May	2763.25	0.472	0.349
13-May	2787.25	0.472	0.349
14-May	2811.25	0.472	0.349
17-May	2883.25	0.472	0.349
18-May	2907.25	0.472	0.349
19-May	2931.25	0.472	0.349
20-May	2955.25	0.472	0.349
21-May	2979.25	0.474	0.351
24-May	3051.25	0.474	0.351
25-May	3075.25	0.474	0.351
26-May	3099.25	0.474	0.351
27-May	3123.25	0.474	0.351
28-May	3147.25	0.474	0.351
31-May	3219.25	0.474	0.351
1-Jun	3243.25	0.474	0.351
2-Jun	3267.25	0.474	0.351
3-Jun	3291.25	0.475	0.352
4-Jun	3315.25	0.475	0.352
7-Jun	3387.25	0.475	0.352
8-Jun	3411.25	0.475	0.352
9-Jun	3435.25	0.475	0.352
10-Jun	3459.25	0.475	0.352
11-Jun	3483.25	0.475	0.352
14-Jun	3555.25	0.481	0.358
16-Jun	3579.25	0.481	0.358
17-Jun	3603.25	0.481	0.358
18-Jun	3627.25	0.481	0.358
21-Jun	3699.25	0.481	0.358
22-Jun	3723.25	0.481	0.358
23-Jun	3747.25	0.481	0.358
24-Jun	3771.25	0.481	0.358
25-Jun	3795.25	0.481	0.358

14-Aug	4995.25	0.493	0.37
15-Aug	5019.25	0.493	0.37
16-Aug	5043.25	0.493	0.37
17-Aug	5067.25	0.494	0.371
18-Aug	5091.25	0.494	0.371
19-Aug	5115.25	0.494	0.371
20-Aug	5139.25	0.494	0.371
21-Aug	5163.25	0.494	0.371
22-Aug	5187.25	0.494	0.371
23-Aug	5211.25	0.494	0.371
24-Aug	5235.25	0.494	0.371
25-Aug	5259.25	0.494	0.371
26-Aug	5283.25	0.494	0.371
27-Aug	5307.25	0.494	0.371
28-Aug	5331.25	0.494	0.371
29-Aug	5355.25	0.494	0.371
30-Aug	5379.25	0.494	0.371
31-Aug	5403.25	0.494	0.371
1-Sep	5427.25	0.494	0.371
2-Sep	5451.25	0.494	0.371
3-Sep	5475.25	0.494	0.371
4-Sep	5499.25	0.494	0.371
5-Sep	5523.25	0.494	0.371
6-Sep	5547.25	0.494	0.371
7-Sep	5571.25	0.494	0.371
8-Sep	5595.25	0.494	0.371
9-Sep	5619.25	0.494	0.371
10-Sep	5643.25	0.494	0.371
11-Sep	5667.25	0.494	0.371
12-Sep	5691.25	0.494	0.371
13-Sep	5715.25	0.494	0.371
14-Sep	5739.25	0.494	0.371
15-Sep	5763.25	0.494	0.371
16-Sep	5787.25	0.494	0.371
17-Sep	5811.25	0.494	0.371
18-Sep	5835.25	0.494	0.371
19-Sep	5859.25	0.494	0.371
20-Sep	5883.25	0.494	0.371
21-Sep	5907.25	0.494	0.371
22-Sep	5931.25	0.494	0.371
23-Sep	5955.25	0.494	0.371
24-Sep	5979.25	0.494	0.371
25-Sep	6003.25	0.494	0.371
26-Sep	6027.25	0.494	0.371
27-Sep	6051.25	0.494	0.371
28-Sep	6075.25	0.494	0.371
29-Sep	6099.25	0.494	0.371

30-Sep	6123.25	0.495	0.372
1-Oct	6147.25	0.496	0.373
2-Oct	6171.25	0.496	0.373
3-Oct	6195.25	0.496	0.373
4-Oct	6219.25	0.496	0.373
5-Oct	6243.25	0.497	0.374
6-Oct	6267.25	0.497	0.374
7-Oct	6291.25	0.498	0.375
8-Oct	6315.25	0.498	0.375
9-Oct	6339.25	0.499	0.376
10-Oct	6363.25	0.5	0.377
11-Oct	6387.25	0.5	0.377
12-Oct	6411.25	0.501	0.378
13-Oct	6435.25	0.501	0.378
14-Oct	6459.25	0.502	0.379
15-Oct	6483.25	0.503	0.38
16-Oct	6507.25	0.503	0.38
17-Oct	6531.25	0.503	0.38
18-Oct	6555.25	0.503	0.38
19-Oct	6579.25	0.504	0.381
20-Oct	6603.25	0.504	0.381
21-Oct	6627.25	0.504	0.381

Tank III

A-30 11 Type 1 30° C

Date:	Hours	Gage	Deflection (in.)
19-Jan	0	0.254	0
19-Jan	0.25	0.436	0.182
19-Jan	0.5	0.47	0.216
19-Jan	0.75	0.49	0.236
19-Jan	1	0.505	0.251
19-Jan	1.25	0.515	0.261
19-Jan	1.5	0.526	0.272
19-Jan	1.75	0.537	0.283
19-Jan	2	0.539	0.285
19-Jan	3	0.558	0.304
19-Jan	4	0.57	0.316
19-Jan	5	0.58	0.326
20-Jan	24	0.625	0.371
21-Jan	48	0.632	0.378
22-Jan	72	0.648	0.394
24-Jan	120	0.659	0.405
26-Jan	168	0.666	0.412
27-Jan	192	0.692	0.438
28-Jan	216	0.71	0.456
29-Jan	240	0.716	0.462
1-Feb	264	0.725	0.471
2-Feb	288	0.735	0.481
3-Feb	312	0.742	0.488
4-Feb	336	0.75	0.496
5-Feb	360	0.752	0.498
6-Feb	384	0.761	0.507
8-Feb	432	0.764	0.51
9-Feb	456	0.771	0.517
10-Feb	480	0.772	0.518
11-Feb	504	0.774	0.52
12-Feb	528	0.782	0.528
15-Feb	600	0.784	0.53
16-Feb	624	0.785	0.531
17-Feb	648	0.785	0.531

