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**REVIEW OF FIELD DEFLECTIONS OF
PLASTIC PIPES UNDER SOIL LOADS**

by

PEGGY ANN JARAMILLO

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requirements for the degree of

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ABSTRACT

The most widely accepted method for the design of flexible and very flexible pipelines buried in trenches is based on the Spangler's Equation. This equation, which is used to predict the anticipated field deflection due to backfill and traffic loads, was developed for corrugated metal pipes of large diameter. Its applicability to the design of the smaller diameter, smooth walled, thermoplastic pipes is investigated in a series of comparisons between pertinent parameters using several miles of actual field deflection measurements of pipes installed in trenches.

This study showed a trend towards increasing deflection and value of E' with depth of cover. It was not possible to establish a relationship between deflection and length of time after installation. In general, pipes of lower stiffness showed more variability in the average deflection as well as greater average deflection.

PREFACE

The author would like to thank her advisor, Professor Bezalel Haimson for seeing this work through to its completion. The author would also like to thank Carlos, Daniel, and Nicolas for their love which got her through the frustrations of writing a thesis while taking care of so many other things. And finally, the author wishes to thank her friend and mentor, Professor Jey K. Jeyapalan for his patience and perseverance without which this endeavor would have not been possible.

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LIST OF SYMBOLS

The following symbols are used in this report:

- A = Percent of line exceeding 5%
- B = Percent of line exceeding 7.5%
- C = Percent of line exceeding 10.0%
- c = Correction factor to Equation 2.1
- d = Initial pipe diameter
- D_1 = Lag factor related to long-term performance
- D_r = Deflection ratio
- e = Modulus of passive pressure of surrounding soil
- E = Modulus of elasticity of pipe material
- E' = Modulus of soil reaction
- E_s^* = Plane-strain elastic modulus of the soil
- F = Force applied
- I = Moment of inertia of pipe
- K = Bedding constant
- PS = Pipe stiffness
- r = Mean radius of the pipe
- S_f = Flexural stiffness of pipe
- t = Average wall thickness of the pipe
- w = prism load
- x = Change in horizontal internal diameter of the pipe
- y = Change in internal diameter in the direction of load application
- Y_{ave} = Average deflection

CHAPTER 1

INTRODUCTION

1.1 General

Buried pipelines form one of the lifelines of civilization as it is known today. Their main applications are (19):

1. To provide a continuous supply of potable water.
2. To transport wastes for treatment.
3. To collect runoff.
4. To transport oil, gas or chemical effluents to or from industry.

Due to their importance, the integrity of the installed pipeline should be assured. Adequate performance should be determined based on compliance with the intended purpose, ie. to carry a fluid undiminished from one place to another. Adequate design procedures and installation specifications should be applied to ensure that the following criteria are met:

1. Maintain hydraulic capacity.
2. Limit losses at the joints and connections.
3. Maintain structural integrity.

In flexible and very flexible pipe design the equation developed by Spangler (28) is routinely used to predict the anticipated field deflections due to backfill and traffic loads. Although this practice has provided numerous reliable designs, there have been failures as well as many cases where the pipeline deflected in excess of the predicted based on the Spangler's equation. For this reason, a thorough evaluation of the Spangler's equation in terms of its ability to predict actual field performance is warranted, particularly in light of the introduction of new pipe materials such as thermoplastics which were not considered in the original analysis.

Installation specifications, which are in many cases job specific, are not as standardized as the design criteria. Adequate specifications should assure that the pipe is installed according to the design assumptions. However, once the pipe is installed, verification of compliance is difficult. Therefore, deflection testing should become an integral part of the specification document.

1.2 Scope of the Research

The purpose of this research is to present deflection measurements obtained from various field installations in the United States of flexible and very flexible pipelines. The pipe diameters included in this study range from 6 inches to 24 inches which are typical of municipal sewer installations. The pipe stiffness ranged from 12.8 psi to 200 psi for materials which included high density polyethylene (HDPE), polyvinyl chloride (PVC) and a composite of lightweight concrete and PVC or acrylonitrile butadiene styrene (ABS). The bedding materials included in the study range from crushed rock to a stiff clay soil.

1.3 Organization of the Research

The literature on pipe deflection and related topics is reviewed in Chapter 2. Current methods of field deflection measurements are reported in Chapter 3. The details of the deflection measurements conducted at one site are discussed in Chapter 4. Chapter 5 presents the data base "Deflection". In addition, the variations of pipe deflection and soil modulus with important parameters are included in this chapter. The conclusions drawn from this research study and the recommendations are presented in

Chapter 6.

CHAPTER 2

LITERATURE REVIEW

The design of any pipeline begins with the selection of the appropriate pipe material. In this chapter the basic concepts of flexible and very flexible pipeline design are described.

2.1 General Classification of Pipes

Pipes are usually classified as rigid, semi-rigid, flexible or very flexible. Rigid pipes are those which deform very little under load and their predominant source of supporting capacity is the inherent strength of the pipe itself.

Flexible pipes are those which deform under vertical load, decreasing in vertical diameter and increasing in horizontal diameter. This results in a mobilization of lateral earth pressures, causing a reduction in the bending moment in the pipe wall and, as a result, produces an increase in the load carrying capacity of the pipe. Semi-rigid pipes would be those which properties fall between rigid and flexible.

Very flexible pipes are those which may deform under their

own weight and require special attention in the field.

2.1.1 Classification based on Deflection

Originally classification was based on the amount of deflection a pipe would undergo without cracking. Rigid pipes were those which would not crack for deflections less than 0.5 %, flexible pipes were those which would undergo deflections greater than 5.0 % without cracking and semi-rigid pipes were those in between ie. those which would undergo deflections from 0.5 % to 5.0 % without cracking.

2.1.2 Classification Based on Pipe Stiffness

Due to the development of pipe of increasing flexibility (Fig 2.1), the trend has been to classify pipes according to their stiffness. Under this method, rigid pipes are those with a stiffness greater than 200 psi, flexible pipes are those with a stiffness between 200 psi and 20 psi, and very flexible pipes are those which stiffness is less than 20 psi (15).

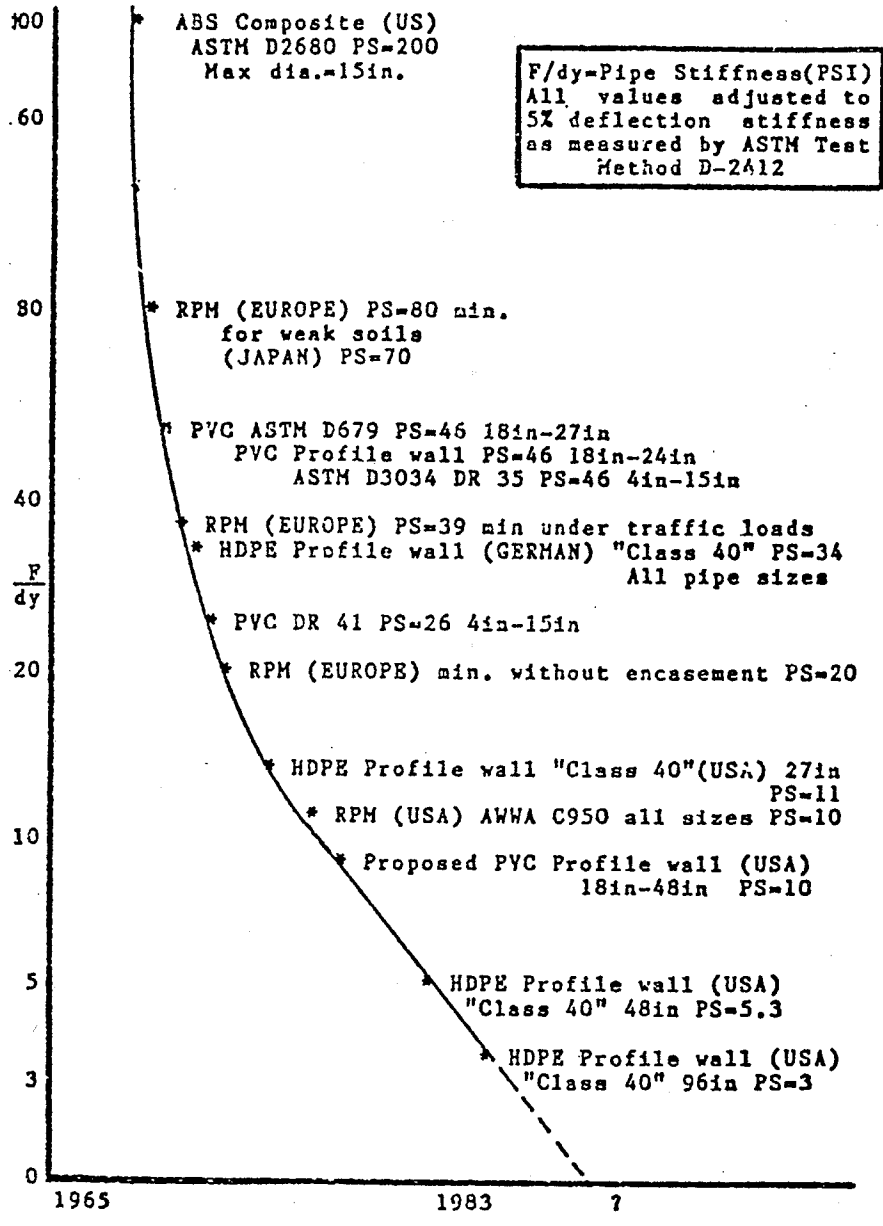


Figure 2.1 Decreasing Pipe Stiffness Trend. (Kienow and Prevost (25))

2.1.3 Determination of Pipe Stiffness

Pipe stiffness may be calculated based on the physical properties of the pipe or it may be measured in the laboratory. According to the American Society for Testing Materials (ASTM) standard D-2412 (3), pipe stiffness is defined as the force per one inch length required to produce a 5% decrease in the vertical diameter under parallel plate loading which is shown in Figure 2.2. This is defined by the equation:

$$PS = F/y \dots \dots \dots 2.1$$

where:

PS = Pipe stiffness (psi)

F = Force applied (lb/in)

y = Change in internal diameter in the direction
of load application (in)

Pipe stiffness may also be obtained from the classical work of Roark (26). In the latter, the pipe stiffness is defined as follows:

$$PS = EI/(0.149*r^3) \dots \dots \dots 2.2$$

where:

PS = Pipe stiffness (psi)

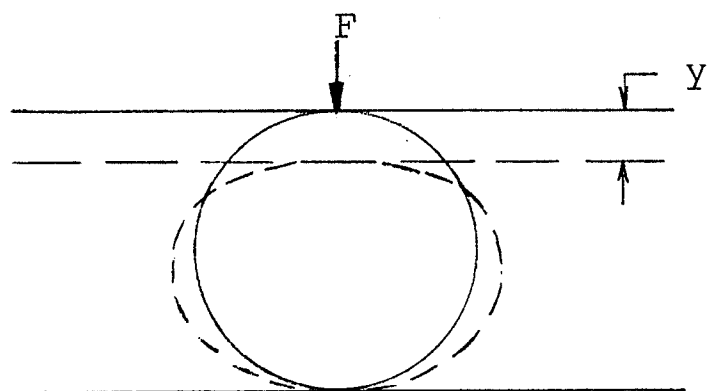


Figure 2.2 Parallel Plate Loading Diagram.

E = Modulus of elasticity of the pipe material
(psi)

I = Moment of inertia of the pipe (in⁴/in)

r = Radius of the pipe (in)

In this form, the pipe stiffness is described in terms of the physical properties of the pipe rather than in terms of a measured load carrying capacity. The numerator of the equation, EI, is a function of the modulus of elasticity of the pipe material and of the moment of inertia, I, where:

$$I = t^3/12 \dots \dots \dots 2.3$$

where:

I = Moment of inertia (in³/in)

t = Average wall thickness (in)

As such, it is a fixed value for a pipe of given material and dimensional properties. However, pipe stiffness as is defined by equation 2.1, is highly dependent on the degree of deflection because as the pipe deflects the radius of curvature changes. For this reason, the greater the deflection at which the pipe stiffness is determined, the greater the magnitude of deviation from the true EI value. By application of the correction factor:

$$c = (1+(y/2d))^3 \dots \dots \dots 2.4$$

where:

c = Correction factor (no units)

y = Deflection in the vertical diameter (in)

d = Initial pipe diameter (in)

the measured pipe stiffness can be related to the true section modulus of the pipe as long as the pipe remains elliptical (3).

2.2 Deflection

Flexible and very flexible pipes require a certain amount of deflection to mobilize lateral passive pressures in order to develop the full supporting strength of the soil-structure system. Deflection, although necessary, should be limited for the following reasons (10,24):

1. Excessive deflection may induce strains which are too high for the pipe wall material leading to structural failure.
2. Joint performance is intimately related to the amount of deflection in the line near the connection.

3. Excessive deflection makes future "tap ins" difficult.
4. Since thermoplastics tend to creep with time under load, immediate deflection provides an estimate of the maximum deflection expected in the pipeline over its useful life.
5. Cleaning of the line is more difficult with excessive deflection.

2.2.1 ASTM Standards

There are many standards which make reference to the deflection of flexible and very flexible pipelines written by ASTM. Some deal with the physical properties of the pipe itself and others deal with the installation. Both PVC and HDPE are covered under the standards pertaining to thermoplastic piping.

ASTM standard D-2321 (2) describes procedures and recommendations for the underground installation of flexible thermoplastic sewer pipe. These procedures are written under the assumption that the pipe will behave according to

"flexible conduit theory". It unfortunately does not define "flexible conduit theory" nor does it provide any information on where this may be found. It states that pipes with stiffness greater than 25 psi, as determined by standard D-2412 (3), have been found to perform satisfactorily when installed according to this standard. In standard D-2321, ASTM takes no position on maximum allowable deflection nor on deflection testing. It further adds that the engineer is responsible for limiting or establishing an acceptable deflection.

In Standards F-679 (6) and D-3034 (5), ASTM recommends (not requires) that the internal diameter should not be reduced by more than 7.5% when measured not less than 30 days following completion of installation. Contrary to standard D-2321 (2), these standards give reference to several pipe stiffnesses and in effect, recommend deflection testing as well as limiting deflection.

A similar standard may be found for the ABS or PVC composite truss pipe. Standard D-2680 requires that the pipe undergo 7.5% deflection in parallel plate loading without rupture of the inner or outer wall. It must also have a pipe stiffness of 200 psi at 5% as measured under standard D-2412. No other reference is made to deflection measurement or testing.

2.2.2 Total Deflections

Total deflections of flexible or very flexible pipelines are composed of the following: deflection due to installation, deflection due to earth loads, deflection due to traffic loads, and deflection due to the effects of time. All factors should be given consideration if the design is to be considered adequate.

2.2.3 Installation-Induced Deflections

Most of the deflection a flexible pipeline will experience during its lifetime will occur during its installation and during the initial consolidation of the backfill. This is called the installation or initial deflection, the majority of which will occur within 30 days of installation. An example of typical values for PVC pipe as recommended by the National Cooperative Highway Research Program of the National Research Council, NCHRP (24), are shown in Table 2.1. The Spangler's equation was developed for calculation of the initial deflection.

TENTATIVE DESIGN INSTALLATION DEFLECTIONS
FOR HAUNCHED PIPE

Pipe Stiffness (lb/in./in.)	Installation Deflection (%) (1)		
	Less Than 85% of Max. Dry Density (2) or Dumped (3)	85 to 95% of Max. Dry Density (2)	Greater Than 95% of Max. Dry Density (3)
Less Than 40	6+	4	3
40 to 100	4+	3	2
Greater than 100	2+	2	1

- Notes:
1. Deflections of unhaunched pipe are significantly larger.
 2. Maximum dry density determined in accordance with AASHTO T 99.
 3. Dumped materials and materials with less than 85% of maximum dry density are not recommended for embedment. Deflection values are provided for information only.
 4. 1 lb/in./in. = 1 psi = 6.9 kPa

**Table 2.1 Tentative Design Installation
Deflections For Haunched Pipe.
(NCHRP (24))**

2.2.4 Time Dependent Deflections

Most pipelines are expected to perform over a period of many years based on their useful life. For this reason the effects of time on the flexible or very flexible pipe must be considered.

Thermoplastics have a tendency to creep with time under constant load (9). This is due to the rearrangement of the chemical bonds which connect the long-chain molecules which form the polymer. This causes an increase in deflection with time and is aggravated by increasing temperature and stress. The modulus of elasticity of the thermoplastic also decreases with time. For example, high density polyethylene's modulus of elasticity drops to approximately 1/5 of its short term value in 50 years time at an ambient temperature of 73.4 degrees Fahrenheit (7,16,25). This phenomenon, which is temperature sensitive, causes a decrease in the pipe stiffness which contributes to an increase in deflection. The designer should take this into account by the selection of a long term rather than a short term modulus of elasticity corresponding to the anticipated design life of the pipeline.

Time also affects the stiffness response of the embedment soil surrounding the pipe. The amount of deflection lag depends on soil type, degree of compaction, water conditions, trench geometry, and other factors (24).

Although most of this consolidation is expected to occur in the first 30 days following installation, Spangler (28) demonstrated that this trend may continue for several years. This is normally taken into account by the use of a lag factor, D_1 , in equation 2.3. The use of lag factors in the range of 1.0 to 1.5 are recommended when using Howard's E' values (14). In addition, NCHRP (24) field tests indicate that this response may be accelerated by traffic during construction.

2.2.5 Spangler's Equation

The most widely accepted method for predicting the deflection in flexible and very flexible pipes is the Modified Spangler's Equation. Spangler relied on the idealized load distribution shown in Figure 2.3 in order to develop this equation given by:

$$x = (D_1 * K * W_C) / (EI/r^3 + 0.061 * E') \dots \dots \dots 2.3$$

where:

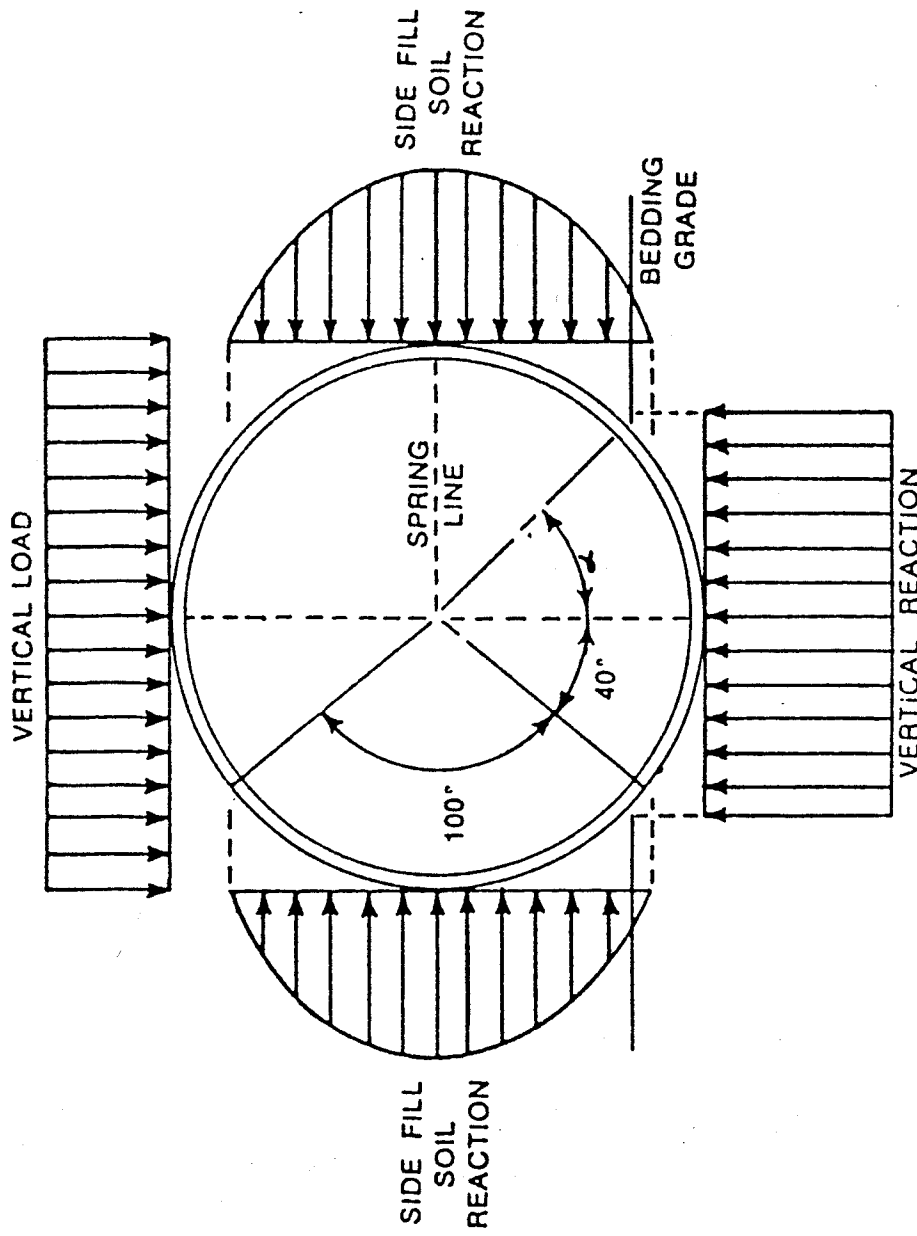


Figure 2.3 Theoretical Load Distribution.
(Spangler (28))

- x = Change in horizontal internal diameter of the pipe (in)
- D_1 = Lag factor related to long-term performance
- K = Bedding constant
- W = Prism load (lb/in)
- E = Modulus of elasticity of the pipe material (psi)
- I = Moment of inertia of the pipe (in⁴/in)
- r = Mean radius of the pipe (in)
- E' = Modulus of the soil reaction (psi)

This equation relies on the use of a pipe stiffness either provided by the manufacturer or measured in the laboratory. Some variation in the actual pipe stiffness may occur due to the tolerances involved in the manufacturing process. This variation is in most cases conservative since the pipe dimensions are given as minimum internal diameters and minimum wall thicknesses. The modulus of soil reaction, E' , will vary considerably as will be shown later. This may cause error in the predicted deflection based on the use of the Spangler's equation. In addition, the magnitude of the prism load will vary depending on the properties of the backfill material on site.

2.2.6 Limitations for the use of the Spangler Equation

The Spangler's Equation was derived using 36-60 inch diameter corrugated metal pipe of stiffness values in the range of 24 to 130 psi with a depth of cover of 15-16 feet. The equation also relies on an empirical distribution for the lateral soil pressures. However, since very little information is available on actual field installations, the applicability of this equation to flexible pipelines manufactured with today's materials is questionable.

According to Spangler and Handy (30), the equation involves elastic constants of the pipe and may not be applicable if stressed beyond the elastic limit. The selection by ASTM of 5 % as a basis for comparison of pipe stiffness was probably chosen for this very reason, since the behavior of most thermoplastic pipe materials can be described as elastic over this range.

In the development of the equation, one of the fundamental assumptions was that the pipe deform elliptically. The elliptical response corresponds to conditions resulting from uniform load and support distributions with homogeneous and isotropic surrounding materials (20). There are several examples of variations from the presumed elliptical behavior which may be found in the literature. Jeyapalan and Abdel-

Magid (18) have shown that a pipe may elongate during initial backfilling, increasing in vertical diameter particularly in the case of very flexible pipe as shown in Figure 2.4. Kienow and Prevost (25) have shown that squaring of the pipe can occur when very flexible pipe is installed in stiff backfill taking the shape which is shown in Figure 2.5. This phenomena will occur if horizontal deflection slows or stops while vertical deflection continues. More recently, Lang and Howard (20) have described the variation in the deformed shape of the pipe with soil type and compactive effort as shown in Figure 2.6. Lang and Howard conclude that the pipe response under backfill load is more nearly elliptical when the embedment is loose. This is however, at the cost of higher deflection and higher pipe wall strains.

The corrugated metal pipes used in the original Spangler experiment (28) had stiffnesses ranging from 24 to 130 psi. The recent trend has been to use pipes of ever increasing flexibility down to a pipe stiffness of 3 psi as is reported by Kienow and Prevost (25). Field data relating to the performance of these pipes is scarce.