3-May	2448	0.826	0.572
4-May	2472	0.827	0.573
5-May	2496	0.828	0.574
6-May	2520	0.835	0.581
7-May	2544	0.835	0.581
10-May	2616	0.835	0.581
11-May	2640	0.835	0.581
12-May	2664	0.835	0.581
13-May	2688	0.835	0.581
14-May	2712	0.835	0.581
17-May	2784	0.835	0.581
18-May	2808	0.835	0.581
19-May	2832	0.835	0.581
20-May	2856	0.835	0.581
21-May	2880	0.835	0.581
24-May	2952	0.835	0.581
25-May	2976	0.835	0.581
26 May	3000	0.835	0.581
27-May	3024	0.835	0.581
28-May	3048	0.835	0.581
31-May	3 120	0.835	0.581
1-Jun	3144	0.835	0.581
2-Jun	3168	0.837	0.583
3-Jun	3192	0.837	0.583
4-Jun	3216	0.837	0.583
7-Jun	3288	0.837	0.583
8-Jun	3312	0.837	0.583
9-Jun	3336	0.837	0.583
10-Jun	3360	0.837	0.583
11-Jun	3384	0.837	0.583
14-Jun	3456	0.838	0.584
15-Jun	3480	0.838	0.584
16-Jun	3504	0.838	0.584
17-Jun	3528	0.838	0.584
18-Jun	3552	0.838	0.584
21-Jun	3624	0.838	0.584
22-Jun	3648	0.839	0.585
23-Jun	3672	0.839	0.585
24-Jun	3696	0.839	0.585
25-Jun	3720	0.839	0.585
28-Jun	3792	0.84	0.586
29-Jun	3816	0.84	0.586
30-Jun	3840	0.84	0.586
1-Jul	3864	0.84	0.586
2-Jul	3888	0.84	0.586
3-Jul	3912	0.84	0.586
4-Jul	3936	0.84	0.586

5-Jul	3960	0.84	0.586
6-JUI	3984	0.84	0.586
7-Jul	4008	0.84	0.586
8-Jul	4032	0.84	0.586
9-Jul	4056	0.84	0.586
10-Jul	4080	0.84	0.586
11-Jul	4104	0.84	0.586
12-Jul	4128	0.84	0.586
13-Jul	41 b2	0.84	0.586
14-Jul	4176	0.84	0.586
15-Jul	4200	0.84	0.586
16-Jul	4224	0.84	0.586
17-Jul	4248	0.84	0.586
18-Jul	4272	0.84	0.586
19-Jul	4296	0.84	0.586
20-Jul	4320	0.84	0.586
21-Jul	4344	0.84	0.586
22-Jul	4368	0.84	0.586
23-Jul	4392	0.84	0,586
24-Jul	441 6	0.84	0.586
25-Jul	4440	0.84	0.586
26-Jul	4464	0.84	0.586
27-JUI	4488	0.84	0.586
28-Jul	4512	0.841	0.587
29-JUI	4536	0.841	0.587
30-Jul	4560	0.841	0.587
31-Ju1	4584	0.841	0.587
1-Aug	4608	0.841	0.587
2-Aug	4632	0.841	0.587
3-Aug	4656	0.841	0.587
4-Aug	4680	0.841	0.587
5-Aug	4704	0.841	0.587
6-Aug	4728	0.841	0.587
7-Aug	4752	0.841	0.587
8.Aug	4776	0.841	0.587
9-Aug	48 00	0.841	0.587
10-Aug	4824	0.841	0.587
11-Aug	4848	0 .841 .	0.587
12-Aug	4872	0.842	0.588
13-Aug	896	0.842	0.588
14-Aug	920	0.842	0.588
15-Aug	4944	0.842	0.588
16-Aug	4968	0.842	0.588
17-Aug	4992	0.842	0:588
18-Aug	5016	0.842	0.588
19-Aug	5040	0.842	0.588
20-Aug	5064	0.842	

21-Aug	5088	0.842	0.588 0.588
22-Aug	5112	0.842	0.588
23-Aug	5136	0.842	0.588
24-Aug	5160	0.842	0.588
25-Aug	5184	0.842	0.588
26-Aug	5208	0.842	0.588
27-Aug	5232	0.842	0.588
28-Aug	5256	0.842	0.588
29-Aug	5280	0.842	0.588
30-Aug	5304	0.842	0.588
31 -Aug	5328	0.842	0.588
1-Sep	5352	0.842	0.588
2-Sep	5376	0.842	0.588
3-Sep	5400	0.842	0.588
4-Sep	5424	0.842	0.588
5-Sep	5448	0.842	0.588
6-Sep	5472	0.842	0.588
7-Sep	5496	0.842	0.588
8-Sep	5520	0.842	0.588
9-Sep	5544	0.842	0.588
10-Sep	5568	0.842	0.588
11 -Sep	5592	0.842	0.588
12-Sep	5616	0.842	0.588
13-Sep	5640	0.842	0.588
14-Sep	5664	0.842	0.588
15-Sep	5688	0.842	0.588
16-Sep	5712	0.842	0.588
17-Sep	5736	0.842	0.588
18-Sep	5760_	0.842	0.588
19-Sep	5784	0.842	0.588
20-Sep	5808	0.842	0.589
21-Sep	5832	0.843	0.59
22-Sep	5856	0.844	0,591
23-Sep	5880	0.845	0.591
24-Sep	5904	0.845	0.591
25-Sep	5928	0.845	0.591
26-Sep	5952	0.845	0.591
27-Sep	5976	0 .845	0.592
28-Sep	6000	0.846	0.592
29 -Sep	6024	0.846	0.592
30-Sep	6048	0.846	0.592
1-Oct	6072	0.846	0.592
2-Oct	6096	0.846	0.592
3-Oct	6120	0.846	0.593
4-Oct	6144	0.847	0.593
5-Oct	168	0.847	0.593
6-Oct	192	0.847	