The discipline of Soil Mechanics has made much progress since the introduction of the Spangler's equation in 1941. However, despite recent advances such as those made by

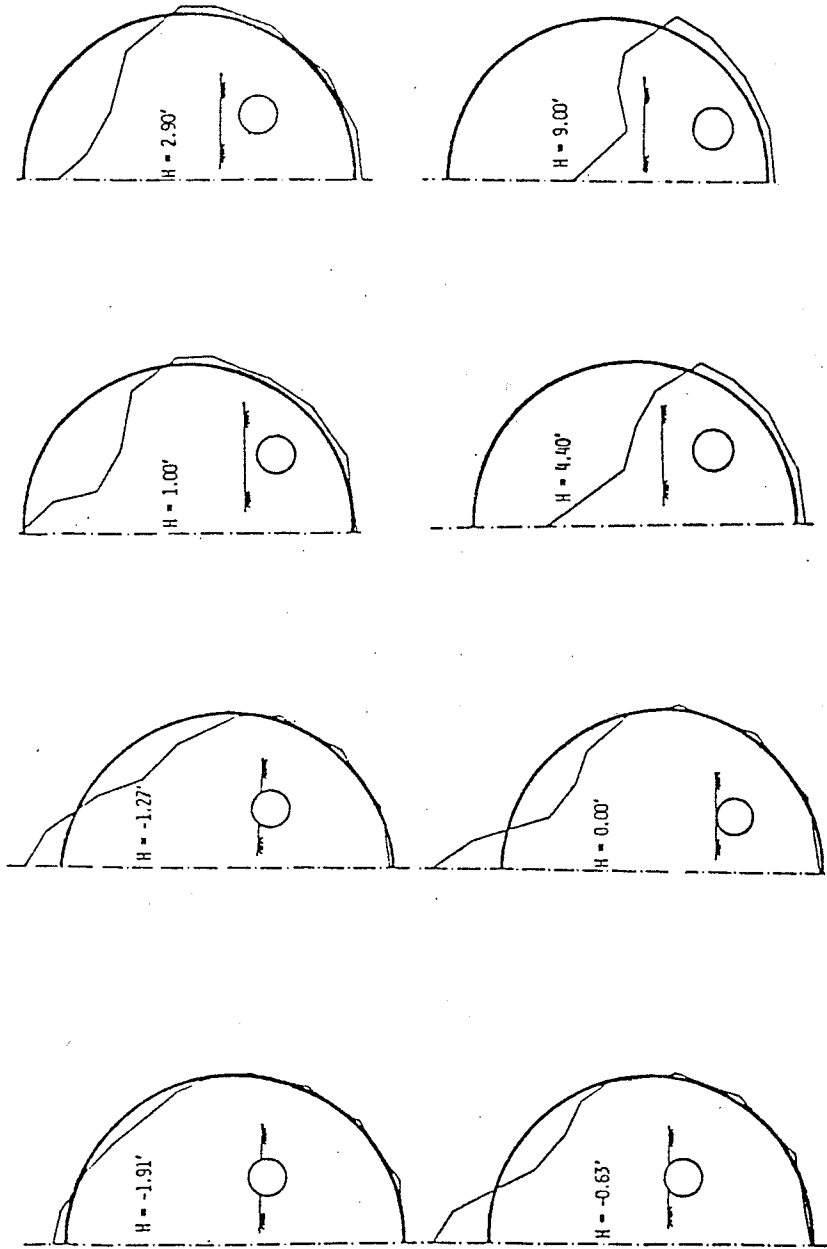


Figure 2.4 Vertical Elongation with Placement of Backfill.
(Jeyapalan and Abdel-Magid (18))

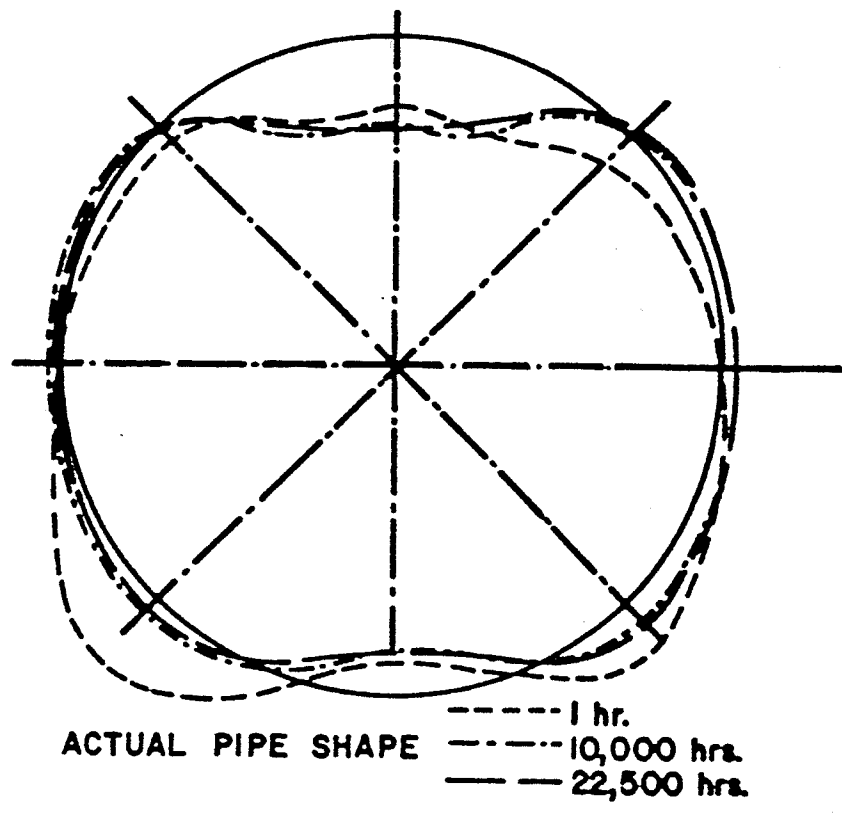


Figure 2.5 Pipe Squaring.
(Prevost and Kienow(25))

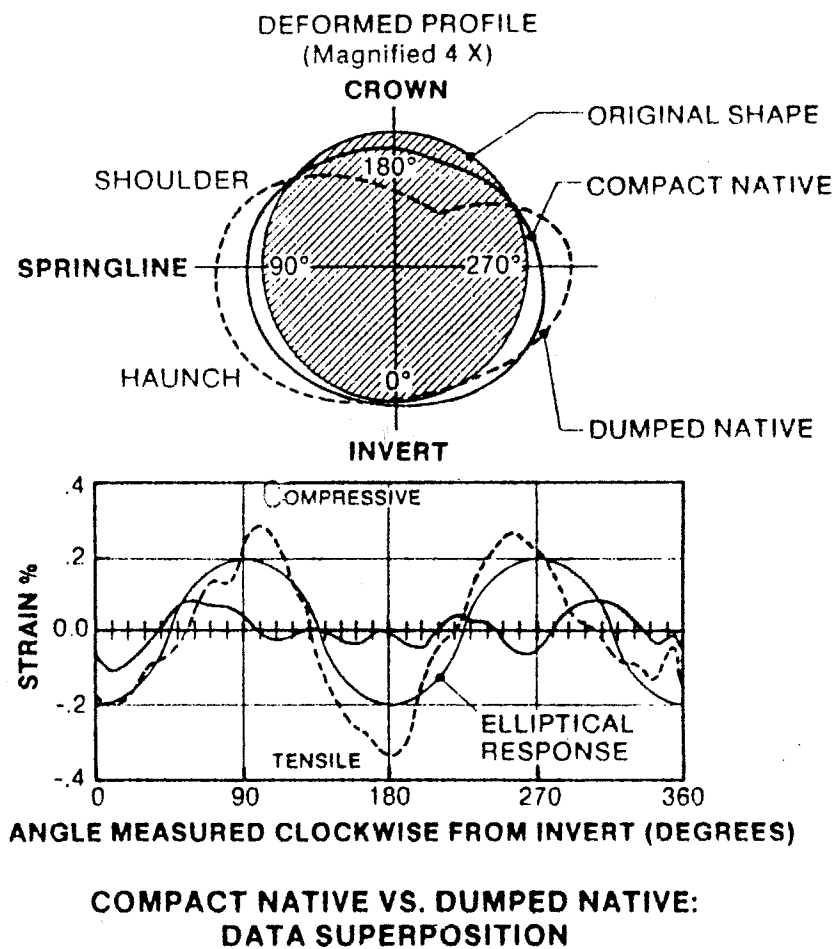


Figure 2.6 Deviation From Elliptical Behavior.
(Lang and Howard (20))

Howard (14), Hartley and Duncan (12,13), as well as many others, very little is known about E' , the modulus of soil reaction. This is a major source of uncertainty in the deflection calculation.

2.3 Effects of Lateral Soil Pressures on Deflection

Lateral pressures provided by the soil surrounding the flexible or very flexible pipe make possible a field supporting strength not available from the pipe alone. Luscher and Hoeg (21) describe the phenomena as lateral earth pressure resisting movement causing a redistribution of pressures around the pipe so as to create pure hoop compression in the tube which is the most efficient means of carrying the load. It is important to note that this description correlates well with Castigliano's second theorem (22), or the method of least work in terms of conservation of energy of a system.

Spangler measured these lateral earth pressures and concluded that they were roughly symmetrical about the springline. It is interesting to note that the lateral earth pressures measured prior to placement of fill above the crown of the pipe were subtracted off based on the assumption that since there was no deflection, these

pressures did not apply (28). According to classical Rankine earth pressure theory, the minimum thrust would be proportional to the at-rest earth pressure which by definition, requires no lateral movement (31). In the case of a very large pipe of low pipe stiffness, these initial pressures would probably have an effect on the behavior of the pipe and would merit consideration in the analysis.

2.4 Modulus of Soil Reaction, E'

Much research has been done on the modulus of soil reaction. In the original work done by Spangler, e , the modulus of passive pressure of the enveloping earth, was found to be constant for a given material (28). E' was defined as:

$$E' = e * r \dots \dots \dots 2.4$$

where:

E' = Modulus of soil reaction (psi)

e = Modulus of passive pressure of the surrounding soil (psi/in)

r = Radius of the pipe (in)

suggesting the interdependence of the soil and the pipe. The values of e from Spangler's work are given in Table 2.2. Later studies done at the Bureau of Reclamation by Howard (14) show the variation of E' with soil type as well as degree of compaction as shown in Table 2.3. More recently, Hartley and Duncan (12,13) demonstrated the variation of E' with depth through the use of hyperbolic soil parameters and finite element analyses of steel pipes (Table 2.4).

Currently the most widely accepted method for the determination of E' has been through the use of Howard's table of values, primarily due to its simplicity. There are several problems with the use of the values reported by Howard and these are as follows:

1. E' , is based solely on the properties of the soil and therefore, can not be expected to describe the interaction which goes on between the soil and the pipe (14).
2. E' is dependent on the depth of cover as shown by Hartley and Duncan (12,13).

Experiment No.	Kind of soil	Value of e , lb. per sq. in. per in.
1	Black silty loam (not compacted)	14
2	Well-graded gravel (not compacted)	32
3	Yellow sandy clay loam (not compacted)	13
	Yellow sandy clay loam (tamped, dry)	27

Table 2.2 Variation of the Modulus of Passive Pressure of the Enveloping Earth. (Spangler (28))

Soil type-pipe bedding material (Unified Classification System*) (1)	E' for Degree of Compaction of Bedding, in pounds per square inch			
	Dumped (2)	Slight, <85% Proctor, <40% relative density (3)	Moderate, 85%–95% Proctor, 40%–70% relative density (4)	High, >95% Proctor, >70% relative density (5)
Fine-grained Soils (LL > 50) ^b Soils with medium to high plasticity CH, MH, CH-MH	No data available; consult a competent soils engineer; Otherwise use E' = 0			
Fine-grained Soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with less than 25% coarse-grained particles	50	200	400	1,000
Fine-grained Soils (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25% coarse-grained particles	100	400	1,000	2,000
Coarse-grained Soils with Fines GM, GC, SM, SC ^c contains more than 12% fines				
Coarse-grained Soils with Little or No Fines GW, GP, SW, SP ^c contains less than 12% fines	200	1,000	2,000	3,000
Crushed Rock	1,000	3,000	3,000	3,000
Accuracy in Terms of Percentage Deflection ^d	±2	±2	±1	±0.5

*ASTM Designation D-2487, USBR Designation E-3.

^bLL = Liquid limit.

^cOr any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).

^dFor ±1% accuracy and predicted deflection of 3%, actual deflection would be between 2% and 4%.

Note: Values applicable only for fills less than 50 ft (15 m). Table does not include any safety factor. For use in predicting initial deflections only, appropriate Deflection Lag Factor must be applied for long-term deflections. If bedding falls on the borderline between two compaction categories, select lower E' value or average the two values. Percentage Proctor based on laboratory maximum dry density from test standards using about 12,500 ft-lb/cu ft (598,000 J/m³) (ASTM D-698, AASHTO T-99, USBR Designation E-11). 1 psi = 6.9 kN/m².

Table 2.3 Bureau of Reclamation's Values of E' for the Spangler's Equation. (Howard (14))

—Design Values of E' (psi)

Type of soil (1)	Depth of cover (ft) (2)	Standard AASHTO Relative Compaction			
		85% (3)	90% (4)	95% (5)	100% (6)
Fine-grained soils with less than 25% sand content (CL, ML, CL-ML)	0-5	500	700	1,000	1,500
	5-10	600	1,000	1,400	2,000
	10-15	700	1,200	1,600	2,300
	15-20	800	1,300	1,800	2,600
Coarse-grained soils with fines (SM, SC)	0-5	600	1,000	1,200	1,900
	5-10	900	1,400	1,800	2,700
	10-15	1,000	1,500	2,100	3,200
	15-20	1,100	1,600	2,400	3,700
Coarse-grained soils with little or no fines (SP, SW, GP, GW)	0-5	700	1,000	1,600	2,500
	5-10	1,000	1,500	2,200	3,300
	10-15	1,050	1,600	2,400	3,600
	15-20	1,100	1,700	2,500	3,800

Table 2.4 Design Values for E' .
(Hartley and Duncan (12))

3. The values given for E' apply only to the initial deflections and no consideration is given to the effects of time (14).
4. The results are not applicable for flexible pipe buried under fills in excess of 50 feet (14).
5. The effects of the interaction between the trench wall material with the bedding material are not taken into account (14).

2.5 Importance of Pipe-Soil Stiffness Ratio in Flexible Pipe Performance

As more importance has been given to the soil-structure interdependence, researchers are paying more attention to the pipe-soil stiffness ratio which is defined as follows:

$$PS_r = EI/E'r^3 \dots \dots \dots 2.5$$

where EI/r^3 represents the pipe stiffness and E' , the soil stiffness.

Gumbel et al. (33) have shown the effects of the pipe-soil stiffness ratio on the distribution of the load as shown in Figure 2.7. The percentage of the total load carried by the pipe depends on this ratio which they defined as follows:

$$Y = E_s^* / S_f \dots \dots \dots 2.6$$

where:

E_s^* = Plane-strain elastic modulus of the soil.

S_f = Flexural stiffness of the pipe.

They have shown that for a pipe-soil stiffness ratio, Y , less than 10, ie. the stiffness of the pipe is high compared to the surrounding soil, more than 90% of the backfill load is carried by the ring bending action of the pipe. For a value of Y between 10 and 1000, the proportion reduces from 90% to 10% and for Y greater than 1000 the pipe carries less than 10% of the load, the remainder being transmitted to the surrounding soil.

Jeyapalan et. al. (17,18) have also studied the importance of pipe-soil stiffness ratio in flexible pipe design. The relation between the pipe-soil stiffness ratio and the deflection ratio, which is defined as the deviation of the

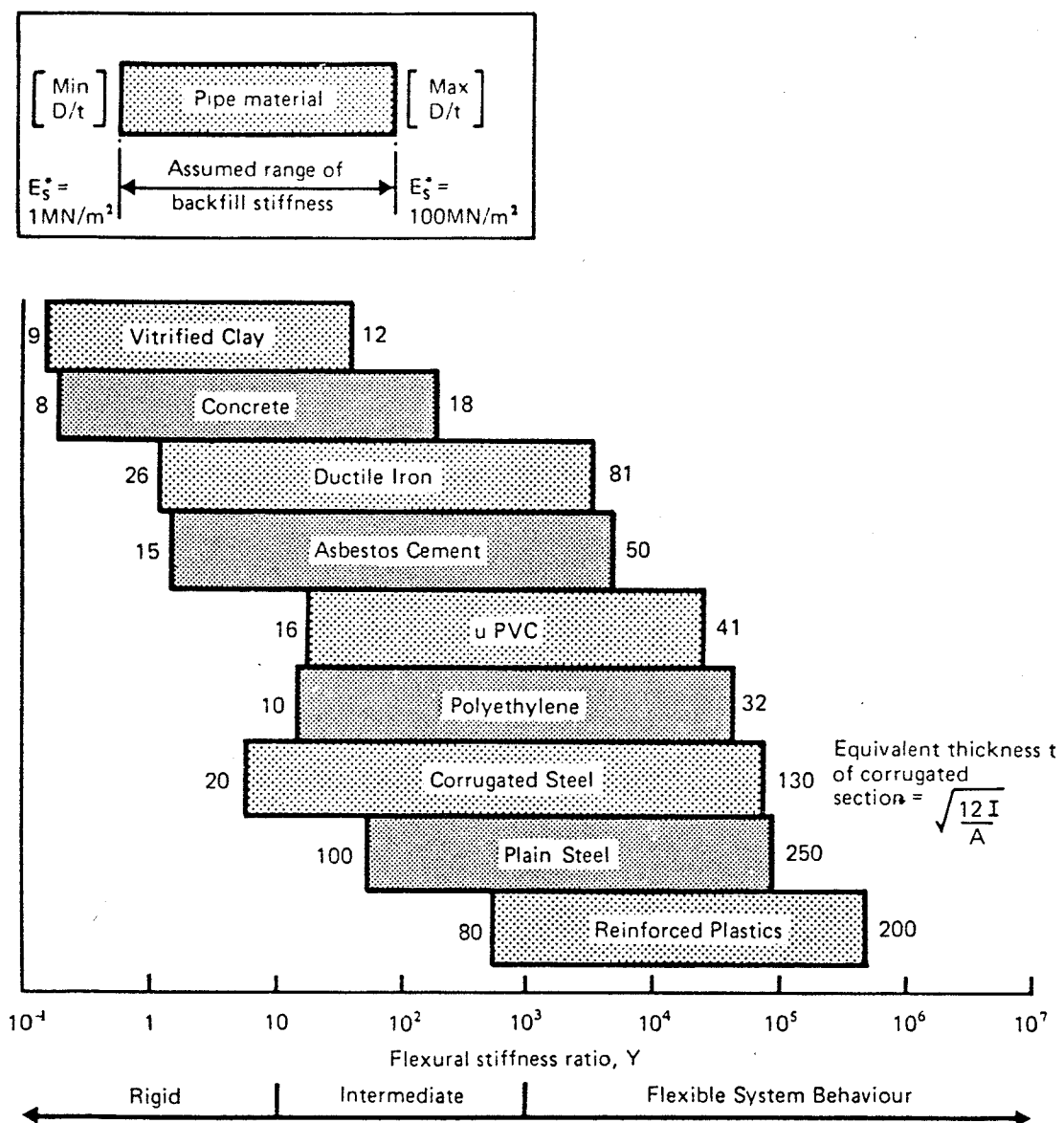


Figure 2.7 Pipe Behavior Based on Pipe-Soil Stiffness Ratio.
 (Gumbel (33))

pipe from the elliptical,

$$D_r = y/x \dots \dots \dots 2.6$$

where:

D_r = Deflection ratio

y = Vertical deflection (%)

x = Horizontal deflection (%)

is shown in Figure 2.8. They conclude that the vertical deflection and the horizontal deflection are not equal for flexible pipes under backfill loads and that the deflection ratio, or the deviation from elliptical behavior, increases with soil stiffness and with decreasing pipe stiffness (18).

Lang and Howard (20) also suggest that there is a shape-deflection trade off which is related to an interaction of the following pipe parameters: pipe thickness, pipe deflection, and deformation factor and the following soil parameters: embedment soil type and degree of embedment compaction. They conclude that stiff backfill and elliptical response are contradictory. The pipe in loose embedment deforms elliptically because the lateral soil pressure is low and therefore does not resist horizontal

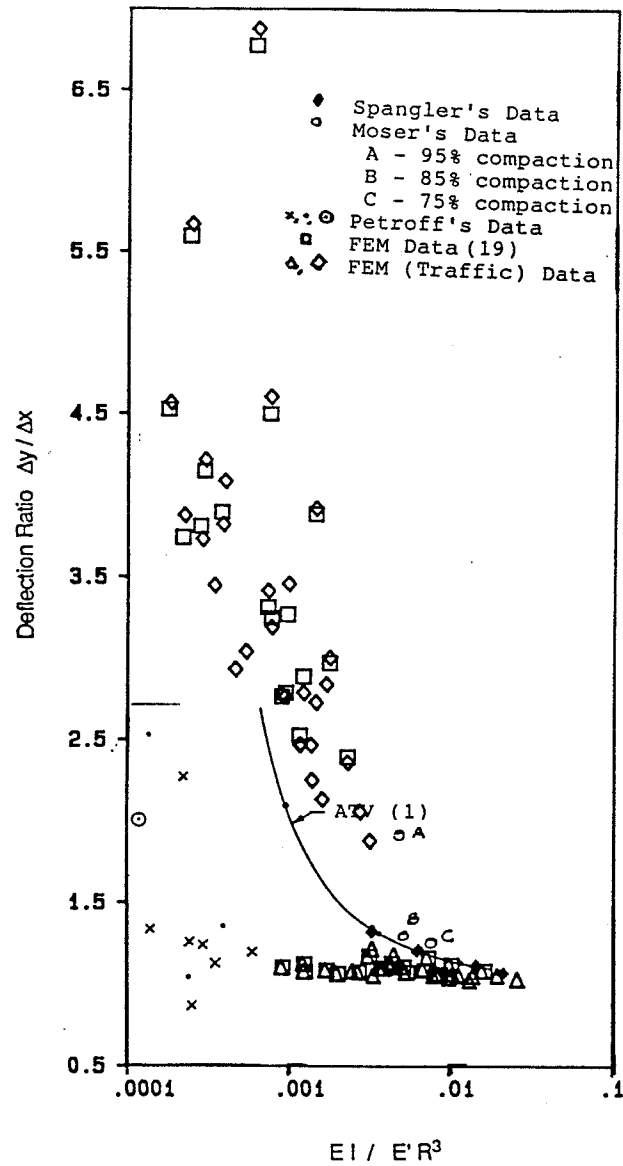


Figure 2.8 Variation of Deflection with Pipe-Soil Stiffness Ratio. (Saleira (27))

deformation. It is also interesting to note that their evidence indicates that compact sand embedment results in a behavior that is essentially more elliptical in nature than in compacted native soil of type ML. They believe this behavior is due to a lower degree of compaction in the sand and the fact that the sand was compacted by saturation and vibration rather than by mechanical tamping which was performed on the compacted native soil.

It is interesting to note that even Spangler back in 1941 (28) suggested the influence of the term, EI , which represents the influence of the pipe strength, with the term $0.061er^4$, which represents the influence of the lateral pressure developed by the fill material.

2.6 Summary

The Spangler's equation was developed based on a very thorough scientific investigation. For its time it was a breakthrough in the design of flexible pipelines. The simple fact that the equation is still in use today, after almost 50 years with very little addition or change, testifies to its thoroughness. Spangler unfortunately did not have the benefit of the developments which were made in soil mechanics over the last 50 years. Nor could he have

developed a general equation which would be applicable to pipe materials which did not exist at the time.

It is the opinion of the author that one can not remain in the past. The scientific community can and must bring this equation up to date with what was learned in the last 50 years or develop an alternative. It is the hope of the author that the presentation of the field data contained within this report makes a contribution towards attaining this goal.

CHAPTER 3

METHODS OF DEFLECTION TESTING

3.1 Introduction

Various methods for determining the extent of deformation under in-situ loading conditions of flexible and very flexible pipelines are available. The amount of deflection is determined by measuring the existing internal diameter of the pipe and subtracting it from a reference internal diameter which is usually obtained from standard specifications such as those of ASTM. The following is a description of the methods currently in use in the United States.

3.2 Lamping

Lamping is a quick method for the determination of the existence or absence of gross deflections along an installed line. This rather crude method consists of shining a

flashlight at one end of the line towards someone standing at the other end of it. The only information obtained is whether large deflections were incurred along the pipeline or not. The operator can, at best, only guess at the location of the problem. This method is routinely used on pipelines where no other method of deflection testing is specified.

3.3 Mandrels

One of the most widely accepted methods of deflection testing is the go, no-go mandrel which is shown in Figure 3.1. Typical dimensions for a 9 arm mandrel are shown in Table 3.1. This apparatus is towed through the line after installation to determine compliance or non-compliance with installation specifications based on passage or non-passage. Non-compliance typically requires the contractor dig up and reinstall or reround the section of deflected pipe which did not permit the passage of the mandrel. One manufacturer of mandrels recommends that testing of the line be performed no earlier than 30 days after reaching final trench grade "provided in the opinion of the engineer that sufficient densification or rainfall has occurred to thoroughly settle the soil throughout the entire trench depth". In addition,

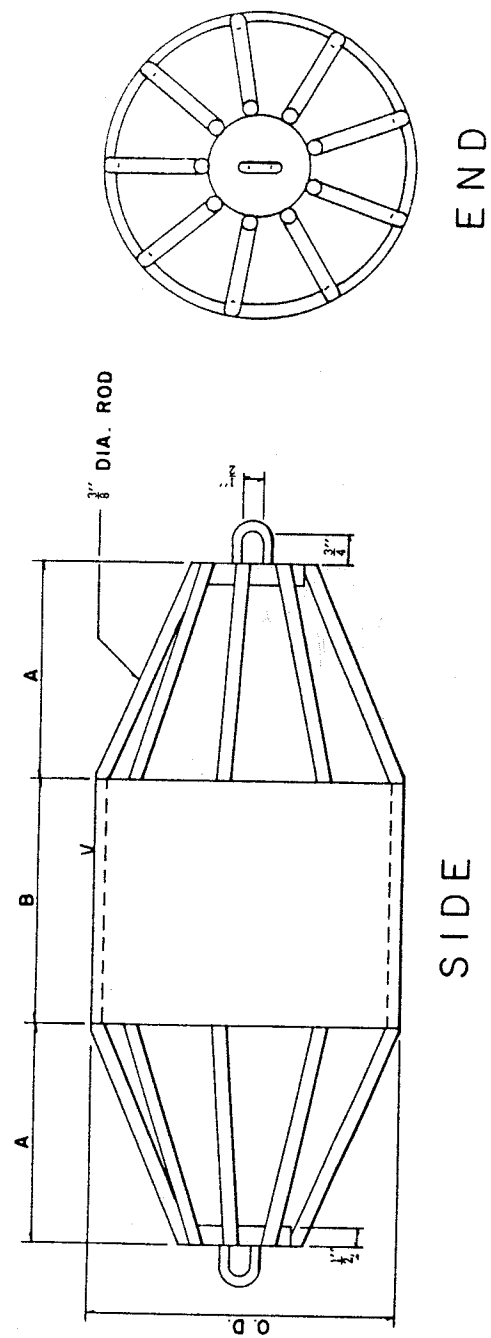


Figure 3.1 Go, No-Go Mandrel.

MANDREL O.D.				
SIZE	A	B	PVC ASTM 3034 DR-35 PSM (XH)	ABS COMPOSITE ASTM 2680
6	4.0	4	5.620	
8	5.3	6	7.520	7.360
10	6.7	6	9.410	9.260
12	8.0	8	11.190	11.160
15	10.0	9		14.010

Table 3.1 Go, No-Go Mandrel Dimensions.

cleaning of the line is recommended prior to testing to prevent erroneous conclusions based on obstructions due to the accumulation of sediment in the bottom of the pipe.

This particular method is quick and inexpensive and requires no special training for its use. Its main drawback is that the only information obtained from the test is compliance versus non-compliance and that no qualitative information on actual deflection along the line is obtained.

3.4 Mechanical Caliper Deflectometers

Caliper deflectometers are an improvement over the go, no-go deflectometers for more accurate deflection testing. These mechanical devices are typically sled-type devices with spring loaded adjustable arms mounted and pivoted at one end. Calibrated scales are fastened to horizontal and vertical arms which are used to measure variations in the horizontal and vertical diameters. One example is shown in Figure 3.2. The caliper is towed through the line after cleaning and after initial calibration of the instrument. It is recommended that the testing be done no earlier than 30 days after completion of the backfill.

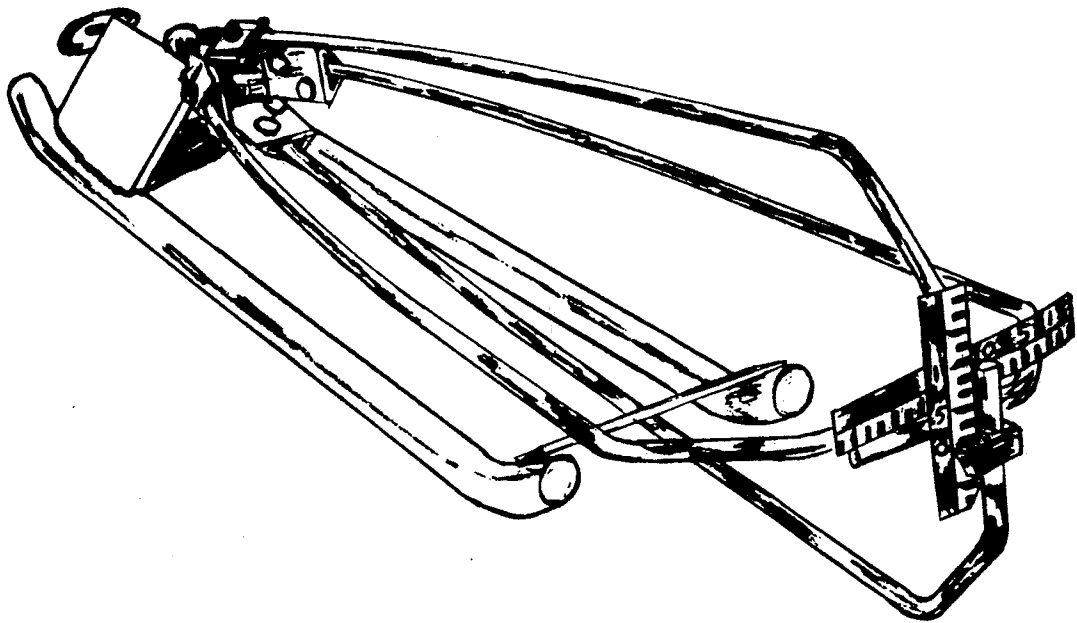


Figure 3.2 Mechanical Caliper Deflectometer.

Although relatively simple to operate, the accuracy of the mechanical caliper is limited to the accuracy of the scale which may only read to the nearest tenth of an inch. These have been used in conjunction with television cameras to obtain additional information about the existing condition of the pipeline.

3.5 Electronic Deflectometers

Other configurations of deflectometers have been developed by some industries for a specific job or purpose. One example is the sled mounted deflectometer which is shown in Figure 3.3. This model includes a strain gage which measures vertical deflection to the nearest one hundredth of an inch if properly calibrated. The data obtained is transmitted automatically to the recorder where graphs like the one shown in Figure 3.4 are produced. Its accuracy is better than that of the mechanical deflectometer but its cost is higher. For this reason it may only be warranted in case of a large project. The main disadvantage of this particular deflectometer is that it is not equipped with an odometer to measure distances.

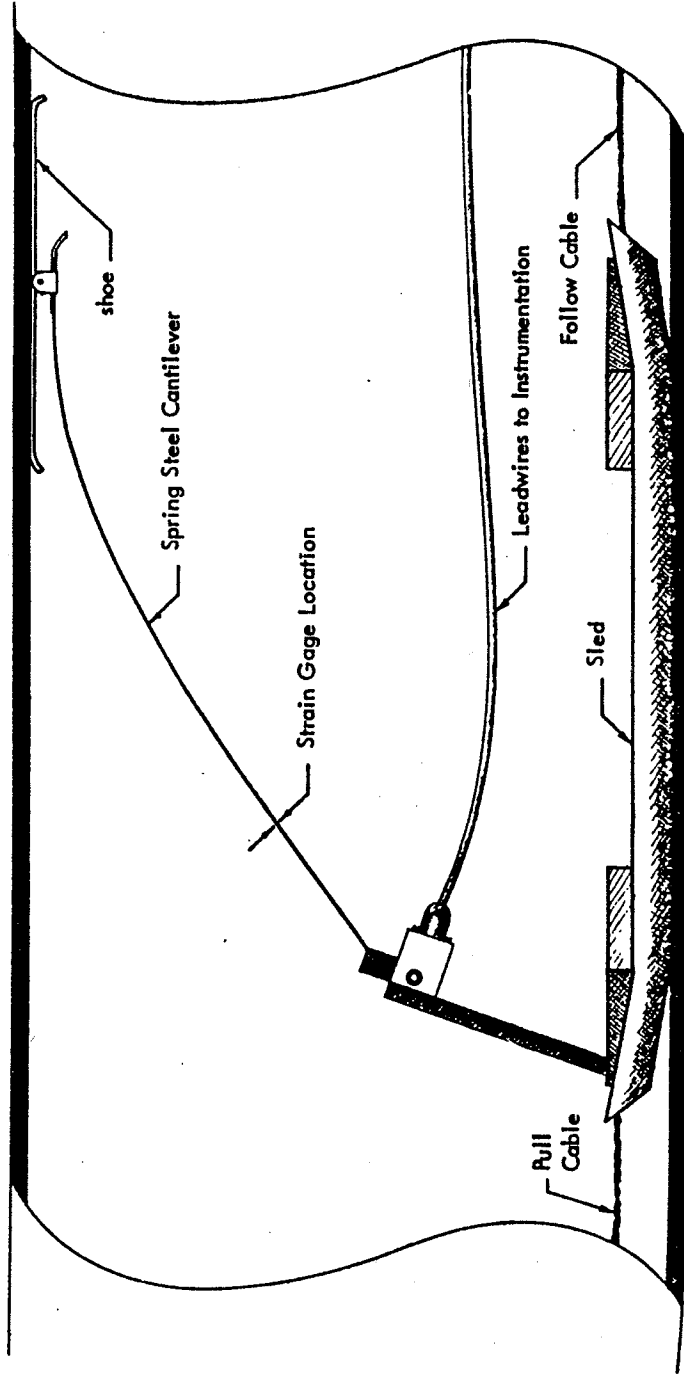


Figure 3.3 Electronic Deflectometer.

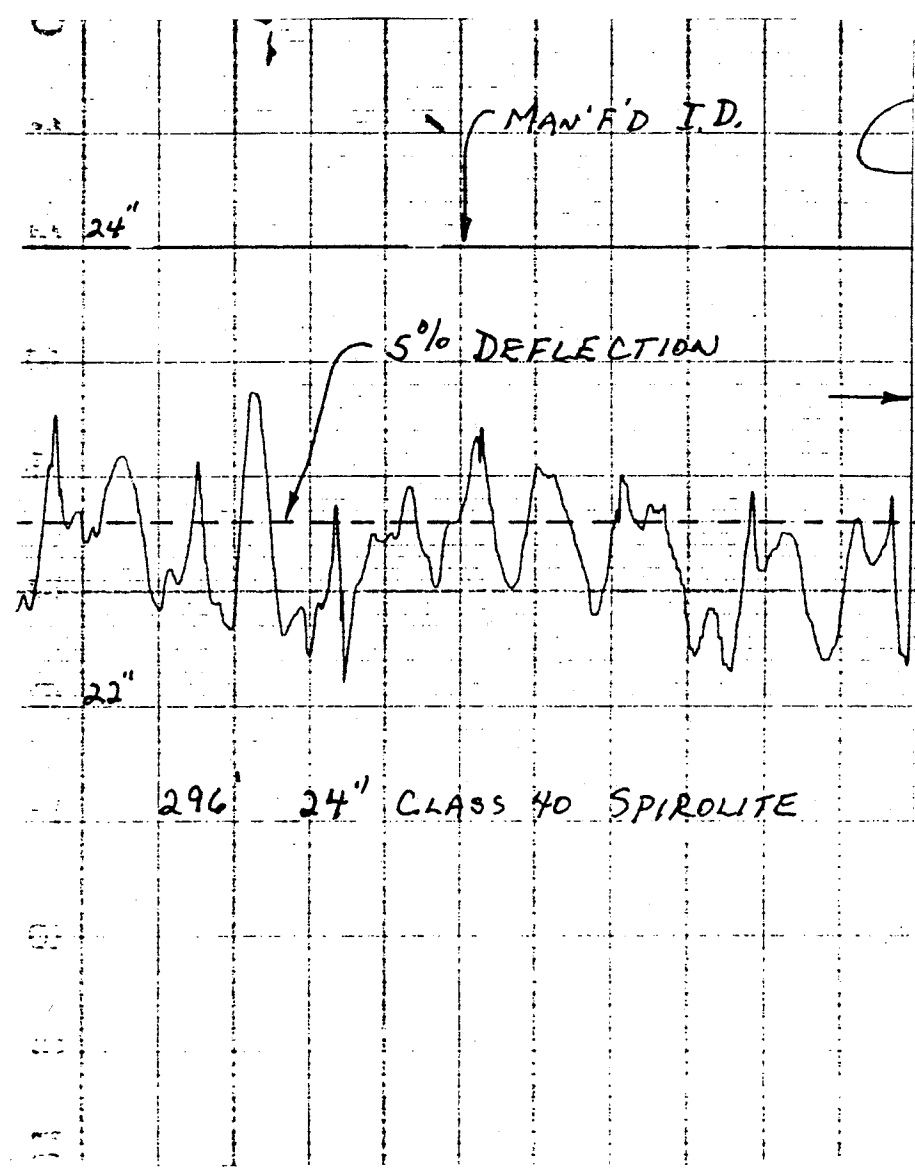


Figure 3.4 Electronic Deflectometer Printout.

3.6 "Smart Pig" Electronic Calipers

"Smart Pig" electronic calipers are used by many operators of major transmission lines to determine the amount of deflection in a line when more qualitative information concerning the degree of out of roundness, its location and its probable cause is desired. One example of an electronic caliper surveyor is shown in Figure 3.5. The pig, once placed in the line, is propelled by the fluid moving through it recording deflection measurements as well as taking odometer readings to later accurately locate sites of excess deflection along the line. An example of the resultant printout is shown in Figure 3.6.

The smart pig which is available in a range of sizes from 8 to 48 inches is diameter specific. Its cost may not be warranted except in the case of a very large project. Its advantages are that once the tool is removed from the line the data is immediately available for automatic chart plotting and on-site interpretation. The accuracy is also enhanced due to electronic vs manual interpretation of the data.

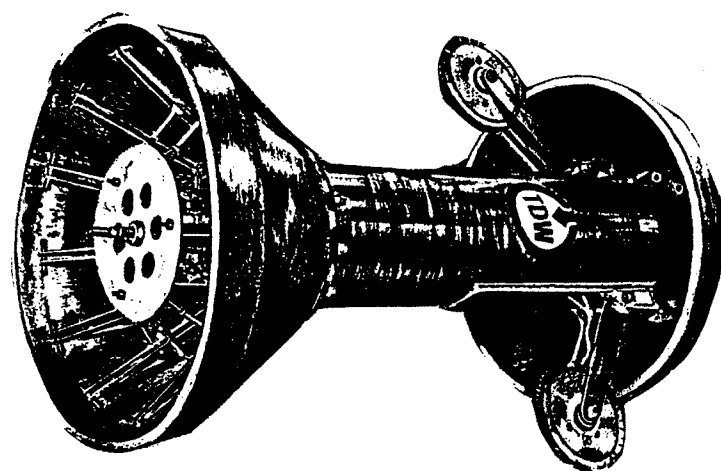
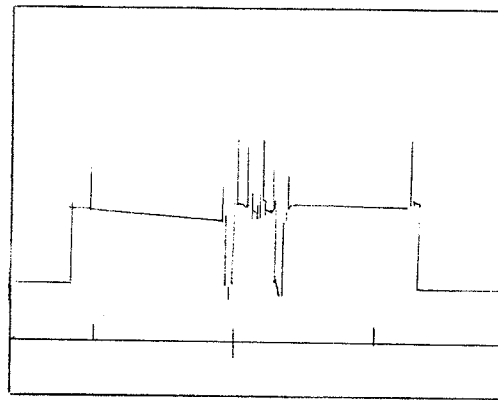


Figure 3.5 Electronic Caliper Surveyor.



1" = 40'

1 cm = 5 meters

Figure 3.6 Electronic Caliper Printout.

CHAPTER 4

DETAILS OF DEFLECTION TESTING AT SANTA MARGARITA

4.1 Introduction

The following is an example of the type of measurements taken at a typical site. Examples of the variation of deflection data which were obtained are shown and the installation techniques and method of measurement are described.

Vertical deflection measurements were taken along the Chiquita Trunk Sewer in the Santa Margarita Water District in June of 1987 using a sled-mounted electronic deflectometer. The measurements were taken several months after the installation of the line. The lines were flushed out prior to measurement to remove any accumulation of sediment and the deflectometer had been properly calibrated prior to its use.

4.2 Description of the Site

The Santa Margarita Water District is located just south of the greater Los Angeles metropolitan area near the city of Mission Viejo, California. Its two treatment plants provide both sewer and water for the cities of Mission Viejo, San Juan Capistrano, Rancho, Codo de Casa, and Santa Margarita. The Chiquita Trunk Sewer is located in a sparsely populated valley and runs through the middle of a cattle ranch on an easement through the property to one of the Santa Margarita treatment facilities.

4.3 Types of Pipe

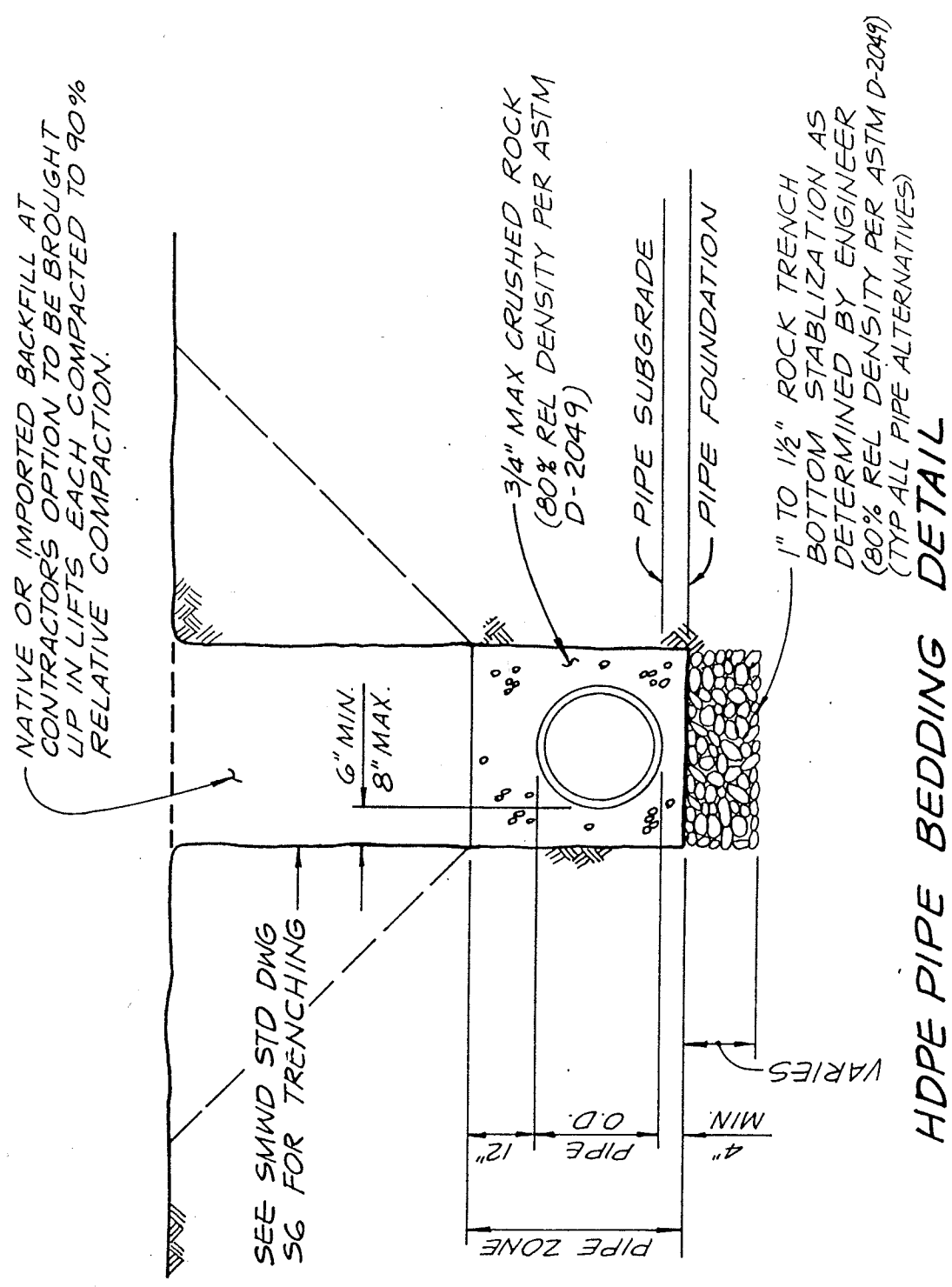
The sections of the Chiquita Trunk Sewer which were tested included 3080 feet of 21 inch and 1560 feet of 24 inch nominal diameter pipe. This class 40, profile wall, high density polyethylene pipe carries the brand name Spirolite. The manufacturer's published initial pipe stiffnesses for the 21 inch and 24 inch pipe are 14 psi and 12.8 psi respectively.

4.4 Construction Techniques

The specifications for the installation of the pipe required the use of 3/4 inch crushed stone bedding from at least 4 inches below the pipe to 12 inches above its crown. Compaction of the bedding material included shovel slicing of the bedding material under the haunches and the remaining portion was probably end-dumped. The contractor was given the option to backfill the remaining portion of the trench in lifts each compacted to 90% relative compaction (sic) with native or imported material. Since the line was not located in a roadway, it is unlikely that imported material was used as backfill. The native material is described as a stiff clay. Excavation of the trench was performed with a backhoe. The trench geometry, given in Figure 4.1, shows the nearly vertical trench walls which were possible in the stiff clay.

4.5 Observations on Deflections

Most of the deflections observed along the lines included in the Santa Margarita study averaged around 5% with most of the variation contained within plus or minus 2.5% of this value. An example of this type of deflection record is shown in Figure 4.2. An example of deflection record



HDPE PIPE BEDDING DETAIL

Figure 4.1 La Margarita - Trench Geometry.

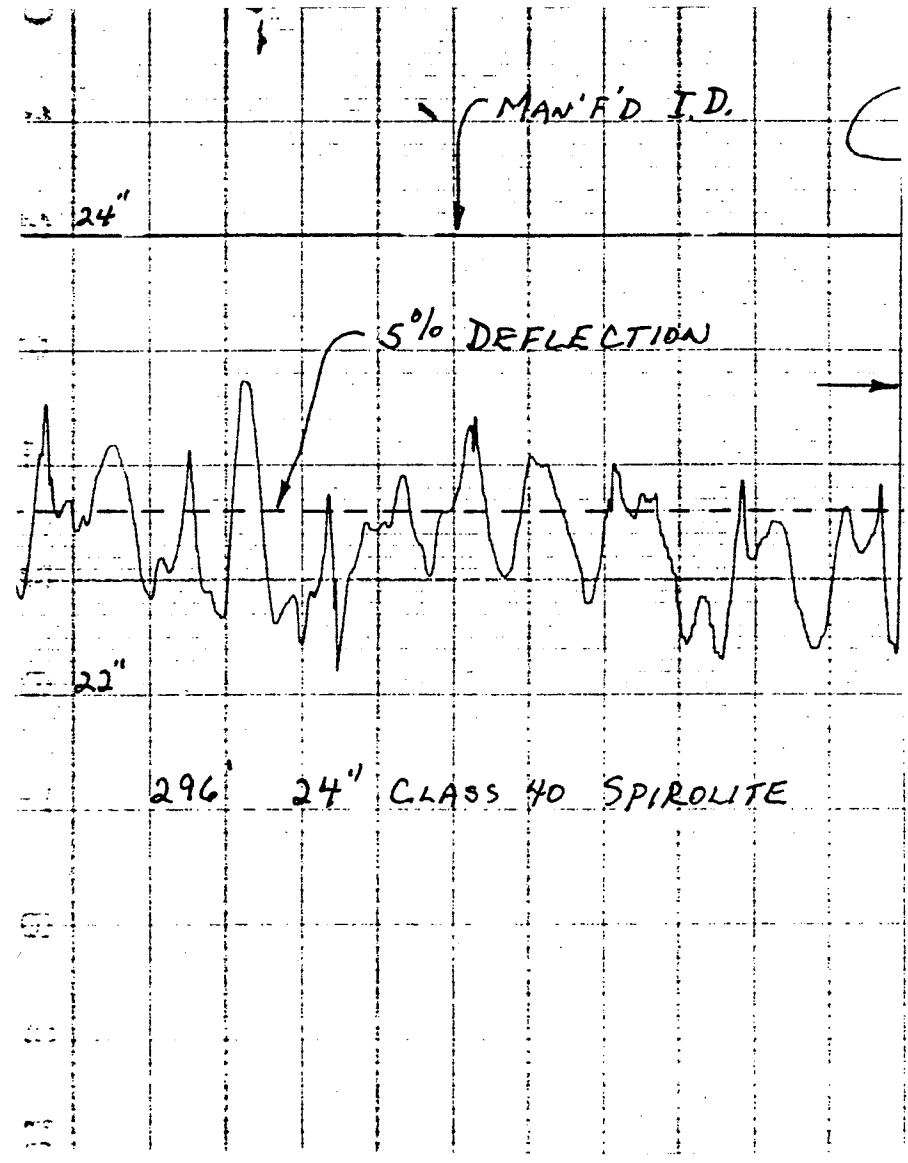


Figure 4.2 Deflections due to Average Installation Techniques - La Margarita.

resulting from consistent installation practice is shown in Figure 4.3. In the latter, the average deflection was approximately 4% and the variation was only on the order of plus or minus 1%. Another example of deflection record is that of a 24 inch pipe which resulted in the majority of the line exceeding 5% deflection and a maximum deflection of 14.6% which is shown in Figure 4.4. In this case the average deflection is high as well as the variation observed along the pipeline.

4.6 Conclusions

It is obvious from the preceding examples of deflection testing records that the installation technique has a dramatic effect on the deflection observed in a line. Although some variation in soil types and their respective properties would be expected along a line, the deflection pattern was more consistent between manholes than from one manhole to the next along the same line. This difference could only be accounted for as being due to installation technique since a change in soil type occurring at the exact location of the manhole would be highly unlikely. This implies the necessity of adequate inspection as well as the need for deflection testing. A quality installation can not and will not be assured without these two.

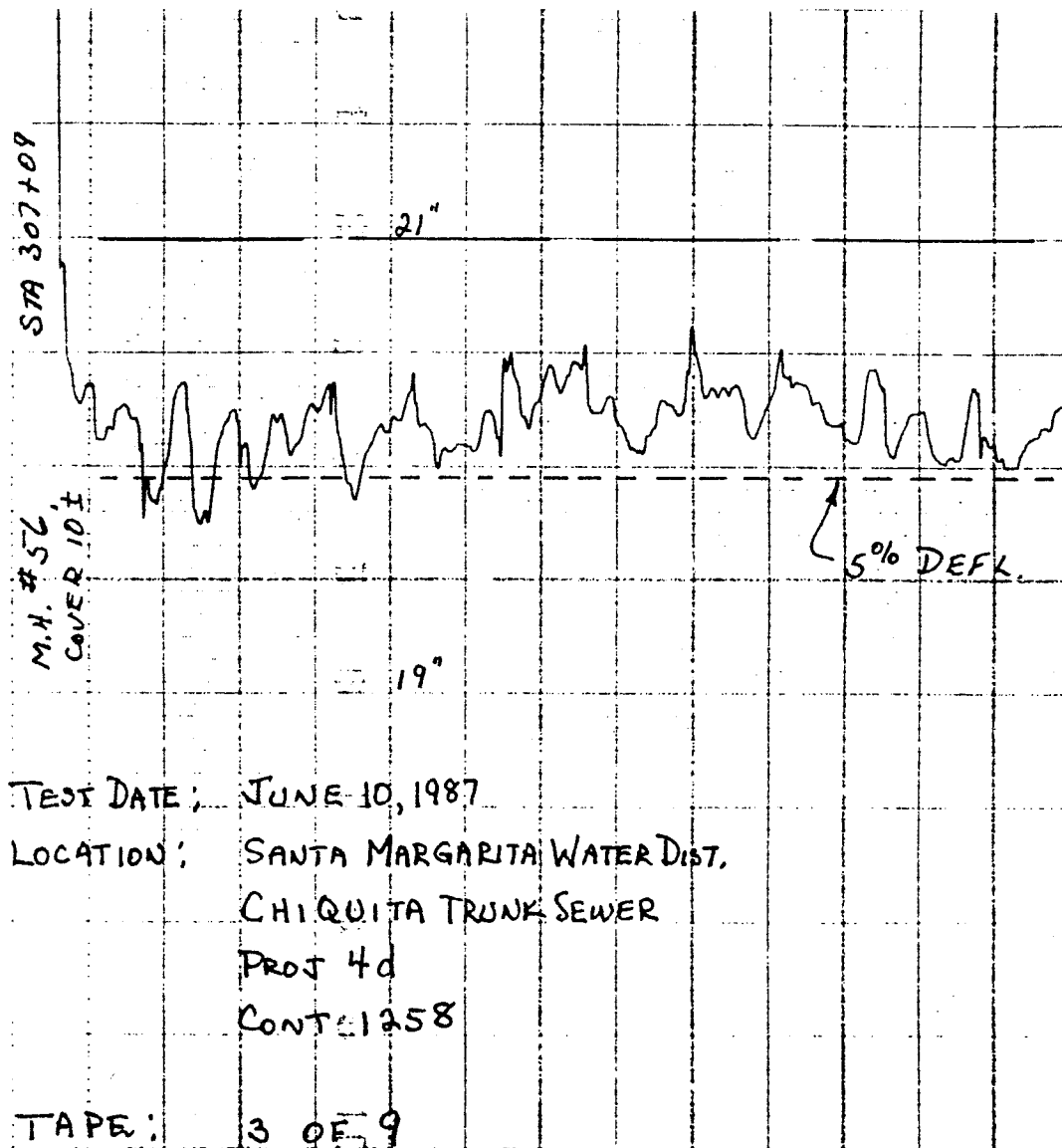


Figure 4.3 Deflections due to Good Installation Techniques - La Margarita.