19-Feb	432	0.802	0.612
22-Feb	504	0.805	0.615
23-Feb	528	0.805	0.615
24-Feb	552	0.813	0.623
25-Feb	576	0.815	0.625
26-Feb	600	0.817	0.627
1-Mar	672	0.817	0.627
3-Mar	720	0.821	0.631
4-Mar	744	0.827	0.637
5-Mar	768	0.827	0.637
8-Mar	840	0.829	0.639
9-Mar	864	0.831	0.641
10-Mar	888	0.832	0.642
11-Mar	912	0.834	0.644
12-Mar	936	0.834	0.644
15-Mar	1008	0.835	0.645
16-Mar	1032	0.839	0.649
18-Mar	1080	0.839	0.649
19-Mar	1104	0.839	0.649
23-Mar	1176	0.85	0.66
24-Mar	1200	0.853	0.663
25-Mar	1224	0.853	0.663
26-Mar	1248	0.853	0.663
29-Mar	1320	0.853	0.663
30-Mar	1344	0.853	0.663
31-Mar	1368	0.854	0.664
1-Apr	1392	0.858	0.668
2-Apr	1416	0.859	0.669
5-Apr	1488	0.861	0.671
6-Apr	1512	0.862	0.672
7-Apr	1536	0.862	0.672
9-Apr	1608	0.862	0.672
13-Apr	1632	0.871	0.681
14-Apr	1656	0.872	0.682
15-Apr	1680	0.872	0.682
16-Apr	1704	0.872	0.682
19-Apr	1776	0.872	0.682
20-Apr	1800	0.872	0.682
21-Apr	1824	0.872	0.682
22-Apr	1848	0.877	0.687
23-Apr	1872	0.878	0.688
26-Apr	1944	0.878	0.688
27-Apr	1968	0.878	0.688
28-Apr	1992	0.885	0.695
29-Apr	2016	0.885	0.695
30-Apr	2040	0.885	0.695
3-May	2112	0.885	0.695

4-May	—2j -36	0.885	0.695
5-May	2160	0.888	0.698
6-May	2184	0.888	0.698
7-May	2208	0.888	0.698
10-May	2280	0.888	0.698
11-May	2304	0.888	0.698
12-May	2328	0.888	0.698
13-May	235	0.888	0.698
14-May	2376	0.888	0.698
17-May	2448	0.888	0.698
18-May	2472	0.888	0.698
19-May	2496	0.888	0.698
20-May	2520	0.888	0.698
21-May	2544	0.889	0.699
24-May	2616	0.889	0.699
25-May	2640	0.889	0.699
26-May	2664	0.889	0.699
27-May	2688	0.889	0.699
28-May	2712	0.889	0.699
31-May	2784	0.889	0.699
1-Jun	2808	0.889	0.699
2-Jun	2832	0.889	0.699
3-Jun	2856	0.889	0.699
4-Jun	2880	0.889	0.699
7-Jun	2952	0.889	0.699
8-Jun	2976	0.889	0.699
9-Jun	3000	0.889	0.699
10-Jun	3024	0.89	0.7
11-Jun	3048	0.898	0.708
14 Jun	3120	0.899	0.709
15-Jun	3144	0.899	0.709
16-Jun	3168	0.901	0.711
17-Jun	3192	0.901	0.711
18-Jun	3216	0.901	0.711
21-Jun	3288	0.901	0.711
22-Jun	3312	0.901	0.711
23-Jun	3336	0.901	0.711
24-Jun	3360	0.901	0.711
25-Jun	3384	0.901	0.711
28-Jun	3456	0.902	0.712
29-Jun	3480	0.902	0.712
30-Jun	3504	0.902	0.712
1-Jul	3528	0.902	0.712
2-Jul	3552	0.903	0.713
3-Jul	3576	0.903	0.713
4-Jul	3600	0.903	0.713
5 Jul	3624	0 .903	0.713 l

6-Jul	3648	0.904	0.714
7-Jul	3672	0.904	0.714
8-Jul	3695	0.904	0.714
9-Jul	3720	0.904	0.714
10-Jul	3744	0.904	0.714
11-Jul	3768	0.904	0.714
12-Jul	3792	0.904	0.714
13-Jul	3816	0.904	0.714
14-Jul	3840	0.904	0.714
15-JUI	3864	0.904	0.714
16-Jul	3888	0.905	0.715
17-Jul	3912	0.905	0.715
18-Jul	3936	0.905	0.715
19-Jul	3960	0.905	0.715
20-Jul	3984	0.905	0.715
21-Jul	4008	0.905	0.715
22-Jul	4032	0.905	0.715
23-Jul	4056	0.905	0.715
24-Jul	4080	0.905	0.715
25-Jul	4104	0.905	0.715
26-Jul	4128	0.905	0.715
27-Jul	4152	0.905	0.715
28 Jul	4176	0.907	0.717
29-Jul	4200	0.907	0.717
30-Jul	4224	0.907	0.717
31 Jul	4248	0.907	0.717
1-Aug	4272	0.907	0.717
2-Aug	429	0.907	0.717
3-Aug	4320	0.907	0.717
4-Aug	4344	0.907	0.717
5-Aug	4368	0.907	0.717
6-Aug	4392	0.907	0.717
7-Aug	4416	0.907	0.717
8 -Aug	4440	0.907	0.717
9-Aug	4464	0.907	0.717
10-Aug	4488	0.907	0.717
11-Aug	45 12	0.907	0.717
12-Aug	45 36	0.915	0.725
13-Aug	45 60	0.915	0.725
14-Aug	4584	0.915	0.725
15-Aug	4608	0.915	0.725
16-Aug	4632	0.915	0.725
1 7-Aug	4 656	0.918	U. 725
18-Aug	4680	0.918	0.728
19-Aug	4704	0.918	0.728
20-Aug	4728	0 .918	0.728
21-Aug	4 752	0.918	0.728

22-Aug	4776	0.918	0.728
23-Aug	4800	0.918	0.728
24-Aug	4824	0.918	0.728
25-Aug	4848	0.918	0.728
26-Aug	4872	0.918	0.728
27-Aug	4896	0.918	0.728
28-Aug	4920	0.918	0.728
29-Aug	4944	0.918	0.728
30-Aug	4968	0.918	0.739
31-Aug	4992	0.929	0.739
1-Sep	5016	0.929	0.739
2-Sep	5040	0.929	0.739
3-Sep	5064	0.929	0.739
4-Sep	5088	0.929	0.739
5-Sep	5112	0.929	0.739
6-Sep	5136	0.929	0.739
7-Sep	5160	0.929	0.739
8-Sep	5184	0.929	0.739
9-Sep	5208	0.929	0.74
10-Sep	5232	0.93	0.74
11-Sep	5256	0.93	0.74
12-Sep	5280	0.93	0.74
13-Sep	5304	0.93	0.74
14-Sep	5328	0.93	0.74
15-Sep	5352	0.93	0.74
16-Sep	5376	0.93	0.74
17-Sep	5400	0.93	0.74
18-Sep	5424	0.93	0.74
19-Sep	5448	0.93	0.74
20-Sep	5472	0.93	0.74
21-Sep	5496	0.93	0.74
22-Sep	5520	0.93	0.74
23-Sep	5544	0.93	0.74
24-Sep	5568	0.93	0.74
25-Sep	5592	0.93	0.74
26-Sep	5616	0.93	0.74
27-Sep	5540	0.93	0.741
28-Sep	5664	0.931	0.741
29-Sep	5688	0.931	0.741
30-Sep	5712	0.931	0.742
1-Oct	5736	0.932	0.743
2-Oct	5760	0.933	0.743
3-Oct	5784	0.933	0.746
4-Oct	5808	0.936	0.746
5-Oct	5832	0.936	0.746
6-Oct	5856	0.936	0.746
7-Oct	5880	0,938	0.748

8-Oct	5904	0.938	0.148
9-Oct	5928	1939	0.749
1 O-Oct	5952	0.94	0.75
11 -Oct	5976	0.941	0.751
12-Oct	6000	0.941	0.751
13-Oct	6024	1941	0.151
14-Oct	6048	0.942	0.752
15-oct	6072	0.942	0.752
16-Oct	6096	0.942	0.752
17-Oct	6120	0.943	0.753
18-Oct	6144	0.943	0.753
19-Oct	6168	0.943	0.153
20-Oct	6192	0.943	0.753
21-OW	6216	0.	0.754

Tank II

H-30 I Type 11 30^{0}C

Date	Hours	Gage	Deflection (in.)
2-Feb	0	0.155	0
2-Feb	0.25	0.321	0.166
2-Feb	0.5	0.35	0.195
2-Feb	0.75	0.371	0.216
2-Feb	1	0.387	0.232
2-Feb	1.25	0.395	0.24
2-Feb	1.5	0.402	0.247
2-Feb	1.75	0.402	0.247
2-Feb	0.2	0.402	0.247
2-Feb	3.25	0.422	0.267
2-Feb	3.5	0.427	0.272
2-Feb	3.75	0.431	0.276
2-Feb	4	0.431	0.276
2-Feb	4.25	0.431	0.276
2-Feb	4.75	0.431	0.276
2-Feb	5.25	0.448	0.293
2-Feb	6.25	0.454	0.299
2-Feb	6.75	0.457	0.302
2-Feb	7.75	0.462	0.307
2-Feb	8.75	0.465	0.31
2-Feb	10.75	0.473	0.318
3-Feb	24	0.5	0.345
3-Feb	24	0.51	0.355
4-Feb	48	0.529	0.374
5-Feb	72	0.535	0.38
6-Feb	96	0.553	0.398
8-Feb	144	0.554	0.399
9-Feb	168	0.587	0.432
10 Feb	192	0.587	0.432
10-Feb	192	0.587	0.432
11-Feb	216	0.587	0.432

12-Feb	240	0.587	0.432
15-Feb	312	0.588	0.433
16-Feb	336	0.589	0.434
17-Feb	360	0.593	0.438
18-Feb	384	0.593	0.438
19-Feb	408	0.593	_0.438
22-Feb	480	0.594	0.439
23-Feb	504	0.594	0.439
24-Feb	528	0.595	0.44
25-Feb	552	0.599	0.444
26-Feb	576	0.601	0.446
1-Mar	648	0.602	0.447
3-Mar	696	0.608	0.453
4-Mar	720	0.608	0.453
5-Mar	744	0.608	0.453
8-Mar	816	0.611	0.456
9-Mar	840	0.625	0.47
10-Mar	864	0.625	0.47
11-Mar	888	0.625	0.47
12-Mar	912	0.625	0.47
15-Mar	984	0.625	0.47
16-Mar	1008	0.625	0.47
18-Mar	1056	0.628	0.473
19-Mar	1080	0.628	0.473
23-Mar	1152	0.629	0.474
24-Mar	1176	0.629	0.474
25-Mar	1200	0.629	0.474
26-Mar	1224	0.629	0.474
29-Mar	1296	0.629	0.474
30-Mar	1320	0.629	0.474
31-Mar	1344	0.631	0.476
1-Apr	1368	0.631	0.476
2-Apr	1392	0.632	0.477
5-Apr	1464	0.632	0.477
6-Apr	1488	0.632	0.477
7-Apr	1512	0.632	0.477
9-Apr	1560	0.635	0.48
13-Apr	1656	0.639	0.484
14-Apr	1680	0.639	0.484
15-Apr	1704	0.639	0.484
16-Apr	1728	0.64	0.485
19-Apr	1800	0.64	0.485
20-Apr	1824	0.64	0.485
21-Apr	1848	0.64	0.485
22-Apr	1872	0.64	0.485
23-Apr	1896	0.64	0.485
26-Apr	1968	0.643	0.488

27-Apr	1992	0.643	0.488
28-Apr	2016	0.645	0.49
29-Apr	2040	0.647	0.492
30-Apr	2064	0.648	0.493
3-May	21	0.648	0.493
4-May	2160	0.648	0.493
5-May	2184	0.648	0.493
6-May	2208	0.652	0.497
7-May	2232	0.662	0 .507
10-May	2304	0.662	0.507
11-May	2328	0.662	0.507
12-May	2352	0.662	0.507
13-May	2376	0.662	0.507
14-May	2400	0.662	0.507
17-May	2472	0.662	0.507
18-May	2496	0.662	0.507
19-May	2520	0.662	0.507
20-May	254	0.664	0.509
21-May	256	0.665	0.51
24-May	26	0.667	0.512
25-May	2664	0.667	0.512
26-May	2688	0.667	0.512
27-May	2712	0.667	0.512
28-May	273	0.667	0.512
31-May	2808	0.667	0.512
1-Jun	2832	0.667	0.512
2-Jun	2856	0.667	0.512
3-Jun	2880	0.667	0.512
4-Jun	2904	0.667	0.512
7-Jun	2928	0.667	0.512
8-Jun	2952	0.667	0.512
9-Jun	2976	0.667	0.512
10-Jun	3000	0.667	0.512
11-Jun	3024	0.667	0.512
14-Jun	30 96	0.667	0.512
15-Jun	3120	0.667	0.512
16-Jun	3144	0.667	0.512
17-Jun	3168	0.667	0.512
18-Jun	3192	0.667	0.512
21-Jun	3264	0.667	0.512
22-Jun	3288	0.667	0.512
23-Jun	3312	0.667	0.512
24-Jun	3336	0.667	0.512
25-Jun	3360	0.667	0.512
28-Jun	3432	0.667	0.512
29-Jun	3456	0.667	0.512
30-Jun	3480	0.667	0.512