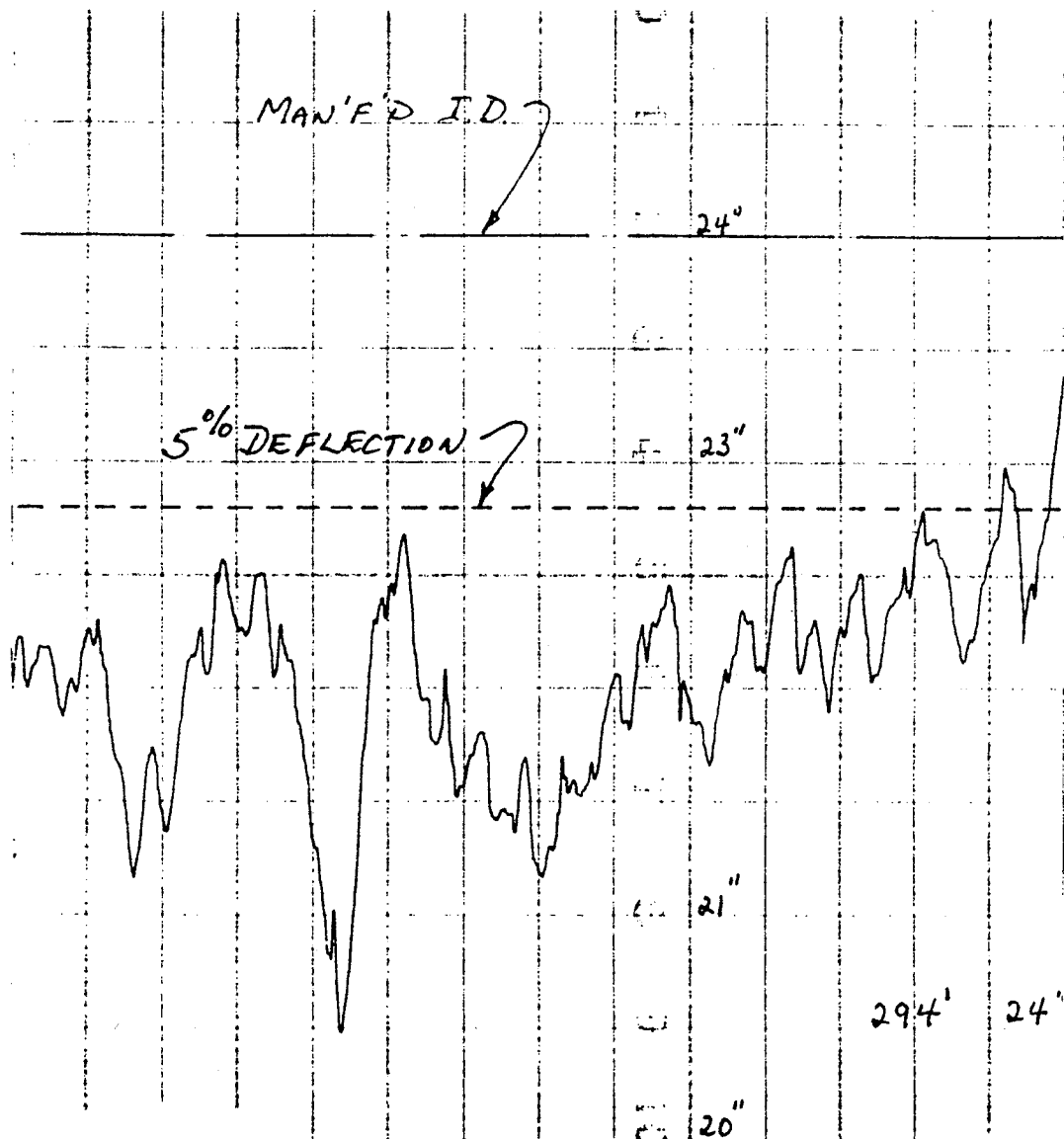


Figure 4.4 Deflections due to Poor Installation Techniques - La Margarita.

CHAPTER 5

SURVEY OF EXPERIENCES

AT SEVERAL SITES

5.1 Introduction

Data from various sources of field deflections of plastic pipe are compiled, analyzed and correlations are made in this chapter. Comparisons with the deflections predicted by the Spangler's equation are also presented.

5.2 Sources of Data

In order to compile a comprehensive data base of available field deflections of flexible and very flexible pipelines, several different sources were sought. These sources include published data found in manufacturer's product literature (8), unpublished data obtained from a comprehensive study on deflections performed by the National Clay Pipe Institute (23), deflections taken from an independent study performed by Donahue and Associates Inc. (11) for the Plastic Pipe Industry and data published in the

original work done by Spangler (28).

5.2.1 General

Pipe stiffnesses, which are summarized in Table 5.1, ranged from a low of 12.8 psi to a maximum of 200 psi. The latter, although not strictly representative of flexible pipelines, was included to show the validity or non-validity of the Spangler's equation in this range of pipe stiffness. Pipe materials represented in the data included high density polyethylene (HDPE), polyvinyl chloride (PVC), a composite of PVC and light weight concrete or acrylonitrile butadiene styrene (ABS) and light weight concrete, and corrugated steel pipe. Pipe diameters ranged from 8 inches to 24 inches. The average and maximum deflections were either provided or calculated based on the information included in each of the sources.

5.2.2 National Clay Pipe Institute's Data

The vertical deflection measurements obtained from the National Clay Pipe Institute (NCPI) data were taken using an sled-mounted electronic deflectometer. The lines which were tested were selected typically by the municipality involved

VALUES FOR PIPE STIFFNESS BASED ON ASTM D-2412 @ 5%		
PIPE CLASS	PIPE STIFFNESS (PSI)	
D-3034 SDR 35 PVC	46	
D-3033 SDR 41 PVC	28	
D-3034 SDR 42 PVC	26	
ARMCO TRUSS (ABS & PVC)	200	

Table 5.1 Pipe Stiffnesses Used in the Spangler's Equation.

which was interested in learning how well the line was performing. Measurements are believed to be reliable since most of the measurements were taken by a team of at least two persons. All lines were adequately flushed prior to measurement and the deflectometer was properly calibrated. In many cases several lines in the same city were tested and in some cases individual lines were retested. The general location of the sites which were included in the analysis are given in Figure 5.1.

The general format used for summarizing the data which was taken in the field is shown in Figure 5.2. The average deflection was calculated based on this data using the following formula:

$$Y_{ave.} = (A-B) * 2.5\% + (B-C) * 6.25\% + C * 8.75\% \dots 5.1$$

where:

$Y_{ave.}$ = Average Deflection in %

A = Percent of line exceeding 5%

B = Percent of line exceeding 7.5%

C = Percent of line exceeding 10.0%

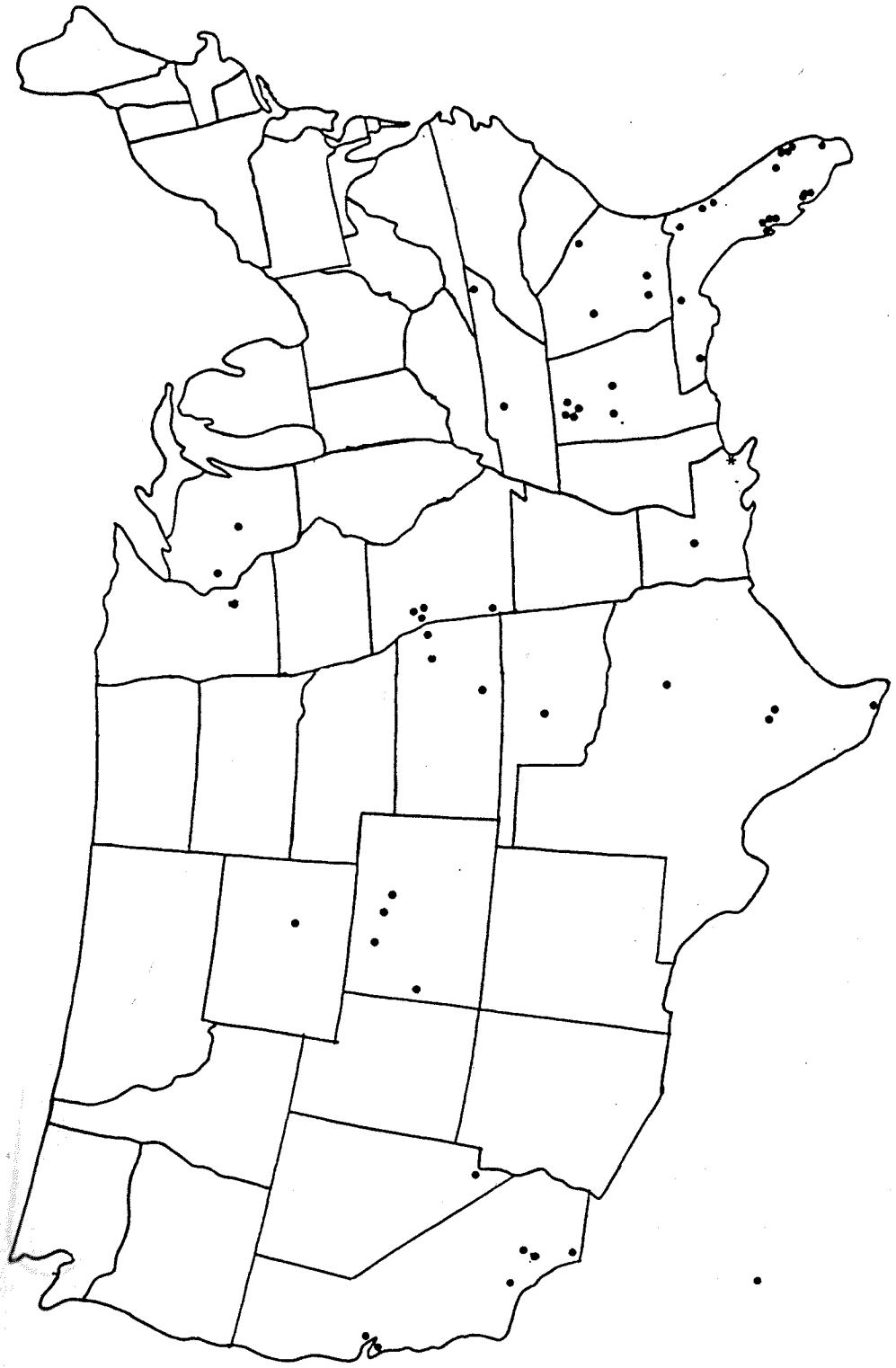


Figure 5.1 Pipe Deflection Measurement Sites.
(National Clay Pipe Institute)



DEFLECTOMETER TEST REPORT

Sheet 1 of 2

CITY Ormond Beach, FL TEST DATE 08-24-83
 RE-TEST DATE _____

GENERAL DESCRIPTION OF TEST LINES: These lines were 8" PVC SDR-35 ASTM 3034 pipe, installed in a sand and possibly shell environment, to the best of anyone's knowledge and backfilled with native soils. Lines have been in approx. 4-5-years.

REASON FOR TESTING LINES: TO determine amount of deflection.

PERSONAL PRESENT: Kirk Roper, Rick Clark, Rodger Stevens, John Altman and Jim Davis with City of Ormond Beach, Bill Walz Bill Johnson, Tom Galvin with Dickey Co.

TEST RESULTS:

LINE NO.	DATE PIPE INSTALLED	TYPE OF PIPE	LENGTH (ft)	DEPTH "h" (ft)	MEASURED UNDEFLECTED DIAMETER (in)	MINIMUM MEASURED DIAMETER (in)	PERCENTAGE OF LINE EXCEEDING		MAXIMUM PERCENT RING DEFLECTION *
							5 %	%	
1	1978-1979	8" PVC	247	2'10"	7.92	7.22	5.5%		8.8%
2	1978-1979	8" PVC	325	2'9"	7.92	7.28	4.9%		8%
3	1978-1979	8" PVC	350	3'4"	7.92	7.20	5.3%		9.09%
4	1978-1979	8" PVC	375	5'7"	7.90	7.28	2.9%		7.95%

COMMENTS AND RECOMMENDATIONS: See Attached.

Note: On 08-16-83 Number 1, 2 and 3 lines failed mandrel pull. On line #4, the clip to the mandrel broke, were unable to finish test.

*NOTE: HORIZONTAL SCALE OF GRAPHS MAY NOT BE CONSISTENT DUE TO RATE OF PULL OF DEFLECTOMETER THROUGH SEWER LINE.
 "FLEXIBLE PIPES ARE CONSIDERED TO HAVE REACHED THE LIMIT OF THEIR SERVICEABILITY WHEN A DEFLECTION OF FIVE PERCENT IS ATTAINED." WPCF MOP #9

**Figure 5.2 Example of Field Data Summary Sheet.
 (National Clay Pipe Institute)**

All values were referenced to the measured undeflected diameter of the pipe rather than to the minimum internal diameters published by ASTM. This took into account the normal variation in the internal diameter of the manufactured product and resulted in more accuracy than would have been possible otherwise.

5.2.3 Contech's Data

The published data which was found in the product literature for truss pipe distributed by Contech was included to represent the higher end of the range of data included in the study, a pipe stiffness of 200 psi. The general configuration of the pipe is shown in Figure 5.3. The locations where the data was taken are shown in Figure 5.4. It is not known how the deflection measurements were made.

5.2.4 Donahue's Data

The data which is found in the Donahue report pertained to PVC pipe of diameters ranging from 8 to 12 inches. The pipe stiffnesses included in the study ranged from 26 psi to 46 psi. All field deflection measurements were taken in the state of Wisconsin using the mechanical deflectometer des-

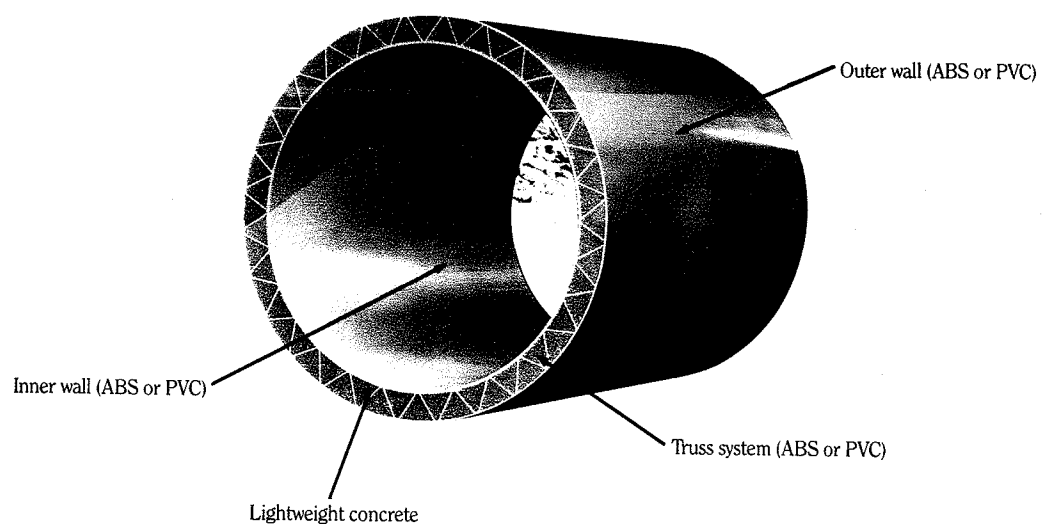


Figure 5.3 Pipe Configuration.
(ARMCO Truss Pipe - Contech)

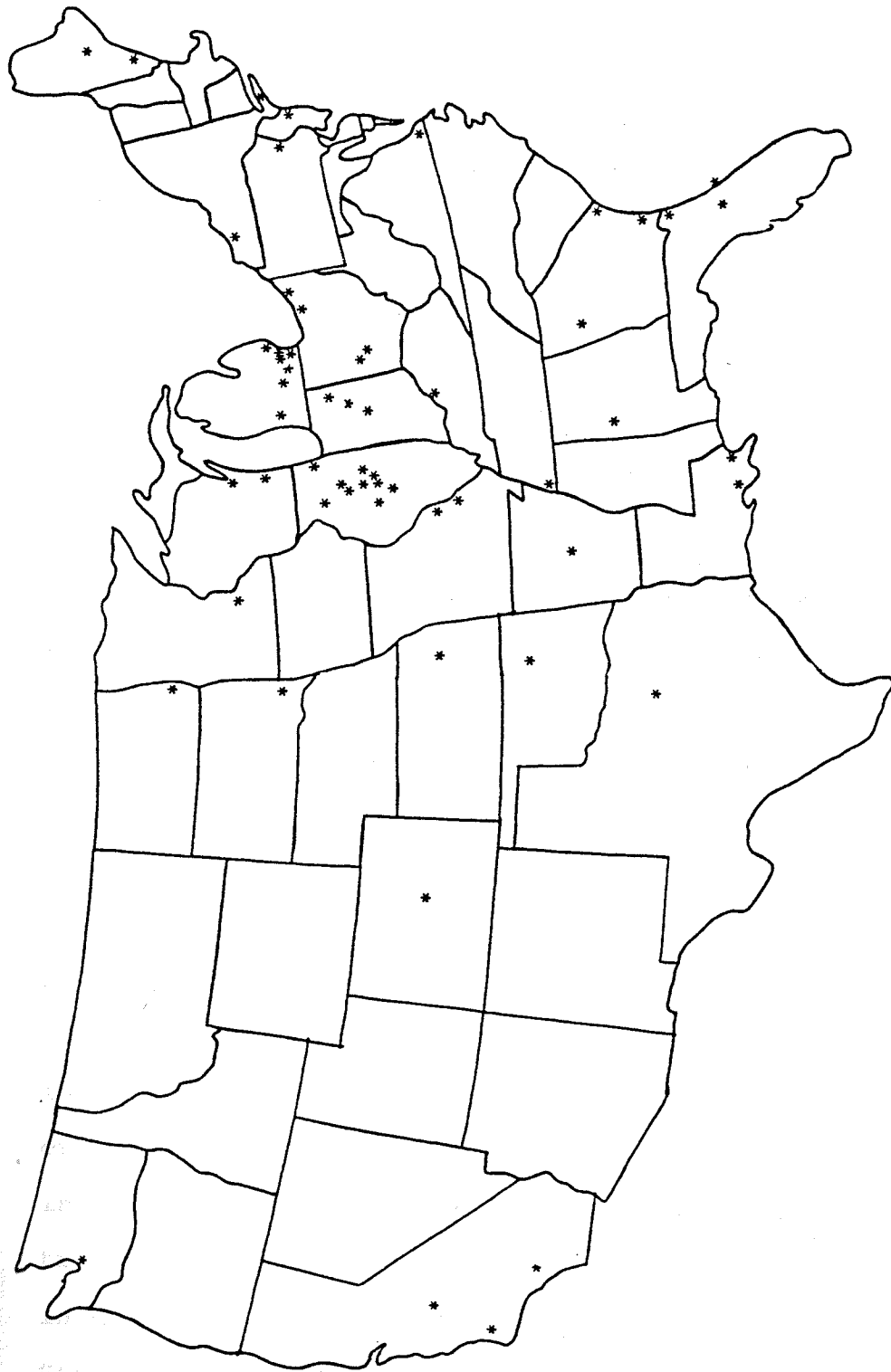


Figure 5.4 Pipe Deflection Measurement Sites.
(ARMCO Truss Pipe - Contech)

cribed in section 3.4 and the site locations are shown in Figure 5.5.

5.2.5 Spangler's Data

In 1941 Spangler published his original report on deflections of 36 to 60 inch diameter corrugated metal pipes installed in 15 to 16 foot embankments. The pipe stiffnesses included in the field experiments ranged from 24 psi to 130 psi. The length of record of the data was 13.3 years, 0.85 years, and 3.62 years for experiments 1, 2, and 3 respectively. Load and deflection measurements as well as the predicted deflections based on the equation presently known as the Spangler's equation are presented in Tables 5.2 through 5.9.

5.3 Data Base "Deflections"

The data base analyzed in this study includes the results of over 94000 feet of deflection testing performed on field installations of PVC pipe as well as an unknown length of truss pipe installations. These installations are located in the many different climatological regions of the United States performed by different contractors with different

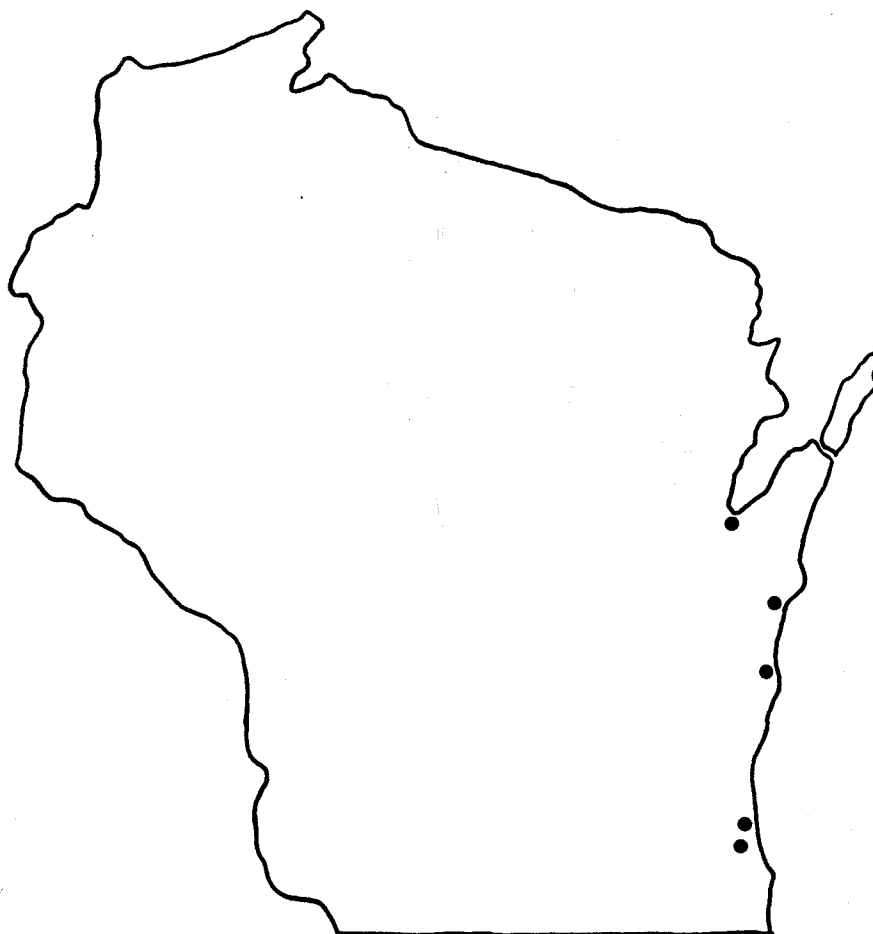


Figure 5.5 Pipe Deflection Measurement Sites.
(Donahue & Associates, Inc.)