1-Jul	3504	0.667	0.512
2-Jul	3528	0.667	0.512
3-Jul	3552	0.667	0.512
4-Jul	3576	0 .667	0.512
5-Jul	3600	0.667	0.512
6-Jul	3624	0.668	0.513
7-Jul	3648	0.668	0.513
8-Jul	3672	0.668	0.513
9-Jul	3695	0.668	0.513
10-Jul	3720	0.668	0.513
11-Jul	3744	0.668	0.513
12-Jul	3768	0.668	0.513
13-Jul	3792	0.668	0.513
14-Jul	3816	0.668	0.513
15-Jul	3840	0.668	0.513
16-Jul	3864	0.668	0,513
17-Jul	3888	0.668	0.513
18-JUI	3912	0.668	0.513
19-Jul	3936	0 .668	0.513
20-Jul	3960	0.668	0.513
21-Jul	398	0.668	0.513
22-Jul	4008	0.668	0.513
23-Jul	4032	0.668	0.513
24-Jul	4056	0.668	0.513
25-Jul	408	0.668	0.513
26-Jul	410	0.668	0.513
27-Jul	4128	0.668	0.513
28-Jul	4152	0:673	0.518
29-Jul	417	0.673	0.518
30-Jul	420	0.673	0.518
31-Jul	422 4	0.673	0.518
1-Aug	424 8	0.673	0.518
2-Aug	42 72	0.673	0.518
3-Aug	4296	0.673	0.518
4-Aug	4320	0.673	0.518
5-Aug	4344	0.673	0.518
6-Aug	43 68	0.673	0.518
7-Aug	4392	0.673	0.518
8-Aug	4416	0.673	0.518
9-Aug	4440	0.673	0.518
10-Aug	4464	0.673	0.518
11-Aug	4488	0.673	0.518
12-Aug	4512	0.691	0.536
13-Aug	4536	0.691	0.536
14-Aug	4560	0.691	0.536
15-Aug	4584	0.691	0.536
16-Aug	4606	0.691	0.536

17-Aug	4632	0.696	0.541
18-Aug	4656	0.696	0.541
19-Aug	4680	0.696	0.541
20-Aug	4704	0.696	0,541
21-Aug	4728	0.696	0, 41
22-Aug	4752	0.696	0.541
23-Aug	4776	0.696	0.541
24-Aug	4800	0.696	0,541
25-Aug	4824	0.696	0.541
26-Aug	4848	0.696	0.541
27-Aug	4872	0.696	0.541
28-Aug	4896	0.696	0.541
29-Aug	4920	0 .696	0.541
30-Aug	4944	0.696	0.541
31-Aug	4968	0.7	0.545
1-Sep	4992	0.704	0.549
2-Sep	5016	0.704	0.549
3-Sep	5040	0.704	0.549
4-Sep	5064	0.704	0.549
5-Sep	5088	0.704	0.549
6-Sep	5112	0.704	0.549
7-Sep	5136	0.704	0.549
8-Sep	5160	0.704	0.549
9-Sep	5184	0.708	0.553
10-Sep	5208	0.72	0.565
11-Sep	5232	0.72	0.565
12-Sep	5256	0.72	0.565
13-Sep	5280	0.72	0.565
1 4 -	5304	0.72	0.565
15-Sep	5328	0.72	0.565
16-Sep	5352	0.72	0.565
17-Sep	5376	0.72	0.565
18-Sep	5400	0.72	0.565
19-Sep	5424	0.72	0.565
20-Sep	5448	0.72	0.565
21-Sep	5472	0.72	0.565
22-Sep	5496	0.72	0.565
23-Sep	5520	0.721	0.566
24-Sep	5544	0.721	0.566
25-Sep	5568	0.721	0.566
26-Sep	5592	0.721	0.566
27-Sep	5616	0.721	0.566
28-Sep	5640	0.721	0.566
29-Sep	5664	0.721	0.566
30-Sep	5688	0.721	0.566
1-Oct	5712	0.721	0.566
2-Oct	5736	21	0.566

3-Oct	5760	0.721	0.566
4-Oct	5784	0.721	0.566
5-Oct	5808	0.721	0.566
6-Oct	5832	0.721	0.566
7-Oct	5856	0.721	0.566
8-Oct	5880	0.721	0.566
9-Oct	5904	0.721	0.566
10-Oct	5928	0.721	0.566
11-Oct	5952	0.721	0.566
12-Oct	5976	0.721	0.566
13-Oct	6000	0.721	0.566
14-Oct	6024	0.721	0.566
15-Oct	6048	0.721	0.566
16-Oct	6072	0.721	0.566
17-Oct	6096	0.721	0.566
18-Oct	6120	0.721	0.566
19-Oct	6144	0.721	0.566
20-Oct	6168	0.721	0.566
21-Oct	6192	0.721	0.566

Tank IV
H-40 Type II 40^{0}C

Date	Hours	Gage	Deflection (in.)
4-Feb	0	0.08	0
4-Feb	0.25	0.389	0.309
4-Feb	0.5	0.423	0.343
4-Feb	0.75	0.441	0.361
4-Feb	1	0.453	0.373
4-Feb	1.25	0.463	0.383
4-Feb	1.5	0.47	0.39
4-Feb	1.75	0.477	0.397
4-Feb	2	0.482	0.402
4-Feb	2.25	0.487	0.407
4-Feb	2.5	0.49	0.41
4-Feb	3.5	0.502	0.422
4-Feb	4.5	0.51	0.43
4-Feb	5.5	0.518	0.438
4-Feb	6.5	0.525	0.445
4-Feb	7.5	0.532	0.452
4-Feb	8.5	0.538	0.458
4-Feb	10	0.56	0.48
5-Feb	24	0.569	0.489
6-Feb	48	0.602	0.522
8-Feb	96	0.605	0.525
9-Feb	120	0.611	0.531
10-Feb	144	0.619	0.539
11-Feb	168	0.621	0.541
12-Feb	192	0.628	0.548
15-Feb	264	0.627	0.547
16-Feb	288	0.656	0.576
17-Feb	312	0.661	0.581
18-Feb	336	0.664	0.584
19-Feb	360	0.666	0.586
22-Feb	432	0.67	0.59
23-Feb	456	0.67	0.59