TABLE 18. VERTICAL LOAD ON THE PIPE OF EXPERIMENT 1

Date	Height of fill, ft.	Load, lb. per lin. ft.				Average
		Section 1	Section 2	Section 3	Section 4	
9-17-27	0.0	0	0	0	0	0
9-23-27	0.5	157	120	75	232	146
9-24-27	1.0	307	218	180	368	268
9-27-27	1.5	510	345	293	570	429
9-28-27	2.0	690	495	458	772	604
9-29-27	2.5	870	645	615	952	770
10- 1-27	2.5	968	705	645	982	825
10- 6-27	2.5	1,080	818	758	1,163	955
10- 8-27	2.5	1,103	832	788	1,208	983
10-11-27	3.0	1,290	1,035	945	1,373	1,161
10-14-27	3.0	1,350	1,095	990	1,433	1,217
10-17-27	4.0	1,853	1,620	1,508	1,928	1,752
10-18-27	4.5	2,033	1,800	1,688	2,100	1,905
10-19-27	5.0	2,235	1,987	1,890	2,280	2,098
10-20-27	5.5	2,356	2,130	1,995	2,370	2,213
10-21-27	6.0	2,506	2,302	2,152	2,512	2,368
10-22-27	6.5	2,640	2,438	2,310	2,662	2,512
10-24-27	7.0	2,865	2,685	2,535	2,859	2,736
10-28-27	7.0	2,956	2,805	2,589	2,918	2,817
10-29-27	7.0	3,090	2,956	2,752	3,052	2,962
10-31-27	7.5	3,256	3,159	2,919	3,188	3,130
11- 1-27	8.0	3,360	3,300	3,038	3,292	3,248
11- 3-27	8.5	3,510	3,488	3,210	3,435	3,411
11- 4-27	9.0	3,638	3,645	3,352	3,556	3,548
11- 5-27	9.0	3,652	3,669	3,360	3,561	3,560
11- 9-27	9.0	3,765	3,840	3,488	3,668	3,690
11-10-27	9.5	3,840	3,900	3,548	3,728	3,754
11-11-27	10.0	3,922	3,998	3,645	3,810	3,844
11-12-27	10.5	3,990	4,095	3,735	3,890	3,928
11-14-27	11.0	4,100	4,251	3,861	3,998	4,050
11-16-27	11.0	4,155	4,298	3,900	4,035	4,097
11-17-27	11.0	4,178	4,320	3,915	4,050	4,116
11-18-27	11.0	4,200	4,359	3,952	4,065	4,144
11-19-27	11.0	4,200	4,431	4,035	4,140	4,216
11-21-27	11.0	4,341	4,500	4,103	4,208	4,288
11-22-27	11.0	4,358	4,530	4,118	4,215	4,305
11-23-27	11.0	4,365	4,560	4,140	4,230	4,324
11-25-27	11.0	4,388	4,605	4,162	4,260	4,354
11-26-27	11.0	4,410	4,635	4,170	4,268	4,371
11-28-27	11.0	4,440	4,672	4,200	4,290	4,400
11-30-27	11.0	4,419	4,658	4,162	4,268	4,377
12- 1-27	11.0	4,440	4,688	4,215	4,306	4,412
12- 3-27	11.75	4,573	4,860	4,373	4,440	4,561
12- 5-27	11.75	4,590	4,898	4,402	4,470	4,590
12- 7-27	14.0	4,880	5,280	4,762	4,778	4,925
12-10-27	14.0	4,955	5,430	4,910	4,898	5,048
12-16-27	15.0	5,188	5,738	5,190	5,123	5,310
12-19-27	15.0	5,250	5,825	5,280	5,198	5,388
12-21-27	15.0	5,265	5,850	5,310	5,220	5,411
12-23-27	15.0	5,287	5,865	5,318	5,220	5,422
12-27-27	15.0	5,318	5,895	5,325	5,213	5,438
1- 2-28	15.0	5,405	6,105	5,559	5,440	5,627
1- 4-28	15.0	5,420	6,105	5,535	5,418	5,619
1- 7-28	15.0	5,400	6,060	5,438	5,240	5,534
1-10-28	15.0	5,460	6,105	5,490	5,255	5,578
1-12-28	15.0	5,452	6,097	5,490	5,288	5,582
1-14-28	15.0	5,452	6,112	5,520	5,340	5,606
1-16-28	15.0	5,460	6,127	5,535	5,462	5,646
1-18-28	15.0	5,460	6,135	5,550	5,377	5,630
1-20-28	15.0	5,415	6,080	5,580	5,370	5,611
1-23-28	15.0	5,467	6,185	5,632	5,480	5,641
1-25-28	15.0	5,467	6,195	5,660	5,520	5,710
1-28-28	15.0	5,480	6,260	5,760	5,618	5,779
2- 1-28	15.0	5,540	6,275	5,708	5,512	5,784
2- 3-28	15.0	5,550	6,290	5,716	5,527	5,771

Table 5.2 Vertical Load on the Pipe of Experiment 1.
(Spangler (28))

TABLE 18. VERTICAL LOAD ON THE PIPE OF EXPERIMENT 1—Continued

Date	Height of fill, ft.	Load, lb. per lin. ft.				Average
		Section 1	Section 2	Section 3	Section 4	
2- 7-28	15.0	5,580	6,290	5,670	5,480	5,755
2- 9-28	15.0	5,565	6,270	5,670	5,487	5,748
2-11-28	15.0	5,565	6,278	5,680	5,512	5,759
2-20-28	15.0	5,558	6,305	5,768	5,632	5,816
2-29-28	15.0	5,655	6,425	5,860	5,655	5,899
3- 6-28	15.0	5,655	6,425	5,860	5,670	5,902
3-20-28	15.0	5,655	6,425	5,852	5,692	5,906
3-31-28	15.0	5,640	6,418	5,837	5,700	5,899
4- 9-28	15.0	5,587	6,300	5,740	5,678	5,826
4-20-28	15.0	5,632	6,360	5,807	5,768	5,892
5- 1-28	15.0	5,700	6,485	5,920	5,875	5,995
5-15-28	15.0	5,605	6,380	5,900	5,887	5,943
5-26-28	15.0	5,632	6,425	5,775	5,812	5,911
6- 1-28	15.0	5,655	6,485	5,790	5,842	5,943
6-14-28	15.0	5,663	6,503	5,790	5,850	5,951
6-29-28	15.0	5,685	6,548	5,798	5,865	5,974
7- 9-28	15.0	5,618	6,495	5,722	5,820	5,914
7-20-28	15.0	5,618	6,503	5,715	5,805	5,910
7-31-28	15.0	5,633	6,540	5,730	5,843	5,936
8-15-28	15.0	5,692	6,608	5,723	5,872	5,974
9- 4-28	15.0	5,648	6,495	5,588	5,805	5,884
10- 2-28	15.0	5,633	6,465	5,558	5,798	5,864
11- 5-28	15.0	5,678	6,473	5,610	5,873	5,908
12- 7-28	15.0	5,670	6,465	5,602	5,895	5,908
1- 2-29	15.0	5,670	6,420	5,625	6,007	5,945
2- 5-29	15.0	5,648	6,285	5,573	6,045	5,888
3-18-29	15.0	5,655	6,173	5,528	6,000	5,839
5-16-29	15.0	5,790	6,573	6,128	6,210	6,177
6-12-29	15.0	5,790	6,608	6,120	6,195	6,178
7-13-29	15.0	5,820	6,675	6,112	6,203	6,202
8- 8-29	15.0	5,887	6,780	6,150	6,270	6,272
9- 5-29	15.0	5,978	6,870	6,172	6,285	6,326
10- 4-29	15.0	6,007	6,892	6,210	6,345	6,364
11- 1-29	15.0	6,000	6,878	6,180	6,330	6,347
12- 4-29	15.0	5,940	6,810	6,112	6,315	6,294
1- 1-30	15.0	5,985	6,848	6,173	6,390	6,349
4-11-30	15.0	6,105	7,073	6,495	6,600	6,568
6-27-30	15.0	6,105	7,020	6,465	6,547	6,534
8-13-30	15.0	6,105	7,095	6,368	6,510	6,519
9-12-30	15.0	6,195	7,192	6,397	6,563	6,587
12- 9-30	15.0	6,053	6,930	6,097	6,420	6,375
1-10-31	15.0	6,008	6,855	6,045	6,390	6,325
3-25-31	15.0	6,030	6,825	6,022	6,390	6,317
6-10-31	15.0	6,255	7,185	6,375	6,607	6,605
9-14-31	15.0	6,060	7,065	6,105	6,435	6,416
11-27-31	15.0	5,978	6,945	5,835	6,300	6,265
2-10-32	15.0	6,098	6,963	5,910	6,353	6,328
5-21-32	15.0	6,233	7,508	6,630	6,435	6,701
7- 2-32	15.0	6,210	7,538	6,600	6,458	6,701
8-16-32	15.0	6,315	7,755	6,690	6,600	6,840
5-24-33	15.0	6,225	7,590	6,608	6,525	6,737
9-27-33	15.0	6,120	7,335	6,405	6,435	6,574
2- 3-34	15.0	5,798	6,885	6,022	6,233	6,235
11- 7-34	15.0	5,392	6,945	5,910	6,045	6,073
4-19-35	15.0	5,415	6,922	5,902	6,075	6,078
5-13-37	15.0	5,700	7,245	6,037	6,255	6,309
9-15-37	15.0	6,210	7,305	6,128	6,315	6,489
1- 9-39	15.0	5,560	7,050	5,635	6,020	6,079
4-28-39	15.0	5,655	7,160	5,815	6,195	6,206
3- 9-40	15.0	5,550	6,980	5,580	6,055	6,041
4-22-41	15.0	5,685	7,200	5,700	6,210	6,199

Table 5.3 Vertical Load on the Pipe of Experiment 1 - Continued. (Spangler (28))

TABLE 19. PIPE DEFLECTIONS OF EXPERIMENT 1

Date	Height of fill, ft.	Deflection, in										De- flection calcu- lated by Eq. 29, in.
		Section 1		Section 2		Section 3		Section 4		Average		
		Horiz- ontal	Verti- cal	Horiz- ontal	Verti- cal	Horiz- ontal	Verti- cal	Horiz- ontal	Verti- cal	Horiz- ontal	Verti- cal	
9-17-27	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9-23-27	0.5	0.04	0.04	0.04	0.03	0.10	0.09	0.09	0.08	0.07	0.06	0.03
9-24-27	1.0	0.06	0.06	0.05	0.05	0.08	0.09	0.12	0.12	0.08	0.08	0.06
9-27-27	1.5	0.10	0.10	0.09	0.08	0.11	0.12	0.16	0.16	0.11	0.11	0.10
9-28-27	2.0	0.13	0.13	0.12	0.12	0.15	0.16	0.21	0.21	0.15	0.15	0.14
9-29-27	2.5	0.16	0.17	0.15	0.15	0.18	0.19	0.25	0.25	0.18	0.19	0.18
10-1-27	2.5	0.17	0.18	0.16	0.16	0.19	0.21	0.27	0.27	0.20	0.21	0.19
10-6-27	2.5	0.22	0.22	0.19	0.19	0.22	0.24	0.31	0.31	0.23	0.24	0.22
10-11-27	3.0	0.27	0.28	0.23	0.24	0.26	0.28	0.37	0.37	0.28	0.29	0.27
10-14-27	3.0	0.29	0.30	0.25	0.25	0.28	0.30	0.39	0.39	0.30	0.31	0.28
10-17-27	4.0	0.41	0.42	0.37	0.36	0.40	0.42	0.52	0.53	0.42	0.43	0.41
10-18-27	4.5	0.45	0.47	0.41	0.41	0.44	0.46	0.57	0.57	0.47	0.48	0.44
10-19-27	5.0	0.51	0.53	0.46	0.46	0.49	0.52	0.62	0.62	0.52	0.53	0.49
10-20-27	5.5	0.54	0.57	0.49	0.49	0.52	0.55	0.65	0.65	0.55	0.56	0.51
10-21-27	6.0	0.58	0.61	0.53	0.53	0.56	0.59	0.69	0.69	0.59	0.61	0.55
10-22-27	6.5	0.62	0.65	0.57	0.57	0.59	0.63	0.73	0.74	0.63	0.65	0.58
10-28-27	7.0	0.74	0.77	0.68	0.69	0.70	0.75	0.84	0.85	0.74	0.76	0.66
10-31-27	7.5	0.80	0.82	0.74	0.74	0.76	0.80	0.90	0.91	0.80	0.82	0.73
11-1-27	8.0	0.82	0.86	0.76	0.77	0.78	0.83	0.92	0.94	0.82	0.85	0.75
11-3-27	8.5	0.86	0.90	0.81	0.82	0.83	0.88	0.96	0.98	0.86	0.90	0.79
11-4-27	9.0	0.89	0.94	0.85	0.86	0.86	0.92	0.99	1.01	0.90	0.93	0.82
11-9-27	9.0	0.95	0.99	0.89	0.91	0.92	0.98	1.05	1.07	0.95	0.99	0.86
11-10-27	9.5	0.96	1.01	0.92	0.93	0.93	0.99	1.06	1.08	0.97	1.00	0.87
11-11-27	10.0	0.98	1.03	0.93	0.94	0.95	1.01	1.07	1.10	0.98	1.02	0.89
11-12-27	10.5	1.00	1.05	0.96	0.96	0.97	1.03	1.10	1.12	1.01	1.04	0.91
11-16-27	11.0	1.05	1.11	1.01	1.02	1.03	1.09	1.15	1.18	1.06	1.10	0.95
11-18-27	11.0	1.07	1.12	1.03	1.04	1.05	1.11	1.17	1.20	1.08	1.12	0.96
11-22-27	11.0	1.10	1.16	1.06	1.08	1.08	1.15	1.20	1.23	1.11	1.15	1.00
11-25-27	11.0	1.12	1.16	1.08	1.09	1.09	1.17	1.22	1.25	1.13	1.17	1.01
11-30-27	11.0	1.14	1.20	1.10	1.11	1.11	1.19	1.24	1.27	1.15	1.19	1.02
12-7-27	12.0	1.23	1.30	1.22	1.23	1.24	1.32	1.35	1.38	1.26	1.31	1.14
12-16-27	15.0	1.33	1.40	1.34	1.36	1.37	1.46	1.48	1.48	1.38	1.43	1.23
1-12-28	15.0	1.44	1.52	1.47	1.49	1.50	1.60	1.60	1.65	1.50	1.56	1.30
1-14-28	15.0	1.45	1.53	1.47	1.49	1.51	1.60	1.61	1.65	1.51	1.57	
1-16-28	15.0	1.46	1.53	1.48	1.49	1.51	1.60	1.61	1.66	1.51	1.57	
1-18-28	15.0	1.46	1.53	1.48	1.50	1.52	1.61	1.62	1.66	1.52	1.58	
1-20-28	15.0	1.46	1.53	1.48	1.50	1.52	1.61	1.62	1.66	1.52	1.58	
1-23-28	15.0	1.47	1.54	1.49	1.51	1.53	1.62	1.63	1.67	1.53	1.59	
1-25-28	15.0	1.47	1.54	1.49	1.51	1.53	1.62	1.64	1.68	1.53	1.59	
1-28-28	15.0	1.47	1.55	1.50	1.52	1.55	1.64	1.65	1.69	1.54	1.60	
2-1-28	15.0	1.48	1.55	1.51	1.52	1.56	1.64	1.66	1.70	1.55	1.60	
2-3-28	15.0	1.48	1.55	1.51	1.53	1.56	1.65	1.66	1.70	1.55	1.61	
2-7-28	15.0	1.49	1.56	1.51	1.53	1.56	1.65	1.66	1.70	1.56	1.61	
2-9-28	15.0	1.49	1.56	1.52	1.53	1.56	1.65	1.66	1.70	1.56	1.61	
2-11-28	15.0	1.49	1.57	1.52	1.53	1.56	1.65	1.66	1.70	1.56	1.61	
2-20-28	15.0	1.50	1.57	1.53	1.54	1.57	1.66	1.67	1.71	1.57	1.62	
2-29-28	15.0	1.51	1.58	1.55	1.56	1.59	1.68	1.69	1.73	1.58	1.64	
3-6-28	15.0	1.51	1.59	1.55	1.56	1.60	1.69	1.69	1.74	1.59	1.64	
3-20-28	15.0	1.53	1.60	1.56	1.58	1.60	1.69	1.70	1.74	1.60	1.65	
3-31-28	15.0	1.54	1.62	1.57	1.59	1.61	1.70	1.71	1.75	1.61	1.66	

Table 5.4 Pipe Deflections of Experiment 1.
(Spangler (28))

TABLE 19. PIPE DEFLECTIONS OF EXPERIMENT 1—Continued

Date	Height of fill, ft.	Deflection, in.										De- flection calcu- lated by Eq. 29, in.
		Section 1		Section 2		Section 3		Section 4		Average		
		Horiz- ontal	Verti- cal	Horiz- ontal	Verti- cal	Horiz- ontal	Verti- cal	Horiz- ontal	Verti- cal	Horiz- ontal	Verti- cal	
4-10-28	15.0	1.54	1.63	1.58	1.60	1.63	1.72	1.72	1.77	1.62	1.68	
4-20-28	15.0	1.55	1.63	1.59	1.61	1.63	1.72	1.73	1.77	1.63	1.68	
4-25-28	15.0	1.56	1.64	1.59	1.61	1.64	1.73	1.74	1.78			
5-2-28	15.0	1.56	1.65	1.60	1.62	1.64	1.74	1.75	1.79	1.64	1.70	
5-15-28	15.0	1.58	1.67	1.62	1.64	1.66	1.76	1.76	1.81	1.65	1.72	
5-26-28	15.0	1.59	1.68	1.63	1.66	1.68	1.77	1.78	1.83	1.67	1.73	
6-2-28	15.0	1.60	1.69	1.64	1.66	1.68	1.78	1.79	1.83	1.68	1.74	
6-14-28	15.0	1.61	1.70	1.65	1.67	1.70	1.79	1.81	1.85	1.69	1.75	
6-28-28	15.0	1.62	1.71	1.67	1.69	1.71	1.80	1.82	1.86	1.70	1.76	
7-10-28	15.0	1.64	1.74	1.69	1.72	1.74	1.82	1.84	1.89	1.73	1.79	
7-20-28	15.0	1.65	1.75	1.71	1.74	1.75	1.84	1.86	1.90	1.74	1.81	
7-31-28	15.0	1.66	1.77	1.72	1.75	1.76	1.85	1.87	1.92	1.75	1.82	
8-15-28	15.0	1.68	1.79	1.74	1.77	1.78	1.87	1.88	1.94	1.77	1.84	
9-4-28	15.0	1.70	1.80	1.76	1.79	1.80	1.89	1.90	1.96	1.79	1.86	
10-2-28	15.0	1.71	1.81	1.77	1.80	1.81	1.90	1.92	1.97	1.80	1.87	
11-5-28	15.0	1.72	1.82	1.78	1.81	1.82	1.91	1.93	1.98	1.81	1.88	
12-7-28	15.0	1.73	1.83	1.79	1.82	1.83	1.92	1.94	1.99	1.82	1.89	
1-3-29	15.0	1.74	1.83	1.80	1.83	1.84	1.93	1.96	2.01	1.83	1.90	
2-5-29	15.0	1.74	1.84	1.80	1.83	1.85	1.93	1.98	2.04	1.84	1.91	
3-18-29	15.0	1.75	1.86	1.80	1.84	1.85	1.95	2.01	2.07	1.85	1.93	
5-16-29	15.0	1.77	1.87	1.82	1.86	1.89	1.99	2.08	2.15	1.89	1.97	
6-12-29	15.0	1.78	1.89	1.84	1.88	1.91	2.01	2.12	2.18	1.91	1.99	
7-11-29	15.0	1.80	1.91	1.85	1.90	1.94	2.04	2.16	2.22	1.94	2.02	
8-8-29	15.0	1.82	1.93	1.88	1.93	1.97	2.07	2.20	2.26	1.99	2.05	
9-5-29	15.0	1.85	1.96	1.92	1.96	2.01	2.09	2.23	2.29	2.00	2.07	
10-4-29	15.0	1.87	1.97	1.94	1.98	2.04	2.11	2.26	2.31	2.03	2.09	
11-1-29	15.0	1.88	1.98	1.95	1.99	2.05	2.13	2.27	2.32	2.04	2.10	
12-4-29	15.0	1.88	1.98	1.96	1.99	2.06	2.14	2.28	2.33	2.05	2.11	
1-1-30	15.0	1.89	1.99	1.96	2.00	2.06	2.14	2.29	2.34	2.05	2.12	
4-11-30	15.0	1.89	2.00	1.98	2.01	2.08	2.17	2.31	2.37	2.06	2.14	
6-27-30	15.0	1.91	2.01	2.00	2.04	2.11	2.19	2.35	2.40	2.09	2.16	
8-13-30	15.0	1.93	2.04	2.03	2.08	2.15	2.23	2.38	2.43	2.12	2.19	
9-12-30	15.0	1.95	2.06	2.06	2.10	2.18	2.25	2.40	2.46	2.15	2.22	
12-9-30	15.0	1.97	2.07	2.09	2.13	2.20	2.28	2.43	2.48	2.17	2.24	
1-10-31	15.0	1.97	2.07	2.09	2.13	2.21	2.28	2.43	2.48	2.18	2.24	
3-25-31	15.0	1.97	2.08	2.10	2.13	2.21	2.28	2.44	2.48	2.18	2.24	
6-10-31	15.0	1.98	2.09	2.10	2.14	2.22	2.29	2.45	2.49	2.19	2.25	
9-14-31	15.0	2.00	2.11	2.12	2.17	2.24	2.31	2.46	2.51	2.20	2.27	
11-27-31	15.0	2.01	2.11	2.14	2.17	2.25	2.31	2.47	2.51	2.22	2.28	
2-10-32	15.0	2.02	2.14	2.15	2.20	2.26	2.34	2.49	2.54	2.23	2.30	
5-21-32	15.0	2.10	2.23	2.24	2.27	2.34	2.41	2.56	2.64	2.31	2.39	
7-2-32	15.0	2.12	2.25	2.27	2.30	2.37	2.44	2.59	2.66	2.34	2.41	
8-16-32	15.0	2.15	2.27	2.30	2.33	2.40	2.46	2.61	2.68	2.36	2.43	
6-2-33	15.0	2.22	2.36	2.41	2.39	2.49	2.54			2.45	2.51	
9-27-33	15.0	2.23	2.36	2.43	2.41	2.51	2.56			2.47	2.52	
2-3-34	15.0	2.26	2.38	2.45	2.44	2.54	2.58			2.50	2.55	
11-7-34	15.0	2.26	2.42	2.47	2.47	2.57	2.60	2.76	2.82	2.51	2.58	
4-19-35	15.0	2.27	2.43	2.48	2.48	2.58	2.62	2.77	2.83	2.52	2.59	
5-13-37	15.0	2.30	2.49	2.52	2.53	2.63	2.66	2.82	2.88	2.57	2.64	
9-15-37	15.0	2.31	2.47	2.53	2.53	2.64	2.67	2.82	2.88	2.58	2.64	
4-22-41	15.0	2.33	2.53	2.55	2.57	2.67	2.63	2.86	2.93	2.60	2.66	

Table 5.5 Pipe Deflections of Experiment 1 Continued. (Spangler (28))

TABLE 20. VERTICAL LOAD ON THE PIPE OF EXPERIMENT 2

Date	Height of fill, ft.	Load, lb. per lin. ft.				Average
		Section 1	Section 2	Section 3	Section 4	
6-5-34	0	0	0	0	0	0
6-6-34	1	282	273	220	356	283
6-7-34	2	606	629	502	701	609
6-8-34	3	879	1,057	796	1,114	961
6-12-34	4	1,140	1,401	1,041	1,422	1,251
6-14-34	5	1,378	1,734	1,311	1,710	1,533
6-16-34	6	1,675	2,126	1,641	2,078	1,880
6-20-34	7	1,912	2,482	1,948	2,399	2,185
6-22-34	8	2,221	2,862	2,242	2,708	2,508
6-26-34	9	2,470	3,218	2,548	3,016	2,813
6-29-34	10	2,803	3,846	2,891	3,337	3,219
7-3-34	11	3,111	4,002	3,246	3,658	3,504
7-5-34	11	3,206	4,145	3,405	3,848	3,651
7-7-34	12	3,491	4,453	3,675	4,061	3,920
7-12-34	13	3,800	4,857	4,018	4,441	4,279
7-17-34	14	4,156	5,285	4,459	4,845	4,686
7-20-34	15	4,394	5,572	4,728	5,106	4,950
7-28-34	16	4,679	5,985	5,120	5,486	5,318
8-3-34	16	4,679	6,092	5,268	5,558	5,374
8-10-34	16	4,798	6,235	5,439	5,748	5,555
8-16-34	16	4,845	6,329	5,512	5,842	5,632
8-22-34	16	4,893	6,472	5,610	5,961	5,734
8-27-34	16	4,964	6,567	5,709	6,056	5,824
8-31-34	16	5,059	6,686	5,757	6,128	5,908
9-11-34	16	5,059	6,710	5,806	6,175	5,938
9-19-34	16	5,296	6,947	6,051	6,484	6,144
9-29-34	16	5,201	6,971	6,027	6,341	6,135
10-13-34	16	5,320	7,066	6,272	6,484	6,285
10-23-34	16	5,391	7,279	6,515	6,698	6,471
12-27-34	16	4,916	7,161	6,321	6,769	6,292
4-19-35	16	5,272	7,791	7,080	6,864	6,752
6-3-35	16		7,659	7,203	7,054	6,804

Table 5.6 Vertical Load on the Pipe of Experiment 2. (Spangler (28))

TABLE 21. PIPE DEFLECTIONS OF EXPERIMENT 2

Date	Height of fill, ft.	Deflection, in.												Deflection calculated by Eq. 20, in.
		Section 1		Section 2		Section 3		Section 4		Average				
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical			
6-5-34	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6-6-34	1	0.08	0.08	0.02	0.03	0.02	0.03	0.02	0.05	0.06	0.06	0.05	0.04	0.04
6-7-34	2	0.12	0.12	0.05	0.06	0.05	0.06	0.05	0.07	0.10	0.10	0.09	0.08	0.09
6-8-34	3	0.16	0.16	0.09	0.10	0.10	0.10	0.10	0.10	0.13	0.13	0.15	0.13	0.14
6-12-34	4	0.19	0.26	0.13	0.17	0.13	0.17	0.13	0.17	0.17	0.22	0.20	0.17	0.18
6-14-34	5	0.24	0.27	0.17	0.19	0.16	0.18	0.16	0.18	0.16	0.26	0.23	0.21	0.22
6-16-34	6	0.28	0.33	0.21	0.24	0.19	0.22	0.19	0.22	0.24	0.33	0.31	0.25	0.28
6-20-34	7	0.36	0.36	0.25	0.28	0.24	0.26	0.24	0.26	0.24	0.38	0.36	0.31	0.32
6-22-34	8	0.38	0.39	0.29	0.31	0.26	0.29	0.26	0.29	0.31	0.43	0.41	0.34	0.37
6-26-34	9	0.43	0.45	0.34	0.37	0.31	0.34	0.31	0.34	0.31	0.48	0.49	0.39	0.41
6-29-34	10	0.48	0.49	0.38	0.41	0.36	0.37	0.36	0.37	0.36	0.52	0.52	0.43	0.47
7-3-34	11	0.58	0.55	0.43	0.46	0.40	0.43	0.40	0.43	0.40	0.58	0.57	0.48	0.51
7-7-34	12	0.59	0.60	0.49	0.51	0.45	0.48	0.45	0.48	0.45	0.66	0.66	0.55	0.57
7-15-34	13	0.68	0.68	0.53	0.59	0.49	0.55	0.49	0.55	0.49	0.71	0.72	0.59	0.63
7-17-34	14	0.68	0.74	0.60	0.64	0.55	0.59	0.55	0.59	0.55	0.78	0.78	0.65	0.69
7-20-34	15	0.73	0.78	0.64	0.69	0.59	0.65	0.59	0.65	0.59	0.82	0.85	0.69	0.73
7-28-34	16	0.79	0.84	0.69	0.74	0.64	0.68	0.64	0.68	0.64	0.88	0.93	0.75	0.78
8-3-34	16	0.80	0.87	0.71	0.77	0.65	0.70	0.65	0.70	0.65	0.91	0.95	0.77	0.79
8-10-34	16	0.81	0.88	0.72	0.78	0.65	0.71	0.65	0.71	0.65	0.92	0.96	0.78	0.81
8-16-34	16	0.83	0.89	0.74	0.80	0.66	0.73	0.66	0.73	0.66	0.93	0.97	0.79	0.82
8-22-34	16	0.85	0.91	0.75	0.82	0.67	0.74	0.67	0.74	0.67	0.94	0.98	0.80	0.84
8-27-34	16	0.88	0.92	0.76	0.83	0.68	0.75	0.68	0.75	0.68	0.96	0.98	0.82	0.85
8-31-34	16	0.89	0.83	0.77	0.84	0.69	0.76	0.69	0.76	0.69	0.96	1.00	0.83	0.87
9-11-34	16	0.89	0.96	0.80	0.86	0.72	0.80	0.72	0.80	0.72	0.98	1.04	0.85	0.87
9-19-34	16	0.93	0.98	0.82	0.87	0.74	0.81	0.74	0.81	0.74	1.01	1.06	0.88	0.90
10-22-34	16	0.97	1.05	0.89	0.98	0.81	0.90	0.81	0.90	0.81	1.08	1.16	0.94	0.95
12-27-34	16	1.07	1.17	0.99	1.08	0.91	1.01	0.91	1.01	0.91	1.21	1.28	1.04	0.92
4-10-35	16	1.26	1.41	1.18	1.28	1.10	1.22	1.10	1.22	1.10	1.40	1.50	1.23	0.90
6-3-35	16	1.34	1.50	1.22	1.34	1.17	1.27	1.17	1.27	1.17	1.43	1.55	1.29	1.00