24-Feb	480	0.67	0.59
25-Feb	504	0.672	0.592
26-Feb	528	0.675	0.595
1-Mar	624	0.676	0.596
3-Mar	672	0.68	0.6
4-Mar	696	0.68	0.6
5-Mar	720	0.688	0.608
8-Mar	792	0.694	0.614
9-Mar	816	0.694	0.614
10-Mar	840	0.697	0.617
11-Mar	864	0.697	0.617
12-Mar	888	0.7	0.62
15-Mar	960	0.705	0.625
16-Mar	984	0.705	0.625
18-Mar	1032	0.707	0.627
19-Mar	1056	0.707	0.627
23-Mar	1152	0.721	0.641
24-Mar	1176	0.721	0.641
25-Mar	1200	0.721	0.641
26-Mar	1224	0.724	0.644
29-Mar	1296	0.728	0.648
30-Mar	1320	0.728	0.648
31-Mar	1344	0.729	0.649
1-Apr	1368	0.729	0.649
2-Apr	1392	0.73	0.65
5-Apr	1464	0.737	0.657
6-Apr	1488	0.737	0.657
7-Apr	1512	0.738	0.658
9-Apr	1560	0.738	0.658
13-Apr	1656	0.741	0.661
14-Apr	1680	0.741	0.661
15-Apr	1704	0.742	0.662
16-Apr	1728	0.744	0.664
19-Apr	1800	0.747	0.667
20-Apr	1824	0.747	0.667
21-Apr	1848	0.747	0.667
22-Apr	1872	0.747	0.667
23-Apr	1896	0.747	0.667
26-Apr	1968	0.753	0.673
27-Apr	1992	0.753	0.673
28-Apr	2016	0.753	0.673
29-Apr	2040	0.754	0.674
30-Apr	2064	0.751	0.671
3-May	2136	0.754	0.674
4-May	2160	0.754	0.674
5-May	2184	0.754	0.674
6-May	2208	0.754	0.674

7-May	2232	0.754	0.674
10-May	2304	0.754	0.674
11-May	2328	0.754	0.674
12-May	2352	0.755	0.675
13-May	2376	0.756	0.676
14-May	2400	0.756	0.676
17-May	2472	0.758	0.678
18-May	2496	0.758	0.678
19-May	2520	0.758	0.678
20-May	2544	0.756	0.676
21-May	2568	0.756	0.676
24-May	2640	0.761	0.681
25-May	2664	0.761	0.681
26-May	2688	0.761	0.681
27-May	2712	0.761	0.681
28-May	2736	0.761	0.681
31-May	2808	0.761	0.681
1-Jun	2832	0.763	0.683
2-Jun	2856	0.763	0.683
3-Jun	2880	0.763	0.683
4-Jun	2904	0.763	0.683
7-Jun	2976	0.763	0.683
8-Jun	3000	0.765	0.685
9-Jun	3024	0.765	0.685
10-Jun	3048	0.765	0.685
11-Jun	3072	0.765	0.685
14-Jun	3144	0.765	0.685
15-Jun	3168	0.766	0.686
16-Jun	3192	0.767	0.687
17-Jun	3216	0.767	0.687
18-Jun	3240	0.767	0.687
21-Jun	3312	0.767	0.687
22-Jun	3336	0. 769	0.689
23-Jun	3360	0.769	0.689
24-Jun	3384	0.769	0.689
25 -Jun	3408	0.769	0.689
28-Jun	3480	0.769	0.689
29-Jun	3504	0.77	0.69
30-Jun	3528	0.77	0.69
1-Jul	3552	0.77	0.69
2-Jul	3576	0.771	0.691
3-Jul	3600	0.771	0.691
4-Jul	3624	0.771	0.691
5-Jul	3648	0.771	0.691
6-Jul	3672	0.772	0.692
7-Jul	3696	0.772	0.692
8-Jul	3720	0.772	0.692

9-Jul	3744	0.772	0.692
10-Jul	3768	0.772	0.692
11-Jul	3792	0.772	0.692
12-Jul	3816	0.773	0.693
13-Jul	3840	0.7 73	0.693
14-Jul	3864	0.774	0.694
15-Jul	3888	0.774	0.694
16-Jul	3912	0.774	0.694
17-Jul	3936	0.774	0.694
18-Jul	3960	0.774	0.694
[19-Jul	3984	0.774	0.694

4-Mar	696	0.97	0.78
5-Mar	720	0.97	0.78
8-Mar	792	0.974	0.784
9-Mar	816	0.977	0.787
10-Mar	840	0.981	0.791
11-Mar	864	0.981	0.791
12-Mar	888	0.981	0.791
15-Mar	960	0.982	0.792
16-Mar	984	0.983	0.793
18-Mar	1032	0.984	0.794
19-Mar	1056	0.984	0.794
23-Mar	1152	0.992	0.802
24-Mar	1176	0.992	0.802
25-Mar	1200	0.992	0.802
26-Mar	1224	0.992	0.802
29-Mar	1296	0.992	0.802
30-Mar	1320	0.992	0.802
31-Mar	1344	0.992	0.802
1-Apr	1368	0.992	0.802
2-Apr	1392	0.994	0.804
5-Apr	1464	0.998	0.808
6-Apr	1488	0.994	0.804
7-Apr	1512	0.998	0.808
9-Apr	1560	0.998	0.808
13-Apr	1656	1.007	0.817
14-Apr	1680	1.007	0.817
15-Apr	1704	1.007	0.817
16-Apr	1728	1.007	0.817
19-Apr	1800	1.008	0.818
20-Apr	1824	1.008	0.818
21-Apr	1848	1.008	0.818
22-Apr	1872	1.008	0.818
23-Apr	1896	1.008	0.818
26-Apr	1968	1.013	0.823
27-Apr	1992	1.013	0.823
28-Apr	2016	1.013	0.823
29-Apr	2040	1.013	0.823
30-Apr	2064	1.014	0.824
3-May	2136	1.014	0.824
4-May	2160	1.015	0.825
5-May	2184	1.015	0.825
6-May	2208	1.017	0.827
7-May	2232	1.021	0.831
10-May	2304	1.021	0.831
11-May	2328	1.021	0.831
12-May	2352	1.021	0.831
13-May	2376	1.021	0.831