Table 5.7 Pipe Deflections of Experiment 2. (Spangler (28))

TABLE 22. PIPE DEFLECTIONS OF EXPERIMENT 3

Date	Height of fill, ft.	Average deflection,* in.							
		60-in. culvert				48-in. culvert			
		Tamped sidefills†		Untamped sidefills‡		Tamped sidefills†		Untamped sidefills‡	
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
6-25-36	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6-30-36	1	0.03	0.04	0.12	0.10	0.05	0.03	0.14	0.14
7- 3-36	2	0.08	0.11	0.20	0.19	0.07	0.09	0.22	0.22
7- 7-36	3	0.12	0.17	0.31	0.30	0.11	0.14	0.30	0.31
7- 9-36	4	0.17	0.23	0.38	0.37	0.17	0.21	0.41	0.42
7-11-36	5	0.23	0.33	0.46	0.49	0.20	0.25	0.46	0.45
7-14-36	6	0.28	0.39	0.55	0.58	0.26	0.30	0.56	0.55
7-17-36	7	0.36	0.47	0.71	0.69	0.31	0.38	0.66	0.64
7-21-36	8	0.41	0.54	0.79	0.79	0.39	0.46	0.81	0.77
7-25-36	9	0.49	0.63	0.97	0.96	0.43	0.51	0.91	0.86
7-30-36	10	0.58	0.74	1.12	1.12	0.51	0.58	1.01	0.96
8- 1-36	11	0.65	0.84	1.21	1.23	0.56	0.64	1.10	1.05
8- 5-36	12	0.72	0.92	1.37	1.38	0.62	0.72	1.24	1.20
8- 8-36	13	0.78	0.99	1.44	1.46	0.70	0.80	1.34	1.25
8-12-36	14	0.86	1.09	1.57	1.57	0.76	0.89	1.45	1.38
8-18-36	15	0.97	1.22	1.74	1.76	0.86	0.98	1.58	1.53
8-20-36	15	0.99	1.24	1.76	1.79	0.86	1.00	1.59	1.53
8-21-36	15	0.99	1.25	1.78	1.81	0.87	1.01	1.60	1.54
8-24-36	15	1.00	1.26	1.79	1.82	0.88	1.02	1.62	1.55
8-26-36	15	1.01	1.26	1.80	1.82	0.88	1.02	1.62	1.56
8-28-36	15	1.01	1.27	1.81	1.83	0.89	1.02	1.62	1.56
8-31-36	15	1.02	1.28	1.81	1.83	0.89	1.02	1.63	1.56
9- 2-36	15	1.01	1.28	1.81	1.83	0.90	1.03	1.63	1.56
9- 8-36	15	1.04	1.29	1.83	1.84	0.91	1.03	1.65	1.58
9-16-36	15	1.05	1.29	1.84	1.84	0.91	1.03	1.65	1.58
9-25-36	15	1.06	1.30	1.87	1.87	0.92	1.05	1.66	1.59
10- 7-36	15	1.08	1.32	1.91	1.91	0.93	1.06	1.69	1.60
10-14-36	15	1.09	1.33	1.93	1.93	0.94	1.06	1.69	1.60
10-22-36	15	1.11	1.34	1.95	1.95	0.96	1.07	1.71	1.62
10-28-36	15	1.12	1.35	1.98	1.96	0.97	1.07	1.72	1.63
11- 5-36	15	1.13	1.35	1.97	1.96	0.97	1.08	1.72	1.63
12- 5-36	15	1.13	1.37	2.00	2.00	0.96	1.10	1.73	1.65
12-23-36	15	1.15	1.39	2.03	2.01	0.97	1.09	1.73	1.65
1- 4-37	15	1.16	1.39	2.02	2.00	0.97	1.10	1.73	1.66
3- 5-37	15	1.17	1.40	2.10	2.08	0.99	1.12	1.77	1.66
3-24-37	15	1.19	1.41	2.12	2.09	1.00	1.12	1.76	1.68
4-14-37	15	1.20	1.43	2.14	2.10	1.00	1.13	1.78	1.70
5-13-37	15	1.18	1.41	2.13	2.11	1.00	1.13	1.77	1.70
6-21-37	15	1.18	1.41	2.14	2.13	1.00	1.12	1.78	1.69
7- 8-37	15	1.19	1.42	2.15	2.13	1.00	1.13	1.78	1.70
8-28-37	15	1.20	1.42	2.18	2.15	1.00	1.13	1.79	1.72
9-11-37	15	1.20	1.42	2.19	2.16	1.01	1.13	1.80	1.71
9-30-37	15	1.20	1.42	2.19	2.18	1.01	1.13	1.79	1.73
11-30-37	15	1.22	1.44	2.22	2.18	1.02	1.14	1.82	1.74
3-22-38	15	1.24	1.45	2.26	2.22	1.04	1.14	1.84	1.77
4-30-38	15	1.23	1.46	2.25	2.23	1.03	1.15	1.83	1.77
5-26-38	15	1.26	1.48	2.27	2.25	1.06	1.19	1.84	1.79
9-26-38	15	1.36	1.69	2.45	2.52	1.13	1.28	1.98	1.90
12-15-38	15	1.39	1.71	2.51	2.54	1.14	1.28	2.02	1.93
2- 4-39	15					1.15	1.29	2.03	1.95
5-29-39	15	1.40	1.73	2.54	2.58	1.15	1.32	2.04	1.97
8- 3-39	15	1.40	1.73	2.56	2.58				
2-30-40	15	1.44	1.78	2.60	2.60	1.18	1.33	2.10	2.02

*Average of the deflections of individual pipe sections.

†Average of sections 1, 2, 3, and 4.

‡Average of sections 6, 7, and 8. Section 5 is omitted from the average.

Table 5.8 Pipe Deflections of Experiment 3.
(Spangler (28))

TABLE 22. PIPE DEFLECTIONS OF EXPERIMENT 3—Continued

Date	Height of fill, ft.	Average deflection,* in.							
		42-in. culvert				36-in. culvert			
		Tamped sidefills†		Untamped sidefills‡		Tamped sidefills†		Untamped sidefills‡	
		Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
6-25-36	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6-30-36	1	0.01	0.02	0.06	0.07	0.02	0.01	0.07	0.07
7- 3-36	2	0.04	0.06	0.17	0.16	0.04	0.04	0.14	0.13
7- 7-36	3	0.09	0.12	0.27	0.25	0.09	0.08	0.21	0.21
7- 9-36	4	0.14	0.16	0.35	0.31	0.11	0.13	0.29	0.28
7-11-36	5	0.17	0.20	0.40	0.37	0.15	0.17	0.34	0.33
7-14-36	6	0.23	0.28	0.50	0.45	0.18	0.20	0.41	0.39
7-17-36	7	0.26	0.30	0.54	0.50	0.23	0.25	0.51	0.49
7-21-36	8	0.36	0.41	0.70	0.64	0.27	0.29	0.58	0.55
7-25-36	9	0.39	0.44	0.76	0.70	0.34	0.37	0.70	0.66
7-30-36	10	0.46	0.50	0.86	0.80	0.39	0.41	0.78	0.74
8- 1-36	11	0.50	0.54	0.95	0.87	0.42	0.46	0.85	0.81
8- 5-36	12	0.56	0.61	1.04	0.97	0.48	0.51	0.97	0.90
8- 8-36	13	0.62	0.68	1.15	1.07	0.54	0.57	1.06	0.99
8-12-36	14	0.67	0.74	1.25	1.17	0.57	0.62	1.14	1.08
8-18-36	15	0.76	0.82	1.36	1.27	0.65	0.70	1.25	1.17
8-20-36	15	0.76	0.83	1.37	1.29	0.66	0.70	1.26	1.17
8-21-36	15	0.76	0.83	1.37	1.30	0.65	0.70	1.27	1.19
8-24-36	15	0.76	0.83	1.38	1.30	0.66	0.71	1.27	1.21
8-26-36	15	0.77	0.84	1.39	1.31	0.67	0.71	1.27	1.21
8-28-36	15	0.77	0.85	1.39	1.30	0.68	0.71	1.28	1.21
8-31-36	15	0.78	0.85	1.39	1.32	0.67	0.73	1.28	1.21
9- 2-36	15	0.78	0.85	1.40	1.32	0.68	0.73	1.28	1.21
9- 8-36	15	0.79	0.85	1.41	1.34	0.69	0.73	1.30	1.21
9-16-36	15	0.80	0.86	1.41	1.33	0.69	0.73	1.30	1.22
9-25-36	15	0.81	0.86	1.43	1.34	0.69	0.74	1.31	1.23
10- 7-36	15	0.82	0.87	1.45	1.36	0.71	0.74	1.33	1.25
10-14-36	15	0.83	0.88	1.46	1.37	0.72	0.75	1.34	1.26
10-22-36	15	0.84	0.89	1.48	1.38	0.72	0.75	1.35	1.27
10-28-36	15	0.85	0.89	1.50	1.39	0.73	0.76	1.37	1.28
11- 5-36	15	0.84	0.89	1.49	1.39	0.72	0.75	1.35	1.27
12- 5-36	15	0.85	0.90	1.50	1.37	0.73	0.76	1.36	1.27
12-23-36	15	0.85	0.91	1.50	1.40	0.73	0.76	1.35	1.27
1- 4-37	15	0.88	0.92	1.50	1.42	0.74	0.76	1.37	1.27
3- 5-37	15	0.87	0.94	1.54	1.44	0.75	0.78	1.40	1.30
3-24-37	15	0.87	0.94	1.55	1.44	0.74	0.78	1.40	1.30
4-14-37	15	0.88	0.94	1.55	1.45	0.75	0.78	1.41	1.30
5-13-37	15	0.88	0.95	1.55	1.45	0.75	0.79	1.40	1.32
6-21-37	15	0.88	0.94	1.55	1.46	0.76	0.79	1.40	1.31
7- 8-37	15								
8-28-37	15	0.88	0.94	1.56	1.46	0.77	0.80	1.41	1.33
9-11-37	15	0.89	0.94	1.57	1.47	0.77	0.80	1.43	1.33
9-30-37	15	0.89	0.94	1.57	1.47	0.78	0.80	1.43	1.35
11-30-37	15	0.91	0.95	1.58	1.49	0.79	0.81	1.46	1.36
3-22-38	15	0.92	0.98	1.64	1.53	0.80	0.83	1.48	1.38
4-30-38	15	0.93	0.99	1.64	1.54	0.80	0.84	1.48	1.38
5-26-38	15	0.94	1.01	1.65	1.56	0.80	0.84	1.47	1.38
9-26-38	15	1.04	1.09	1.81	1.70	0.93	0.94	1.57	1.47
12-15-38	15	1.07	1.11	1.86	1.75	0.95	0.97	1.61	1.49
2- 4-39	15	1.08	1.13	1.89	1.77	0.96	0.97	1.61	1.51
5-29-39	15	1.09	1.16	1.93	1.81	0.96	0.98	1.63	1.51
8- 3-39	15	1.10	1.17	1.93	1.81	0.96	0.98	1.63	1.53
3-30-40	15	1.14	1.21	1.96	1.85	0.98	1.01	1.65	1.55

*Average of the deflections of individual pipe sections.

†Average of sections 1, 2, 3, and 4.

‡Average of sections 6, 7, and 8. Section 5 is omitted from the average.

Table 5.9 Pipe Deflections of Experiment 3 Continued. (Spangler (28))

installation specifications.

5.3.1 Parameters

The data collected included information on the following: length of the line (not available for Contech's data), age, depth of cover, embedment type, average deflection, and maximum deflection. The predicted deflection based on the Spangler's equation was calculated using a bedding constant of 0.10, a lag factor of 1.2, values for E' from Howard (14) assuming 85% or less compaction, and a prism load assuming a moist density of the backfill of 120 pcf. A bedding constant of 0.10 represents an installation which included haunching of the pipe midway and some inspection. A lag factor of 1.2 represents a 20% increase in deflection from the time of the initial installation. E' was also back-calculated using this same equation and the observed average and maximum deflections. The pipe-soil stiffness ratios were based on these values for E' .

5.3.2 Structure

The data base analysed in this thesis was organized using an IBM compatible PC. The data provided by each source such

as: average deflection, maximum deflection, and length of the pipeline, were entered into a spreadsheet where additional parameters were either calculated or back-calculated. The statistics which are included in this study were also calculated at this time. The correlations between the different parameters were prepared using computer generated graphics.

Summaries of the data including the statistical computations for the NCPI's data are given in Tables 5.10 - 5.14 for various bedding materials. The values for E' which were used in the Spangler's equation for purposes of comparison with the field data are shown in Table 5.15.

Similar summaries of the Contech's truss pipe data and of the Donahue's data are found in Tables 5.16 - 5.26 and in Tables 5.28 - 5.33, respectively, for various pipe diameters and bedding classes. The corresponding values of E' for comparison with the Spangler's equation are shown in Table 5.27 and 5.34.

5.3.3 Benefits

Due to the size of the data base and the variation of installation conditions, the trends presented here are

PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL
FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
8 INCH SDR35 PVC PIPE						
UNKNOWN BEDDING MATERIAL						
SOURCE: NATIONAL CLAY PIPE INSTITUTE						
LENGTH (FT)	103	275	105	110	110	28832
AGE (YRS)	110	2.02	2.16	12.0	0.1	
DEPTH (FT)	105	7.98	2.77	18.0	3.5	
PERCENT OF LINE EXCEEDING 5%	110	17.63	23.60	97.0	0.0	
PERCENT OF LINE EXCEEDING 7.5%	110	4.52	10.39	62.0	0.0	
PERCENT OF LINE EXCEEDING 10%	110	0.81	3.59	33.0	0.0	
AVERAGE DEFLECTION (%)	110	3.29	1.14	7.7	2.5	
MAXIMUM DEFLECTION (%)	110	9.18	4.92	30.5	1.1	
E' BASED ON AVERAGE DEFLECTION (PSI)	110	293	191	952	-112	
E' BASED ON MAXIMUM DEFLECTION (PSI)	110	63	181	1378	-112	
DEFLECTION AS PREDICTED BY SPANGLER E'=400 PSI (%)	110	2.44	1.01	5.76	0.00	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	110	0.020	0.129	0.509	-1.195	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	110	0.355	2.208	20.805	-4.300	

Table 5.10 Field Deflections of Underground Pipelines - Unknown Bedding. (National Clay Pipe Institute)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES									
8 INCH SDR35 PVC PIPE CLASS II BEDDING									
SOURCE: NATIONAL CLAY PIPE INSTITUTE									
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL			
LENGTH (FT)	46	240	87	400	100	11039			
AGE (YRS)	45	2.21	1.56	5.1	0.1				
DEPTH (FT)	46	9.30	1.62	4.0	5.0				
PERCENT OF LINE EXCEEDING 5%	46	12.08	21.69	98.0	0.0				
PERCENT OF LINE EXCEEDING 7.5%	46	1.07	3.78	6.0	0.0				
PERCENT OF LINE EXCEEDING 10%	46	0.00	0.00	0.0	0.0				
AVERAGE DEFLECTION (%)	46	2.98	0.88	6.5	2.5				
MAXIMUM DEFLECTION (%)	46	7.53	3.21	18.6	3.5				
E' BASED ON AVERAGE DEFLECTION (PSI)	46	426	135	779	145				
E' BASED ON MAXIMUM DEFLECTION (PSI)	46	118	78	264	-31				
DEFLECTION AS PREDICTED BY SPANGLER E'=1000 PSI (%)	46	1.37	0.24	2.06	0.74				
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	46	0.018	0.008	0.047	0.009				
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	46	-0.013	0.735	2.744	-3.872				

Table 5.11 Field Deflections of Underground Pipelines - Class II Bedding. (National Clay Pipe Institute)

PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL
FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
8 INCH SDR35 PVC PIPE SAND BEDDING						
SOURCE: NATIONAL CLAY PIPE INSTITUTE						
LENGTH (FT)	55	221	84	400	30	12181
AGE (YRS)	57	3.01	1.99	9.0	0.2	
DEPTH (FT)	57	8.50	3.31	6.0	3.0	
PERCENT OF LINE EXCEEDING 5%	57	7.42	4.29	85.0	0.0	
PERCENT OF LINE EXCEEDING 7.5%	57	1.98	6.45	44.0	0.0	
PERCENT OF LINE EXCEEDING 10%	57	0.12	0.59	4.1	0.0	
AVERAGE DEFLECTION (%)	57	2.83	0.69	6.8	2.5	
MAXIMUM DEFLECTION (%)	57	6.45	3.48	6.2	1.9	
E' BASED ON AVERAGE DEFLECTION (PSI)	57	406	230	871	60	
E' BASED ON MAXIMUM DEFLECTION (PSI)	57	202	226	748	-58	
DEFLECTION AS PREDICTED BY SPANGLER E'=1000 PSI (%)	57	1.25	0.49	2.35	0.44	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	57	0.030	0.028	0.114	0.008	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	57	-0.080	0.600	2.359	-2.850	

Table 5.12 Field Deflections of Underground Pipelines - Sand Bedding. (National Clay Pipe Institute)

PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL
LENGTH (FT)	25	258	104	439	126	6456
AGE (YRS)	28	2.47	1.66	4.6	0.1	
DEPTH (FT)	28	7.93	1.93	1.5	5.0	
PERCENT OF LINE EXCEEDING 5%	28	8.14	14.54	60.0	0.0	
PERCENT OF LINE EXCEEDING 7.5%	28	1.21	2.53	10.0	0.0	
PERCENT OF LINE EXCEEDING 10%	28	0.00	0.00	0.0	0.0	
AVERAGE DEFLECTION (%)	28	2.84	0.60	4.9	2.5	
MAXIMUM DEFLECTION (%)	28	6.41	2.56	1.5	3.3	
E' BASED ON AVERAGE DEFLECTION (PSI)	28	366	147	619	71	
E' BASED ON MAXIMUM DEFLECTION (PSI)	28	132	131	531	-23	
DEFLECTION AS PREDICTED BY SPANGLER E'=1000 PSI (%)	28	1.17	0.28	1.69	0.81	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	28	0.024	0.017	0.097	0.011	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	28	0.285	1.147	5.452	-0.692	

Table 5.13 Field Deflections of Underground Pipelines - Crushed Stone to the Springline.
(National Clay Pipe Institute)

PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL
LENGTH (FT)	60	273	121	840	46	16370
AGE (YRS)	61	2.67	1.88	9.2	0.2	
DEPTH (FT)	61	7.91	3.17	28.0	4.0	
PERCENT OF LINE EXCEEDING 5%	61	6.21	9.29	36.0	0.0	
PERCENT OF LINE EXCEEDING 7.5%	61	1.04	2.33	14.0	0.0	
PERCENT OF LINE EXCEEDING 10%	61	0.03	0.19	1.0	0.0	
AVERAGE DEFLECTION (%)	61	2.76	0.39	4.0	2.5	
MAXIMUM DEFLECTION (%)	61	8.13	5.08	26.6	0.6	
E' BASED ON AVERAGE DEFLECTION (PSI)	61	366	209	1723	54	
E' BASED ON MAXIMUM DEFLECTION (PSI)	61	112	279	844	-73	
DEFLECTION AS PREDICTED BY SPANGLER E'=3000 PSI (%)	61	0.42	0.17	1.47	0.24	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	61	0.023	0.016	0.128	0.004	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	61	0.057	0.294	0.813	-1.365	

Table 5.14 Field Deflections of Underground Pipelines - Crushed Stone Envelope. (National Clay Pipe Institute)

VALUES FOR E' USED IN THE SPANGLER'S EQN. (BASED ON HOWARD (14))		
APPLICATION: NATIONAL CLAY PIPE INSTITUTE DATA		
BEDDING MATERIAL	E'	(PSI)
UNKNOWN BEDDING	400	
CLASS II BEDDING	1000	
SAND BEDDING	1000	
CRUSHED STONE TO THE SPRINGLINE	1000	
CRUSHED STONE ENVELOPE	3000	

Table 5.15 Values of E' Used in the Spangler's Equation.
(National Clay Pipe Institute)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES		CLASS I BEDDING MATERIAL		MINIMUM
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM
AGE (YRS)	18	2.89	2.04	5.3
DEPTH (FT)	18	11.08	5.62	30.0
AVERAGE DEFLECTION (%)	18	0.70	0.28	1.3
MAXIMUM DEFLECTION (%)	18	1.71	0.45	2.8
E' BASED ON AVERAGE DEFLECTION (FSI)	18	3664	7016	32298
E' BASED ON MAXIMUM DEFLECTION (FSI)	18	620	547	2456
DEFLECTION AS PREDICTED BY SPANGLER E'=3000 PSI (%)	18	0.52	0.26	1.41
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	18	0.028	0.050	0.233
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	18	-0.039	0.354	0.133

Table 5.16 Field Deflections of Underground Pipelines.
 8 Inch Pipe - Class I Bedding.
 (ARMCO Truss Pipe - CONTECH)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
8 INCH NOMINAL DIAMETER		CLASS II BEDDING MATERIAL				
SOURCE: ARMCO TRUSS PIPE (CONTECH)						
PIPE STIFFNESS = 200 PSI						
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	53	1.42	1.29	5.5	0.2	
DEPTH (FT)	53	10.92	5.26	35.0	2.0	
AVERAGE DEFLECTION (%)	53	0.83	0.51	3.0	0.0	
MAXIMUM DEFLECTION (%)	53	2.06	0.91	4.0	0.0	
E' BASED ON AVERAGE DEFLECTION (PSI)	53	2792	3993	20276	-57	
E' BASED ON MAXIMUM DEFLECTION (PSI)	53	786	2038	16767	-253	
DEFLECTION AS PREDICTED BY SPANGLER E'=1000 PSI (%)	53	1.20	0.58	3.85	0.22	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	53	0.056	0.272	0.515	-0.522	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	53	0.201	1.843	12.973	-3.079	

Table 5.17 Field Deflections of Underground Pipelines.
8 Inch Pipe - Class II Bedding.
(ARMCO Truss Pipe - CONTECH)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
8 INCH NOMINAL DIAMETER CLASS III BEDDING MATERIAL						
SOURCE: ARMO TRUSS PIPE (CONTECH)						
PIPE STIFFNESS = 200 PSI						
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	10	1.17	0.88	3.6	0.3	
DEPTH (FT)	10	8.50	3.64	16.5	3.5	
AVERAGE DEFLECTION (%)	10	0.85	0.48	1.8	0.1	
MAXIMUM DEFLECTION (%)	10	1.97	0.63	3.4	1.2	
E' BASED ON AVERAGE DEFLECTION (PSI)	10	2730	4441	15904	356	
E' BASED ON MAXIMUM DEFLECTION (PSI)	10	221	209	576	-100	
DEFLECTION AS PREDICTED BY SPANGLER E'-400 PSI (%)	10	1.57	0.67	3.04	0.64	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	10	0.032	0.024	0.084	0.002	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	10	-0.163	0.932	0.712	-2.870	

Table 5.18 Field Deflections of Underground Pipelines.
8 Inch Pipe - Class III Bedding.
(ARMO Truss Pipe - CONTECH)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
8 INCH NOMINAL DIAMETER		CLASS IV BEDDING MATERIAL				
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	12	1.01	1.00	3.1	0.2	
DEPTH (FT)	12	12.92	8.76	30.0	4.0	
AVERAGE DEFLECTION (%)	12	0.83	0.41	1.6	0.1	
MAXIMUM DEFLECTION (%)	12	2.01	0.72	3.1	0.6	
E' BASED ON AVERAGE DEFLECTION (PSI)	12	2229	2274	7708	410	
E' BASED ON MAXIMUM DEFLECTION (PSI)	12	377	496	1678	-48	
DEFLECTION AS PREDICTED BY SPANGLER E'=200 PSI (%)	12	2.60	2.08	7.14	0.95	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	12	0.028	0.020	0.073	0.004	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	12	0.264	0.447	1.090	-0.615	

Table 5.19 Field Deflections of Underground Pipelines.
8 Inch Pipe - Class IV Bedding.
(ARMCO Truss Pipe - CONTECH)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
10 INCH NOMINAL DIAMETER		CLASS I BEDDING MATERIAL				
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	3	0.66	0.32	0.9	0.2	
DEPTH (FT)	3	21.00	5.35	28.0	15.0	
AVERAGE DEFLECTION (%)	3	1.58	0.73	2.6	0.9	
MAXIMUM DEFLECTION (%)	3	2.41	0.52	3.0	1.7	
E' BASED ON AVERAGE DEFLECTION (PSI)	3	2088	1048	3337	772	
E' BASED ON MAXIMUM DEFLECTION (PSI)	3	959	304	1348	604	
DEFLECTION AS PREDICTED BY SPANGLER E'=3000 PSI (%)	3	0.99	0.25	1.32	0.70	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	3	0.020	0.013	0.039	0.009	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	3	0.035	0.011	0.049	0.022	

Table 5.20 Field Deflections of Underground Pipelines.
10 Inch Pipe - Class I Bedding.
(ARMCO Truss Pipe - CONTECH)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
10 INCH NOMINAL DIAMETER		CLASS II BEDDING MATERIAL				
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	13	0.95	0.45	1.5	0.2	
DEPTH (FT)	13	14.81	6.10	24.0	7.5	
AVERAGE DEFLECTION (%)	13	0.86	0.55	1.7	0.0	
MAXIMUM DEFLECTION (%)	13	2.20	0.79	4.2	1.4	
E' BASED ON AVERAGE DEFLECTION (PSI)	13	23582	60148	30249	222	
E' BASED ON MAXIMUM DEFLECTION (PSI)	13	798	724	2072	-197	
DEFLECTION AS PREDICTED BY SPANGLER E'=1000 PSI (%)	13	1.63	0.67	2.64	0.83	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	13	0.032	0.045	0.134	0.000	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	13	0.037	0.160	0.494	-0.252	

**Table 5.21 Field Deflections of Underground Pipelines.
10 Inch Pipe - Class II Bedding.
(ARMCO Truss Pipe - CONTECH)**

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
10 INCH NOMINAL DIAMETER CLASS III BEDDING MATERIAL						
SOURCE: ARMCO TRUSS PIPE (CONTECH)						
PIPE STIFFNESS = 200 PSI						
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	3	1.60	1.56	3.8	0.5	
DEPTH (FT)	3	10.00	1.41	12.0	9.0	
AVERAGE DEFLECTION (%)	3	0.92	0.44	1.5	0.4	
MAXIMUM DEFLECTION (%)	3	2.14	0.72	3.1	1.5	
E' BASED ON AVERAGE DEFLECTION (PSI)	3	1716	997	3110	831	
E' BASED ON MAXIMUM DEFLECTION (PSI)	3	325	144	488	138	
DEFLECTION AS PREDICTED BY SPANGLER E'=400 PSI (%)	3	1.85	0.26	2.21	1.66	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	3	0.023	0.011	0.036	0.010	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	3	0.121	0.068	0.216	0.061	

Table 5.22 Field Deflections of Underground Pipelines.
 10 Inch Pipe - Class III Bedding.
 (ARMCO Truss Pipe - CONTECH)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	2	1.50	1.40	2.9	0.1	
DEPTH (FT)	2	11.25	0.25	11.5	11.0	
AVERAGE DEFLECTION (%)	2	0.51	0.38	0.9	0.1	
MAXIMUM DEFLECTION (%)	2	1.59	0.70	2.3	0.9	
E' BASED ON AVERAGE DEFLECTION (PSI)	2	7506	5877	13382	1630	
E' BASED ON MAXIMUM DEFLECTION (PSI)	2	936	601	1538	335	
DEFLECTION AS PREDICTED BY SPANGLER E'=3000 PSI (%)	2	0.53	0.01	0.54	0.52	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	2	0.010	0.008	0.018	0.002	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	2	0.054	0.035	0.089	0.019	

Table 5.23 Field Deflections of Underground Pipelines
 12 Inch Pipe - Class I Bedding.
 (ARMCO Truss Pipe - CONTECH)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
12 INCH NOMINAL DIAMETER		CLASS II BEDDING MATERIAL				
SOURCE: ARMCO TRUSS PIPE (CONTECH)						
PIPE STIFFNESS = 200 PSI						
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	11	1.32	1.43	5.2	0.2	
DEPTH (FT)	11	18.23	5.94	25.0	8.0	
AVERAGE DEFLECTION (%)	11	0.97	0.66	2.0	0.0	
MAXIMUM DEFLECTION (%)	11	2.52	1.28	4.0	0.8	
E' BASED ON AVERAGE DEFLECTION (PSI)	11	3209	2744	9757	1530	
E' BASED ON MAXIMUM DEFLECTION (PSI)	11	1000	783	2503	321	
DEFLECTION AS PREDICTED BY SPANGLER E'=1000 PSI (%)	11	2.01	0.65	2.75	0.88	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	11	0.011	0.007	0.020	0.003	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	11	0.049	0.028	0.093	0.012	

Table 5.24 Field Deflections of Underground Pipelines
 12 Inch Pipe - Class II Bedding.
 (ARMCO Truss Pipe - CONTECH)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	2	3.60	3.40	7.0	0.2	
DEPTH (FT)	2	16.50	10.50	27.0	6.0	
AVERAGE DEFLECTION (%)	2	1.04	0.86	1.9	0.2	
MAXIMUM DEFLECTION (%)	2	2.34	0.54	2.9	1.8	
E' BASED ON AVERAGE DEFLECTION (PSI)	2	12065	12036	24101	29	
E' BASED ON MAXIMUM DEFLECTION (PSI)	2	912	1058	1970	147	
DEFLECTION AS PREDICTED BY SPANGLER E'=3000 PSI (%)	2	0.78	0.49	1.27	0.28	
PIPE-SOIL STIFFNESS RATIO	2	0.512	0.510	1.022	0.001	
AVERAGE DEFLECTION	2	-0.094	0.109	0.015	-0.203	
PIPE-SOIL STIFFNESS RATIO	2					
MAXIMUM DEFLECTION	2					

Table 5.25 Field Deflections of Underground Pipelines
 15 Inch Pipe - Class I Bedding.
 (ARMCO Truss Pipe - CONTECH)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
15 INCH NOMINAL DIAMETER		CLASS II BEDDING MATERIAL				
SOURCE: ARMCO TRUSS PIPE (CONTECH)						
PIPE STIFFNESS = 200 PSI						
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
AGE (YRS)	5	1.06	0.98	2.9	0.1	
DEPTH (FT)	5	19.50	4.82	28.0	15.0	
AVERAGE DEFLECTION (%)	5	1.09	0.26	1.4	0.7	
MAXIMUM DEFLECTION (%)	5	2.20	0.75	3.6	1.6	
E' BASED ON AVERAGE DEFLECTION (PSI)	5	2591	886	3610	1433	
E' BASED ON MAXIMUM DEFLECTION (PSI)	5	1066	447	1588	345	
DEFLECTION AS PREDICTED BY SPANGLER E'=1000 PSI (%)	5	2.15	0.53	3.08	1.65	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	5	0.013	0.005	0.021	0.008	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	5	0.038	0.025	0.087	0.019	

Table 5.26 Field Deflections of Underground Pipelines
 15 Inch Pipe - Class II Bedding.
 (ARMCO Truss Pipe - CONTECH)

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I I VALUES FOR E' USED IN THE SPANGLER'S EQN.
I I (BASED ON HOWARD (14))
I I
I I
I I
I I APPLICATION: ARMCO TRUSS PIPE
I I DATA (CONTECH)
I I
=====
I I BEDDING MATERIAL I I E'
I I I I
I I I I
I I I I (PSI)
I I
=====
I I CLASS I BEDDING I I 3000
I I
I I CLASS II BEDDING I I 1000
I I
I I CLASS III BEDDING I I 400
I I
I I CLASS IV BEDDING I I 200
I I
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Table 5.27 Values of E' used in the Spangler' Equation.
(ARMCO Truss Pipe - CONTECH)

PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL
FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
8 INCH SDR35 PVC PIPE CRUSHED STONE ENVELOPE						
SOURCE: DONAHUE & ASSOCIATES, INC.						
LENGTH (FT)	4	292	24	315	268	1168
AGE (YRS)	4	2.00	0.40	2.4	1.6	
DEPTH (FT)	4	16.90	1.60	18.5	15.2	
AVERAGE DEFLECTION (%)	4	1.00	1.10	2.5	1.3	
MAXIMUM DEFLECTION (%)	4	4.40	1.40	6.3	2.5	
E' BASED ON AVERAGE DEFLECTION (PSI)	2	681	764	1854	871	
E' BASED ON MAXIMUM DEFLECTION (PSI)	4	607	313	1084	281	
DEFLECTION AS PREDICTED BY SPANGLER E'=3000 PSI (%)	4	0.89	0.09	0.97	0.80	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	2	0.003	0.003	0.008	0.004	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	4	0.015	0.007	0.024	0.006	

Table 5.28 Field Deflections of Underground Pipelines.
8 Inch SDR35 - Crushed Stone Envelope.
(Donahue & Associates, Inc.)

PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL
LENGTH (FT)	23	225	53	291	130	5194
AGE (YRS)	23	2.10	1.32	4.0	0.5	
DEPTH (FT)	23	9.31	1.29	11.3	7.0	
AVERAGE DEFLECTION (%)	23	3.37	0.99	5.2	1.3	
MAXIMUM DEFLECTION (%)	23	10.45	2.92	15.5	6.5	
E' BASED ON AVERAGE DEFLECTION (PSI)	23	438	211	1175	154	
E' BASED ON MAXIMUM DEFLECTION (PSI)	23	87	43	206	26	
DEFLECTION AS PREDICTED BY SPANGLER E'=1000 PSI (%)	23	1.43	0.20	1.73	1.07	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	23	0.116	0.005	0.027	0.004	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	23	0.064	0.039	0.162	0.020	

Table 5.29 Field Deflections of Underground Pipelines.
 8 Inch SDR41 - Sand Bedding.
 (Donahue & Associates, Inc.)

PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL
FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
8 INCH SDR42 PVC PIPE SAND BEDDING						
SOURCE: DONAHUE & ASSOCIATES, INC.						
LENGTH (FT)	3	236	7	245	231	707
AGE (YRS)	3	0.63	0.40	1.2	0.3	
DEPTH (FT)	3	10.17	0.47	10.5	9.5	
AVERAGE DEFLECTION (%)	3	2.51	1.02	3.8	1.3	
MAXIMUM DEFLECTION (%)	3	7.10	2.58	10.0	3.8	
E' BASED ON AVERAGE DEFLECTION (PSI)	3	732	330	1179	394	
E' BASED ON MAXIMUM DEFLECTION (PSI)	3	208	104	351	108	
DEFLECTION AS PREDICTED BY SPANGLER E'=1000 PSI (%)	3	1.57	0.07	1.62	1.46	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	3	0.006	0.003	0.010	0.003	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	3	0.023	0.010	0.036	0.011	

Table 5.30 Field Deflections of Underground Pipelines.
8 Inch SDR42 - Sand Bedding.
(Donahue & Associates, Inc.)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES									
8 INCH SDR42 PVC PIPE CRUSHED STONE ENVELOPE									
SOURCE: DONAHUE & ASSOCIATES, INC.									
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL			
LENGTH (FT)	27	273	59	386	197	7363			
AGE (YRS)	27	1.29	0.89	2.8	0.1				
DEPTH (FT)	27	11.24	1.41	16.0	8.5				
AVERAGE DEFLECTION (%)	27	1.11	1.10	3.8	0.0				
MAXIMUM DEFLECTION (%)	27	6.22	2.30	15.0	3.8				
E' BASED ON AVERAGE DEFLECTION (PSI)	16	636	602	1571	381				
E' BASED ON MAXIMUM DEFLECTION (PSI)	26	250	108	482	111				
DEFLECTION AS PREDICTED BY SPANGLER E'=3000 PSI (%)	27	0.60	0.08	0.86	0.46				
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	16	0.003	0.003	0.010	0.002				
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	26	0.017	0.008	0.035	0.008				

Table 5.31 Field Deflections of Underground Pipelines.
8 Inch SDR42 - Crushed Stone Envelope.
(Donahue & Associates, Inc.)

FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
10 INCH SDR42 PVC PIPE CRUSHED STONE ENVELOPE						
SOURCE: DONAHUE & ASSOCIATES, INC.						
PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	
LENGTH (FT)	15	270	58	348	217	
AGE (YRS)	15	1.33	1.11	4.0	0.1	
DEPTH (FT)	15	12.93	1.44	16.0	11.4	
AVERAGE DEFLECTION (%)	15	2.68	1.89	6.0	0.0	
MAXIMUM DEFLECTION (%)	15	7.62	3.08	15.0	3.0	
E' BASED ON AVERAGE DEFLECTION (PSI)	13	776	609	1865	304	
E' BASED ON MAXIMUM DEFLECTION (PSI)	15	259	124	579	84	
DEFLECTION AS PREDICTED BY SPANGLER E'=3000 PSI (%)	15	0.69	0.08	0.86	0.61	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	13	0.005	0.004	0.013	0.002	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	15	0.019	0.010	0.046	0.007	

Table 5.32 Field Deflections of Underground Pipelines.
 10 Inch SDR42 - Crushed Stone Envelope.
 (Donahue & Associates, Inc.)

PARAMETER	NUMBER OF ENTRIES	AVERAGE	STANDARD DEVIATION	MAXIMUM	MINIMUM	TOTAL
FIELD DEFLECTIONS OF UNDERGROUND PIPELINES						
12 INCH SDR42 PVC PIPE CRUSHED STONE ENVELOPE						
SOURCE: DONAHUE & ASSOCIATES, INC.						
LENGTH (FT)	3	333	26	370	315	1000
AGE (YRS)	3	2.60	1.23	4.0	1.0	
DEPTH (FT)	3	15.23	2.50	7.0	1.7	
AVERAGE DEFLECTION (%)	3	1.97	0.40	8.6	7.7	
MAXIMUM DEFLECTION (%)	3	6.75	0.00	6.8	6.8	
E' BASED ON AVERAGE DEFLECTION (PSI)	3	1233	251	1589	1038	
E' BASED ON MAXIMUM DEFLECTION (PSI)	3	306	61	350	221	
DEFLECTION AS PREDICTED BY SPANGLER E'=3000 PSI (%)	3	0.93	0.13	0.91	0.63	
PIPE-SOIL STIFFNESS RATIO AVERAGE DEFLECTION	3	0.003	0.001	0.037	0.002	
PIPE-SOIL STIFFNESS RATIO MAXIMUM DEFLECTION	3	0.013	0.003	0.018	0.011	

Table 5.33 Field Deflections of Underground Pipelines.
12 Inch SDR42 - Crushed Stone Envelope.
(Donahue & Associates, Inc.)

VALUES FOR E' USED IN THE SPANGLER'S EQN. (BASED ON HOWARD (14))		
APPLICATION: DONAHUE DATA		
BEDDING MATERIAL	E'	(PSI)
SAND BEDDING	1000	
CRUSHED STONE ENVELOPE	3000	

Table 5.34 Values of E' Used in the Spangler's Equation.
(Donahue and Associates, Inc.)

considered to be representative of the typical field installation in the United States. This provides an opportunity to evaluate the accuracy with which the Spangler's equation, which is the basis for most flexible and very flexible pipeline design, is predicting deflection.

5.4 Types of Correlations

Many graphs were produced from the data base "Deflections". Their purpose is to investigate the correlations between important pipe and/or soil parameters and the Spangler's equation. These include: vertical deflection vs time, depth of cover, pipe stiffness, and pipe-soil stiffness ratio; E' vs depth of cover, pipe-soil stiffness ratio and embedment type; and a comparison of the observed deflections with those predicted by the Spangler's equation.

5.4.1 General

All correlations are presented in graphical form to most clearly demonstrate the trends in the data. In addition, the statistics on the data are given in the Tables described in section 5.3.2. The complete collection of graphs is found in Appendix A1.

5.4.2 Variation of Deflection with Time

A study was performed to determine the effects of time on the vertical deflection of a pipeline. The age of each of the lines is the length of time since completion of the installation. In most cases multiple readings of the same line were not available.

The NCPI data shows scatter as well as the trend towards increasing deflection with time, which the flexible pipeline theory suggests, is not clearly defined. This may be due to the fact that the minimum deflection was set at 2.5% and the points occurring below this are not shown. This trend is most clearly represented in Figure 5.6.

The truss pipe data also shows much scatter as shown in Figure 5.7. The trend towards increasing deflection with age is, at best, weak. The author also studied the effect of different diameters on this correlation and no new information or trend was discovered.

The Donahue data does not provide any additional information.

It is interesting to note that the Spangler data shows a clear increase in vertical deflection with time. This is

VERTICAL DEFLECTION VS AGE
8 INCH SDR35 PVC PIPE - SAND BEDDING

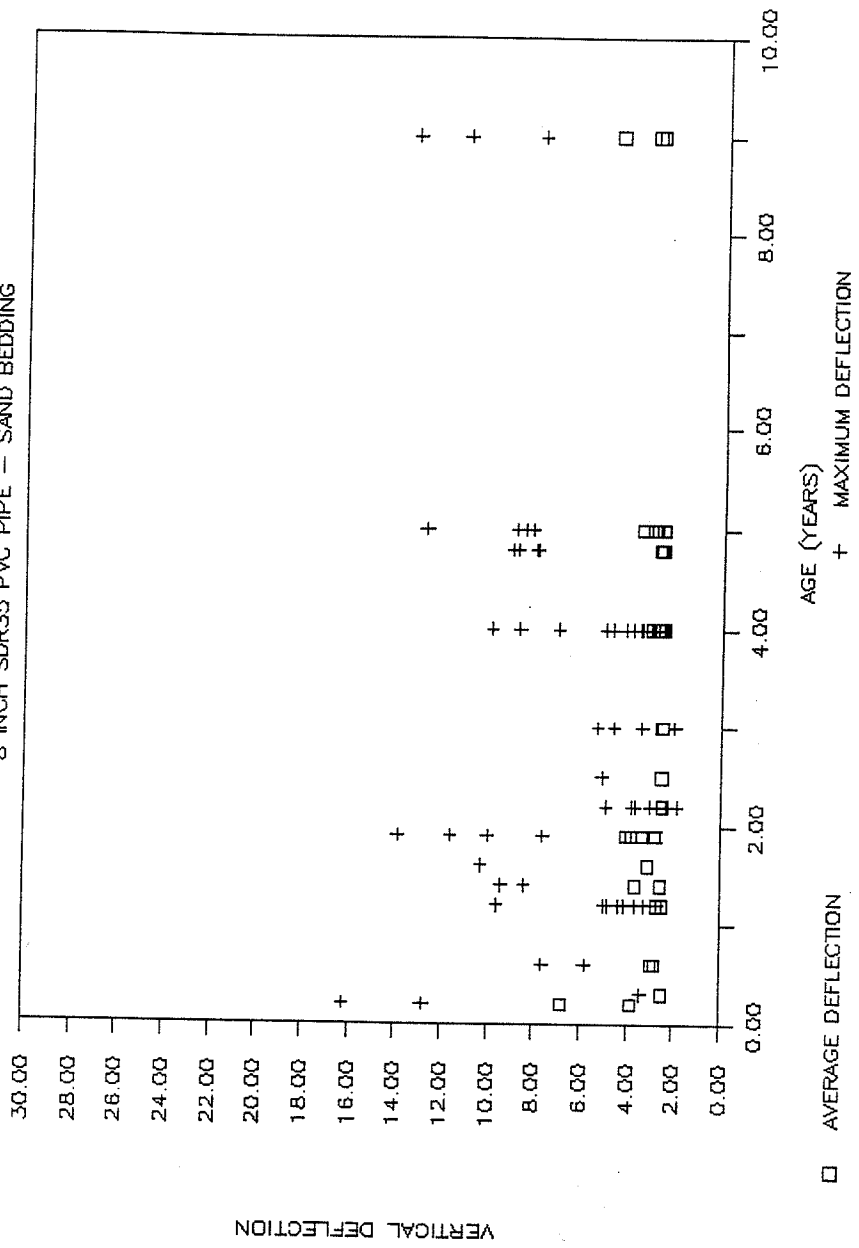
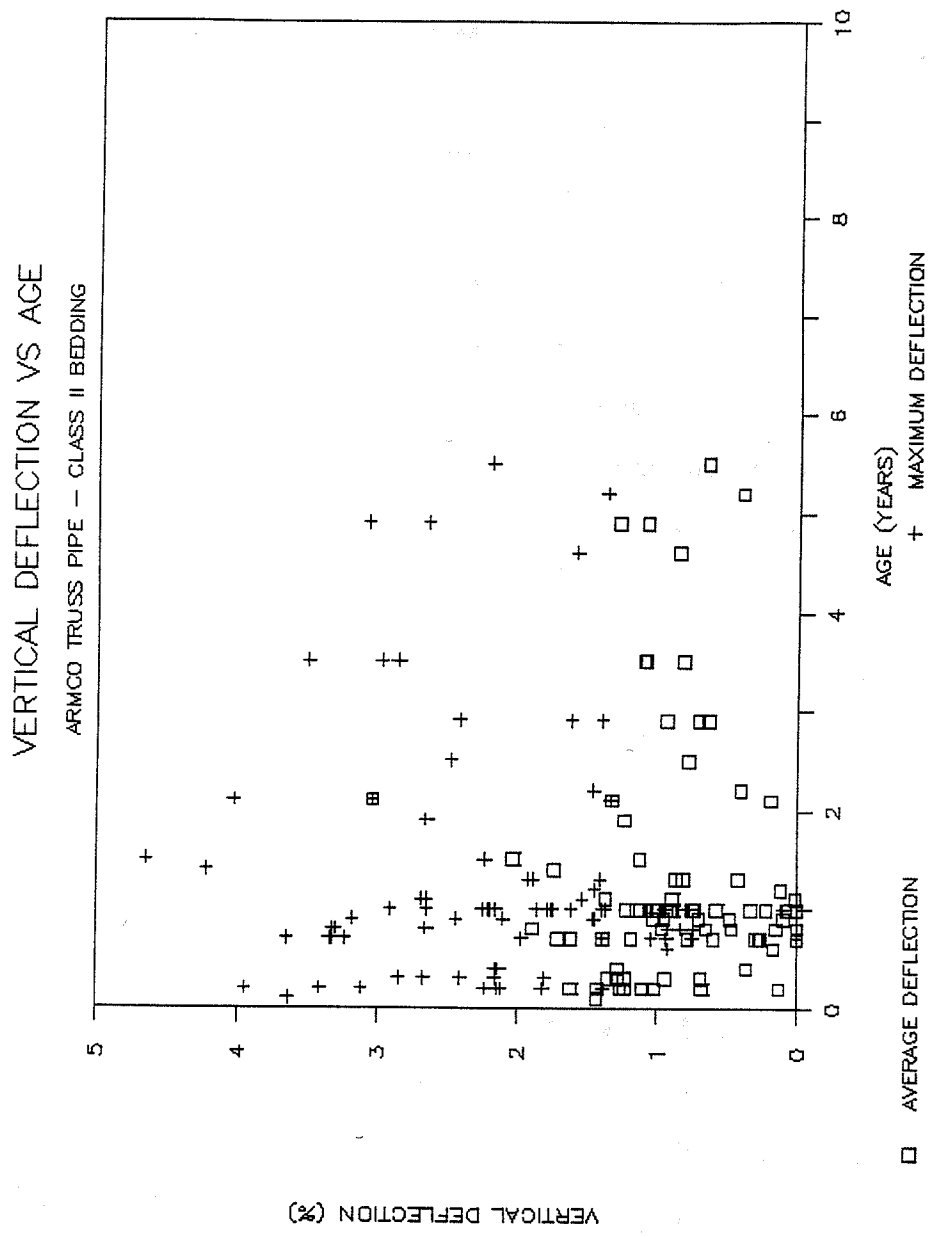


Figure 5.6 Vertical Deflection vs Age.
8 Inch SDR35 PVC Pipe - Sand Bedding.
(National Clay Pipe Institute)



**Figure 5.7 Vertical Deflection vs Age.
8 Inch Truss Pipe - Class
II Bedding.
(Contech Construction Products Inc.)**

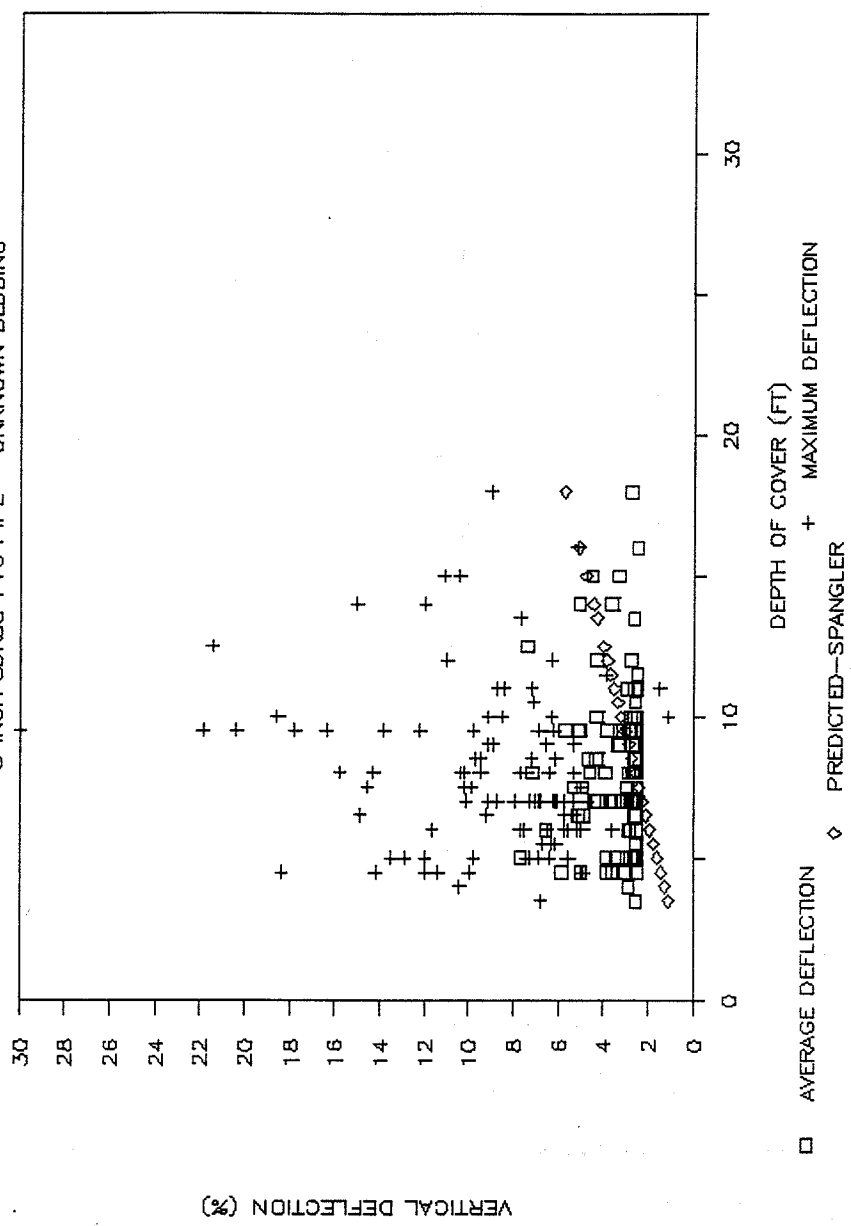
due to the existence of multiple readings of the same line over a period of years. Spangler states that based on his observations of corrugated metal pipes, there is a time lag in the development of the maximum load on the pipe and that the deflection increases after this maximum load is reached (28). In fact, Experiment 1 shows a 69% increase in deflection from the time of completion of the installation to the last reading and Spangler adds "in no instance was equilibrium ever attained." Spangler attributes this increase in deflection to the load lag and to the natural settlement of the fill. The discrepancy between Spangler's results and those which are presented here may be due to the different types of installation used. The Spangler's data is based on a projecting conduit installation and the field data is based on a ditch installation.