14-May	2400	1.021	0.831
17-May	2472	1.022	0.832
18-May	2496	1.022	0.832
19-May	2520	1.022	0.832
20-May	2544	1.022	0.832
21-May	2568	1.023	0.833
24-May	2640	1 .025	0.835
25-May		1.026	0.836
26-May	2688	1.026	0.836
27-May	2712	1.026	0.836
28-May	2736	1.026	0.836
31-May	2808	1.03	0.84
1-Jun	2832	1.03	0.84
2-Jun	2856	1.03	0.84
3-Jun	2880	1.03	0.84
4-Jun	2904	1.03	0.84
7-Jun	2976	1.032	0.842
8-Jun	3000	1.032	0.842
9-Jun	3024	1.032	0.842
10-Jun	3048	1.032	0.842
11-Jun	3072	1.032	0.842
14-Jun	3144	1.035	0.845
15-Jun	3168	1.035	0.845
16-Jun	3192	1.035	0.845
17-Jun	3216	1.035	0.845
18-Jun	324	1.035	0.845
21-Jun	3312	1.038	0.848
22-Jun	3336	1.038	0.848
23-Jun	3360	1.038	0.848
24-Jun	3384	1.038	0.848
25-Jun	3408	1.038	0.848
28-Jun	3480	1.039	0.849
29-Jun	3504	1.039	0.849
30-Jun	3528	1.039	0.849
1-Jul	35 52	1.039	0.849
2-Jul	3576	1.039	0.849
3-Jul	3600	1.039	0.849
4-Jul	3624	1.039	0.849
5-Ju1	3648	1.039	0.849
6-Jul	3672	1.044	0.854
7-Jul	3696	1.044	0.854
8-Jul	3720	1.044	0.854
9-Jul	3744	1.044	0.854
110-Jul	3768	1.044	0.854
11-Jul	3792	1.044	0.854
12-Jul	3816	1.044	0.854
13-Jul	3840	1.044	0.854

14-Jul	3864	1.044	0.854
15-Jul	3888	1.044	0.854
16-Jul	3912	1.044	0.854
17-Jul	3936	1.044	0.854
18-Jul	3960	1.044	0.854
19-Jul	3984	1.044	0.854

Tank VI
H-50I Type II 50^{0}C

Date	Hours	Gage	Deflection (in.)
9-Mar	0	0.017	0
9-Mar	0.016667	0.31	0.293
9-Mar	0.033333	0.36	0.343
9-Mar	0.05	0.452	0.435
9-Mar	0.066667	0.463	0.446
9-Mar	0.1	0.497	0.48
9-Mar	0.266667	0.513	0.496
9-Mar	0.433333	0.525	0.508
9-Mar	0.6	0.532	0.515
9-Mar	0.766667	0.537	0.52
9-Mar	0.933333	0.555	0.538
9-Mar	1	0.573	0.556
9-Mar	2	0.592	0.575
9-Mar	3.5	0.608	0.591
10-Mar	24	0.628	0.611
11-Mar	48	0.634	0.617
12-Mar	72	0.686	0.669
15-Mar	144	0.736	0.719
16-Mar	168	0.742	0.725
18-Mar	216	0.748	0.731
19-Mar	240	0.786	0.769
23-Mar	312	0.79	0.773
24-Mar	336	0.79	0.773
25-Mar	360	0.79	0.773
26-Mar	384	0.801	0.784
29-Mar	456	0.801	0.784
30-Mar	480	0.801	0.784
31-Mar	504	0.801	0.784
1-Apr	528	0.801	0.784
2-Apr	552	0.801	0.784
5-Apr	624	0.813	0.796
6-Apr	648	0.813	0.796
7-Apr	672	0.813	0.796
9-Apr	720	0.815	0.798
13-Apr	816	0.833	0.816
14-Apr	840	0.847	0.83
15-Apr	864	0.848	0.831
16-Apr	888	0.848	0.831
17-Apr	912	0.851	0.834
20-Apr	984	0.851	0.834

21-Apr	1008	0.851	0.834
22-Apr	1032	0.852	0.835
23-Apr	1056	0.852	0.835
26-Apr	1128	0.855	0.838
27-Apr	1152	0.856	0.839
28-Apr	1176	0.856	0.839
29-Apr	1200	0.856	0.839
30-Apr	1224	0.856	0.839
3-May	1320	0.856	0.839
4-May	1344	0.856	0.839
5-May	1368	0.856	0.839
6-May	1392	0.857	0.84
7-May	1416	0.859	0.842
10-May	1488	0.86	0.843
11-May	1512	0.86	0.843
12-May	1536	0.861	0.844
13-May	1560	0.861	0.844
14-May	1584	0.861	0.844
17-May	1656	0.865	0.848
18-May	1680	0.869	0.852
19-May	1704	0.869	0.852
20-May	1728	0.87	0.853
21-May	1752	0.871	0.854
24-May	1824	0.875	0.858
25-May	1848	0.877	0.86
26-May	1872	0.878	0.861
27-May	1896	0.878	0.861
28-May	1920	0.878	0.861
31-May	1992	0.886	0.869
1-Jun	2016	0.886	0.869
2-Jun	2040	0.886	0.869
3-Jun	2064	0.886	0.869
4-Jun	2088	0.886	0.869
7-Jun	2160	0.888	0.871
8-Jun	2184	0.889	0.872
9-Jun	2208	0.889	0.872
10-Jun	2232	0.889	0.872
11-Jun	2256	0.889	0.872
14-Jun	2328	0.889	0.872
15-Jun	2352	0.893	0.876
16-Jun	2376	0.893	0.876
17-Jun	2400	0.893	0.876
18-Jun	2424	0.893	0.876
21-Jun	2496	0.9	0.883
22-Jun	2520	0.9	0.883
23-Jun	2544	0.9	0.883
24-Jun	2568	0.9	0.883

25-Jun	2592	0.9	0.883
28-Jun	2664	0.903	0.886
29-Jun	2688	0.903	0.886
30-Jun	2712	0.903	0.886
1-Jul	2736	0.903	0.886
2-Jul	2760	0.903	0.886
3-Jul	2784	0.903	0.886
4-Jul	2808	0.903	0.886
5-Jul	2832	0.903	0.886
6-Jul	2856	0.911	0.894
7-Jul	2880	0.911	0.894
8-Jul	2904	0.911	0.894
9-Jul	2928	0.911	0.894
10-Jul	2952	0.911	0.894
11-Jul	2976	0.911	0.894
12-Jul	3000	0.914	0.897
13-Jul	3024	0.914	0.897
14-Jul	3048	0.914	0.897
15-Jul	3072	0.914	0.897
16-Jul	3096	0.914	0.897
17-Jul	3120	0.914	0.897
18-Jul	3144	0.914	0.897
19-Jul	3168	0.915	0.898

CHAPTER

9

DISCUSSI

ON

The discussion of the experimental and analytical findings is focused on certain recent concerns, associated with the HDPE piping related to deflection, longitudinal, and transverse stresses, long-term performance and service life prediction.

The characteristic length of the pipe, which is equal to the distance between the two inflection points for a concentrated live loading for a pipe on Winkler foundation (equations 3.1, 3.2 and 3.3), was used for the length of the specimens. The CPPA (Corrugated Polyethylene Pipe Association) and AASHTO (American Association of State Highway Transportation Officials) both specify a minimum cover of one foot. Htruck loading was of degradation. Oxidation reactions occur quite fast at super-ambient temperatures and could lead to erroneous predictions of long-term properties of HDPE pipe specimens. In view of the strong time and temperature dependence of polyethylene, application of super-ambient temperatures alone (40°C and 50°C) was used to accelerate the failure mechanisms for service life prediction of the viscoelastic HDPE pipe. A 7.5 % vertical change of diameter (the failure criterion) or more was observed for the specimens heated at 50°C and under the maximum loading.

As Aklonis and MacKnight [1983] pointed out, WLF time-temperature superposition is not an effective methodology for the prediction of long-term behavior of semi crystalline HDPE pipe [Ahn, 1999]. Therefore, life prediction, based on vertical changes of diameter, was determined from the Arrhenius equation and the Bi-directional Shifting Function Method. Both methods give similar life predictions but the BSM being more conservative.

For HDPE piping, the yield stress should not exceed 3,000 psi. Test results indicated that the maximum circumferential stress at the shoulder was approximately 436.82 psi, which is much less than the CPPA limit referred to above. The effective stress was even smaller (379.17 psi). It seems that the limit, which is based on yielding due to longitudinal bending, is not reasonable for the general failure criterion of the buried HDPE pipe subjected to live loading for the deflection 7.5% of the diameter.

The FEM software used (CANDE) has limitations for modeling of the corrugation and valley without prismatic finite elements, and cannot take into account non-uniform longitudinal soil properties and compaction. The creep was simulated from measurements of the decrease of the flexural modulus as a function of time [Ahn, 1999].

There is an agreement between experimental and CANDE deflections. The source of the error is that CANDE is two-dimensional software and surface loadings only can be defined as segmented uniform loads. CANDE cannot also take account of non-uniform longitudinal soil properties and compaction. The backfill modulus can vary along the pipe because the degree of saturation and the density of backfill soil change with time. For long-term service, it is difficult to ensure that the surrounding backfill environment will remain uniform along the pipe as in the installation stage. The backfill modulus can decrease if the degree of saturation increases. The backfill modulus can also vary along the pipe because of the degree of saturation and the density of backfill soil changing with time [Drumm et al., 1997]. Also, improper installation of the pipe and backfill soil can cause non-uniformity. Therefore, a need was identified to evaluate the long-term performance of the pipe, buried in non-uniform backfill conditions. This was addressed by an investigation of jointed pipes with the joints at the interfaces of two different soil media, simulating non-uniformity of the backfill (varying saturation and density).
Investigation of the ring showed that the rates of modulus decay are quite similar for both Type I and II notched and un-notched specimens for long-term properties.

QA (Quality Assurance)/QC (Quality Control) conditions must be clearly specified for the installation, maintenance and repair of the HDPE piping to reduce the problems associated with non-uniform backfill conditions (for example ASTM D2321 Section S and 6, and AASHTO LRFD Design Specification Sections 12.4.1 and 12.6.2).

CONCLUSIONS

The analytical and experimental investigation provided valuable information on the long-term behavior of buried HDPE pipes. Both circumferential and longitudinal bending was observed.

A 7.5 % vertical change of diameter (the failure criterion), or more, was observed at approximately 3,200 hours for the specimens heated at 50°C, and subjected to maximum service loading. A 6% to 7% vertical change of diameter was observed at 10,000 hours for the specimens heated at 40°C and subjected to maximum service loading. Therefore, extrapolation for the vertical diametral change had to be made for the ambient, i.e. 20°C temperature, to determine the corresponding time of failure. From this, life prediction at ambient temperatures (20°C), corresponding to a 7.5% change in the vertical diameter, was made from the Arrhenius and the Bi-directional Methods. The maximum service lives for specimens at ambient temperature and subjected to maximum loading, were about 80 and 30 years for unnotched and notched specimens, respectively, assuming proper installation and a 90% compaction. Notches accelerated the vertical changes of diameter but no creep-rupture was observed within the time frame of **10,000** hours.

A supplementary investigation with notched and unnotched ring specimens, exposed at the same temperatures, showed similar behavior of time transient deformation; the behavior for Types I and II was also quite similar, ii) approximately after 3,500 hours, both specimen Types I and II at 20°C became quite stable with few changes, while the specimens at temperature over 20°C indicated changes in the deflection trend. The long-term rates of modulus decay were also quite similar. But no cracking was found in all the specimens during creep testing at super-ambient temperature levels.

CANDE 2-D analysis can be used to determine longitudinal bending, if several cross-sectional locations are analyzed, and the deflections are used to define the longitudinal profile with curve fitting. This analysis for 5,6001b loading gave a deflection value of 0.20 in. compared to the experimental deflection of 0.194 in. at commencement of testing the buried pipe. The approximations associated with CANDE analysis are its restriction to two dimensions, and the specification of surface loading as segmented uniform loading. CANDE cannot also take into account non-uniform longitudinal soil properties and compaction. In the field, the backfill modulus can vary along the pipe because of varying degrees of saturation and densities. Also, it is not possible to model the corrugations.

The CPPA limit (3,000 psi), which is based on yielding due to circumferential bending, is not reasonable for the general failure criterion of the buried HDPE pipe subjected to live loading. The deflection threshold should be the governing failure criterion.

Both experimental and numerical results clearly showed that longitudinal bending moments can occur in a jointed pipe, embedded in soil with varying properties; that are high enough to open the joints and cause leakage.

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