5.4.3 Variation of Deflection with Depth

The depth of cover above the crown of the pipe and its effect on vertical deflection was also analysed. The NCPI's data which is best represented in Figure 5.8 shows an increase in vertical deflection with depth of cover. This is particularly true for the upper bound values of average deflection. The trend is not clear for maximum deflection as would be expected nor is it as neat as that predicted by

VERTICAL DEFLECTION VS DEPTH OF COVER

8 INCH SDR35 PVC PIPE - UNKNOWN BEDDING



**Figure 5.8 Vertical Deflection vs Depth of Cover
8 inch SDR35 PVC Pipe - Unknown
Bedding Class.
(National Clay Pipe Institute)**

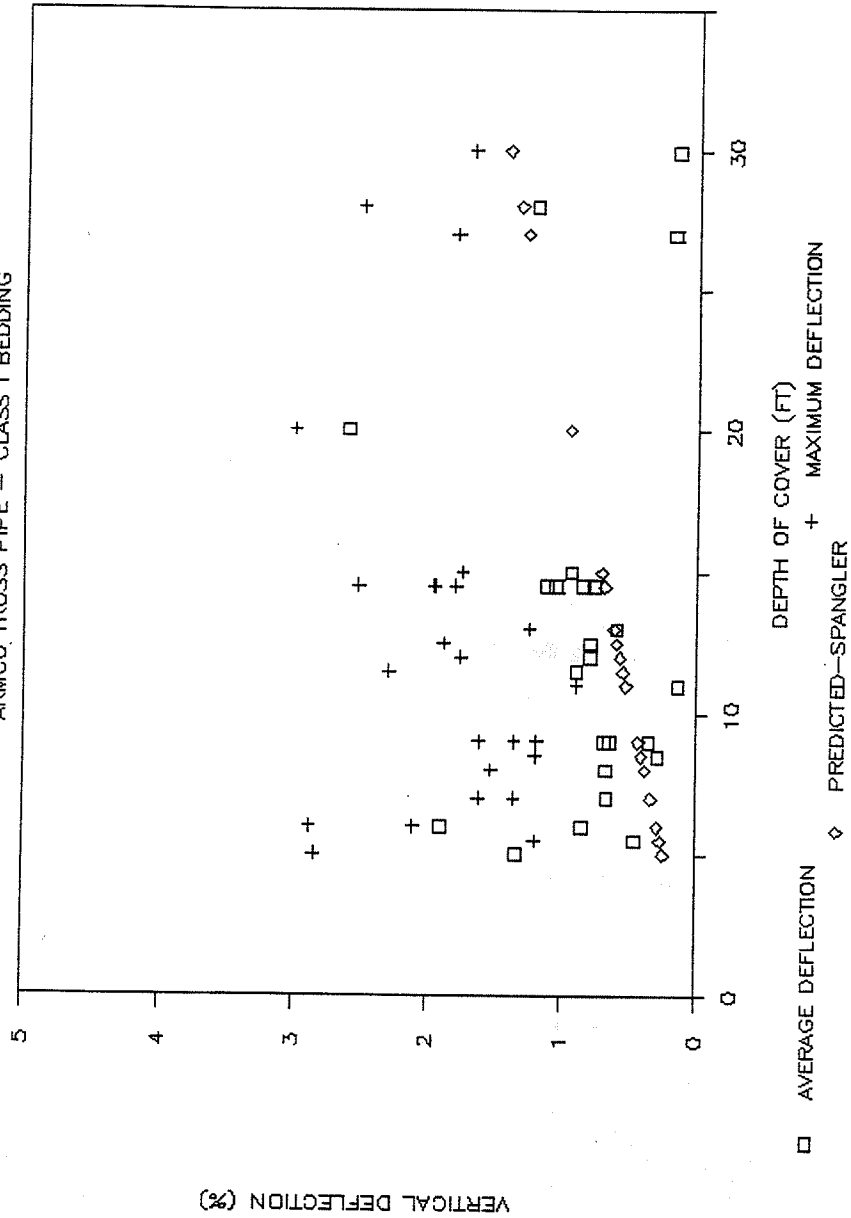
Spangler. It is interesting to note that the predicted vertical deflection crosses the observed field deflection at about the midpoint of the data. This may be due to the use of one value for E' rather than varying it with the depth of cover. An explanation for the amount of scatter may be due to the use of one value, the average depth, to represent conditions throughout the line.

The truss pipe data shows a similar trend as demonstrated by Figure 5.9. The vertical deflection increases with the depth of cover. The deflection which was predicted by the Spangler's equation is much more conservative for this data set than for the NCPI data. This may be due to the fact that the truss pipe has a stiffness of 200 psi and is at the upper limit of pipe stiffness for flexible pipe.

The Donahue's data, which is represented in Figure 5.10, also confirms this trend particularly in the upper bound values when sufficient data points are available. It is interesting to note that in Figure 5.11, the data shows 3 lines of deflection readings. A review of the data base indicates that for 8 inch ASTM D-3033 SDR41 PVC Pipe bedded in sand, there is a better correlation between deflection and time than deflection and depth of cover. This trend was not apparent in the other groups presented.

VERTICAL DEFLECTION VS DEPTH OF COVER

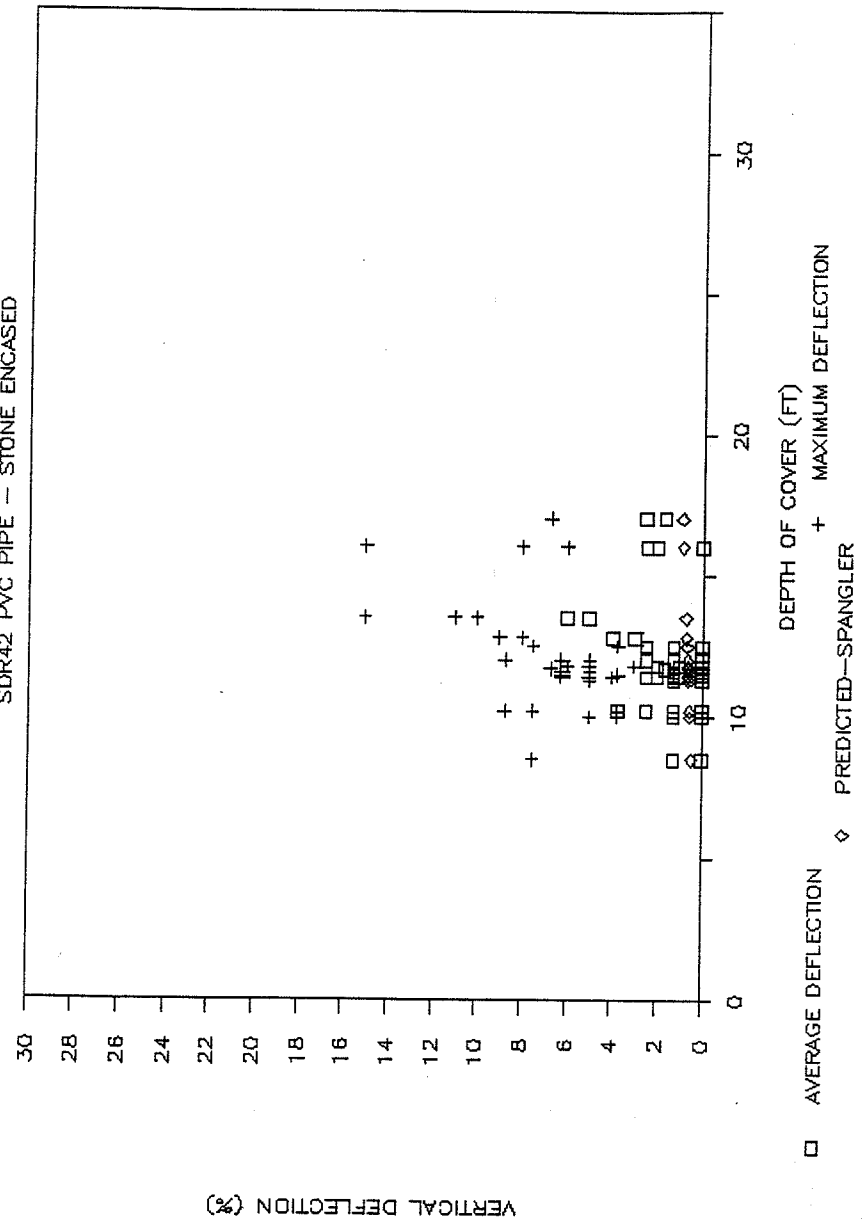
ARMCO TRUSS PIPE - CLASS I BEDDING



**Figure 5.9 Vertical Deflection vs Depth of Cover
Truss Pipe - All Diameters
Class I Bedding.
(Contech Construction Products Inc.)**

VERTICAL DEFLECTION VS DEPTH OF COVER

SDR42 PVC PIPE - STONE ENCASED



**Figure 5.10 Vertical Deflection vs Depth of Cover
SDR42 PVC Pipe - All Diameters
Crushed Stone Envelope.
(Donahue & Associates Inc.)**

VERTICAL DEFLECTION VS DEPTH OF COVER
8 INCH SDR41 PVC PIPE - SAND BEDDING

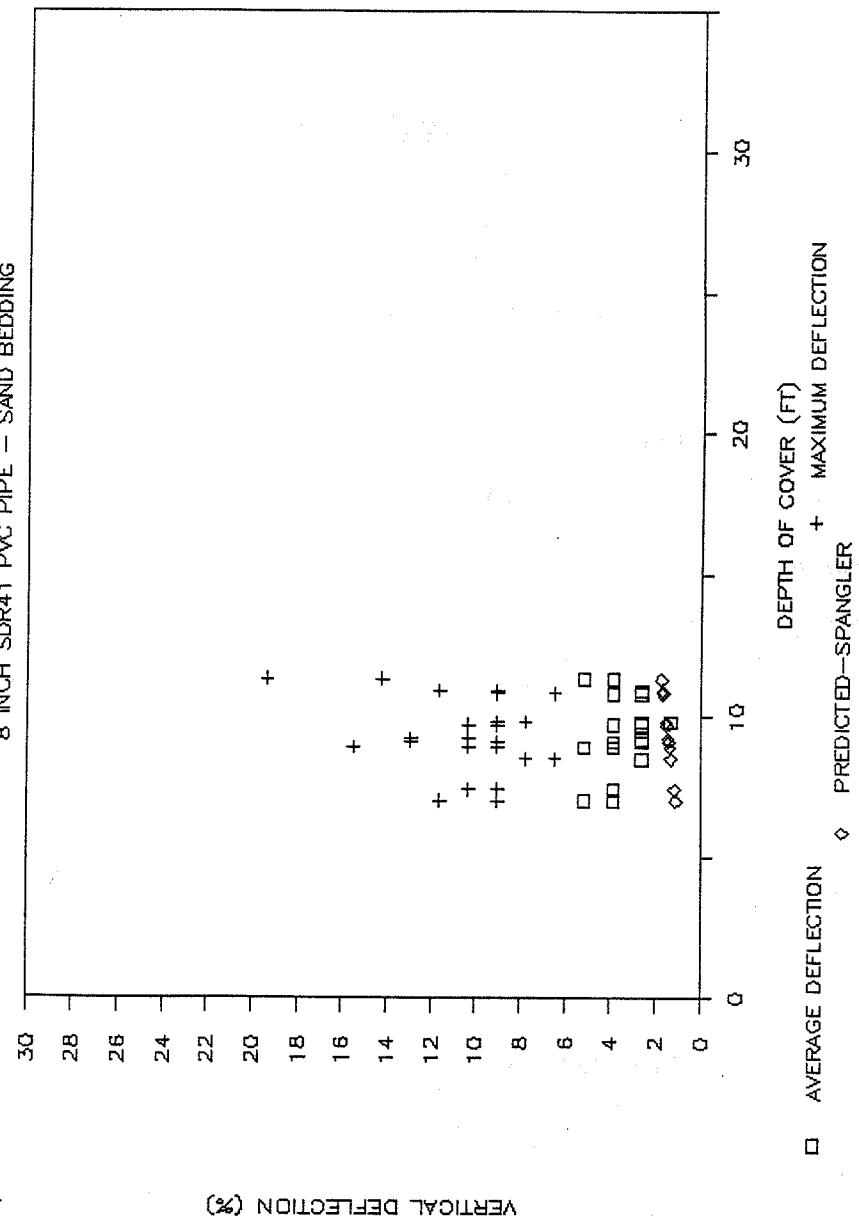


Figure 5.11 Vertical Deflection vs Depth of Cover
8 inch SDR41 PVC Pipe - Sand Bedding.
(Donahue & Associates Inc.)

Spangler's data indicates that there is an increase in vertical deflection with an increase in load on the pipe. However, due to the "load lag" phenomena, no correlation between vertical deflection and depth of cover is presented.

5.4.4 Variation of Deflection with Pipe Stiffness

The vertical deflection vs pipe stiffness correlations are represented by Figure 5.12 for average deflection and in Figure 5.13 for maximum deflection according to bedding class. The data included in these figures does not include the Spangler's data. The data indicates an increase in the variation as well as the magnitude of average deflection and maximum deflection with a decrease in pipe stiffness, although in the later the trend is not as clear. This confirms that as the pipe stiffness decreases, controlling the variability in deflection of the installation as well as limiting the amount of deflection become more difficult.

5.4.5 Variation of Deflection with Pipe-Soil Stiffness Ratio

The correlations between vertical deflection and the pipe-soil stiffness ratio are summarized in Figure 5.14 for both

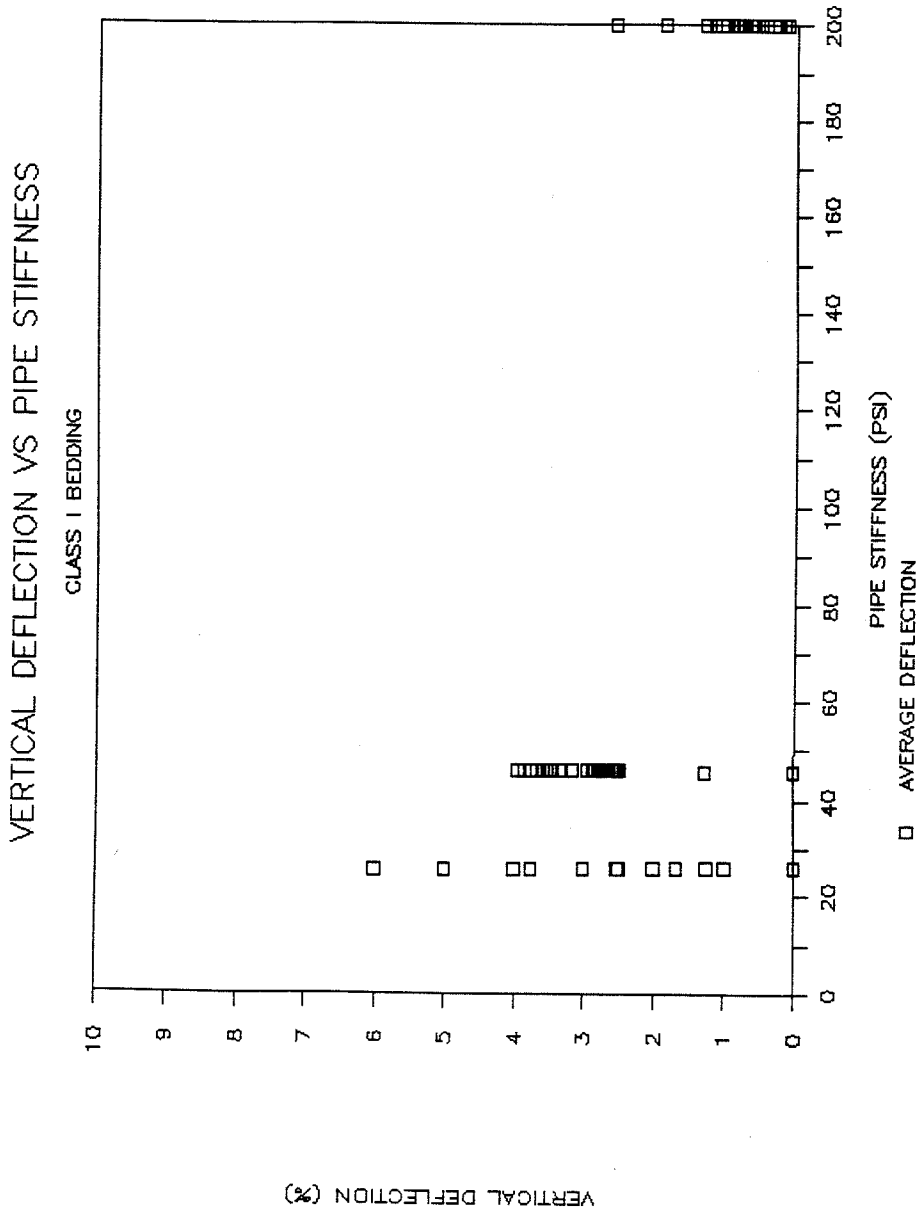


Figure 5.12 Vertical Deflection vs Pipe Stiffness
Average Deflection - Class I Bedding.

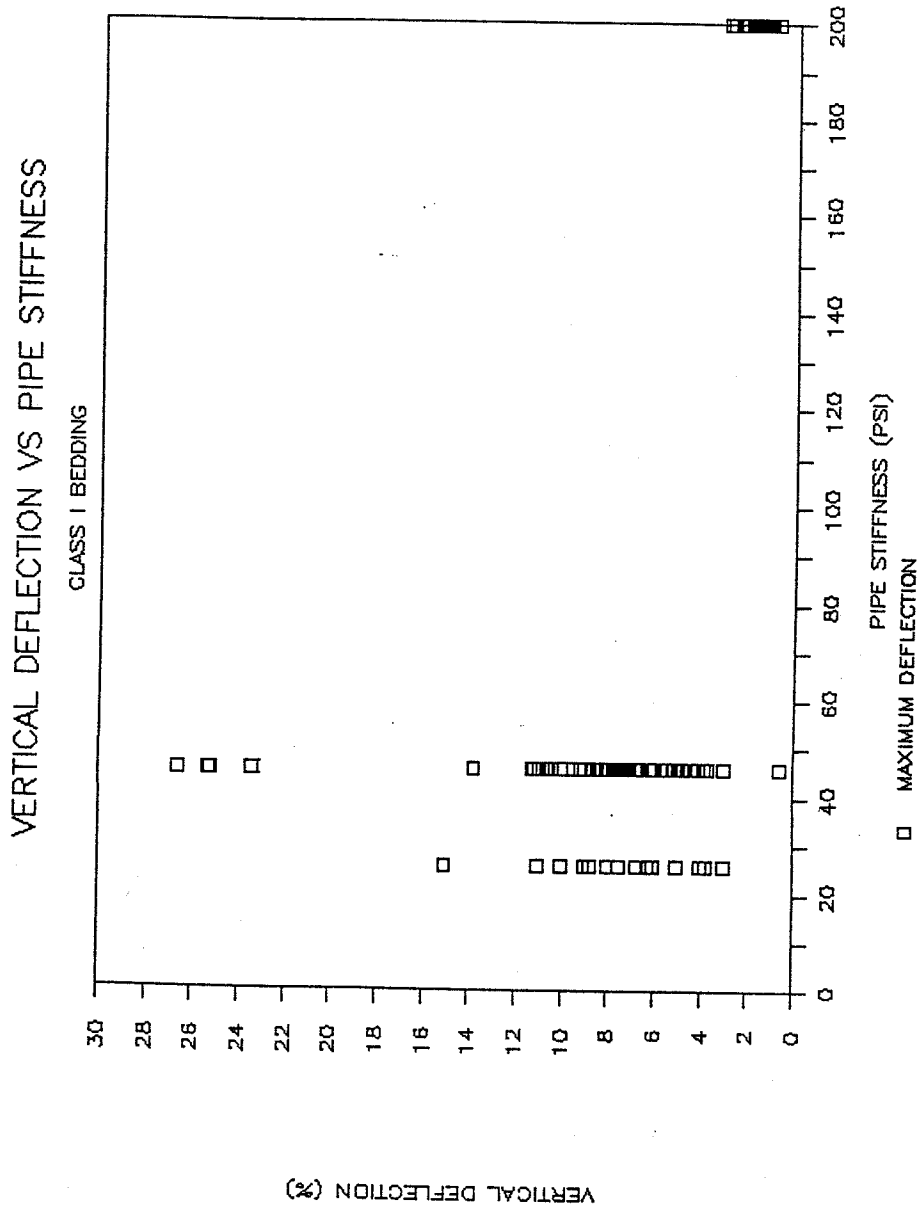


Figure 5.13 Vertical Deflection vs Pipe Stiffness
Maximum Deflection - Class I Bedding.

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - UNKNOWN BEDDING

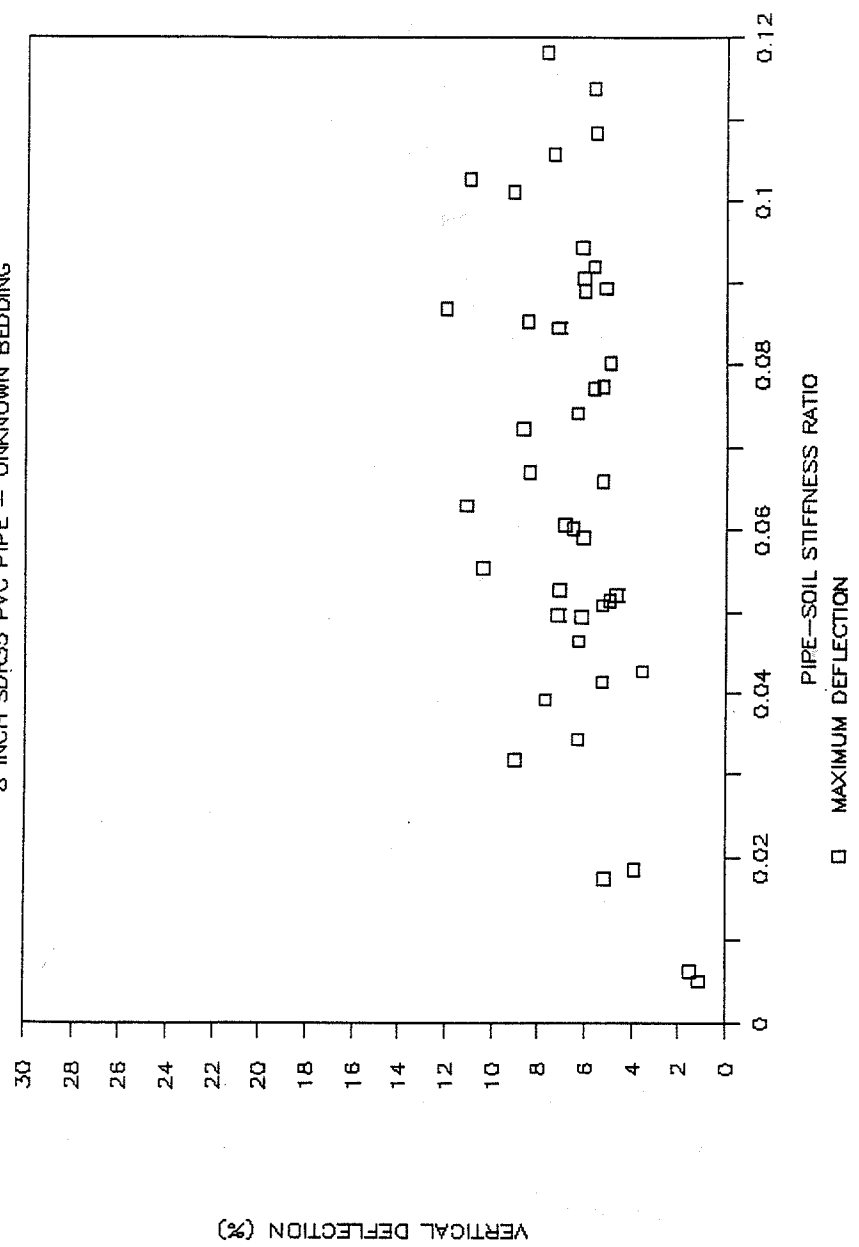


Figure 5.14 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection SDR35 PVC Pipe - Unknown Bedding. (National Clay Pipe Institute)

average and maximum deflections. All graphs are for a single embedment class. In general, as the pipe-soil stiffness ratio decreases (greater relative soil stiffness than pipe stiffness), the vertical deflection tends to decrease. NCPI's and Contech's data also suggest that a range of pipe-soil stiffness ratios may produce a given average deflection for a particular pipe. Donahue's data presents, on the other hand, a very clear linear relation between average deflection and pipe-soil stiffness ratio as shown in Figure 5.15.

5.4.6 Variation of E' with Depth

The variation of E' with depth of cover is presented in Figure 5.16. The NCPI data demonstrates a clear trend, that E' increases with the depth of cover for SDR35 PVC pipe in the diameters and bedding conditions represented in the data set for both average and maximum deflections. It is interesting to note that several values of negative E' resulted from the analysis especially from the maximum deflection data. This suggests that the Spangler's equation is breaking down possibly due to an absence of soil support at some location(s) along the pipeline.

The truss pipe data resulted in a scatter of points and no clear trend was apparent. The values for E' for the same

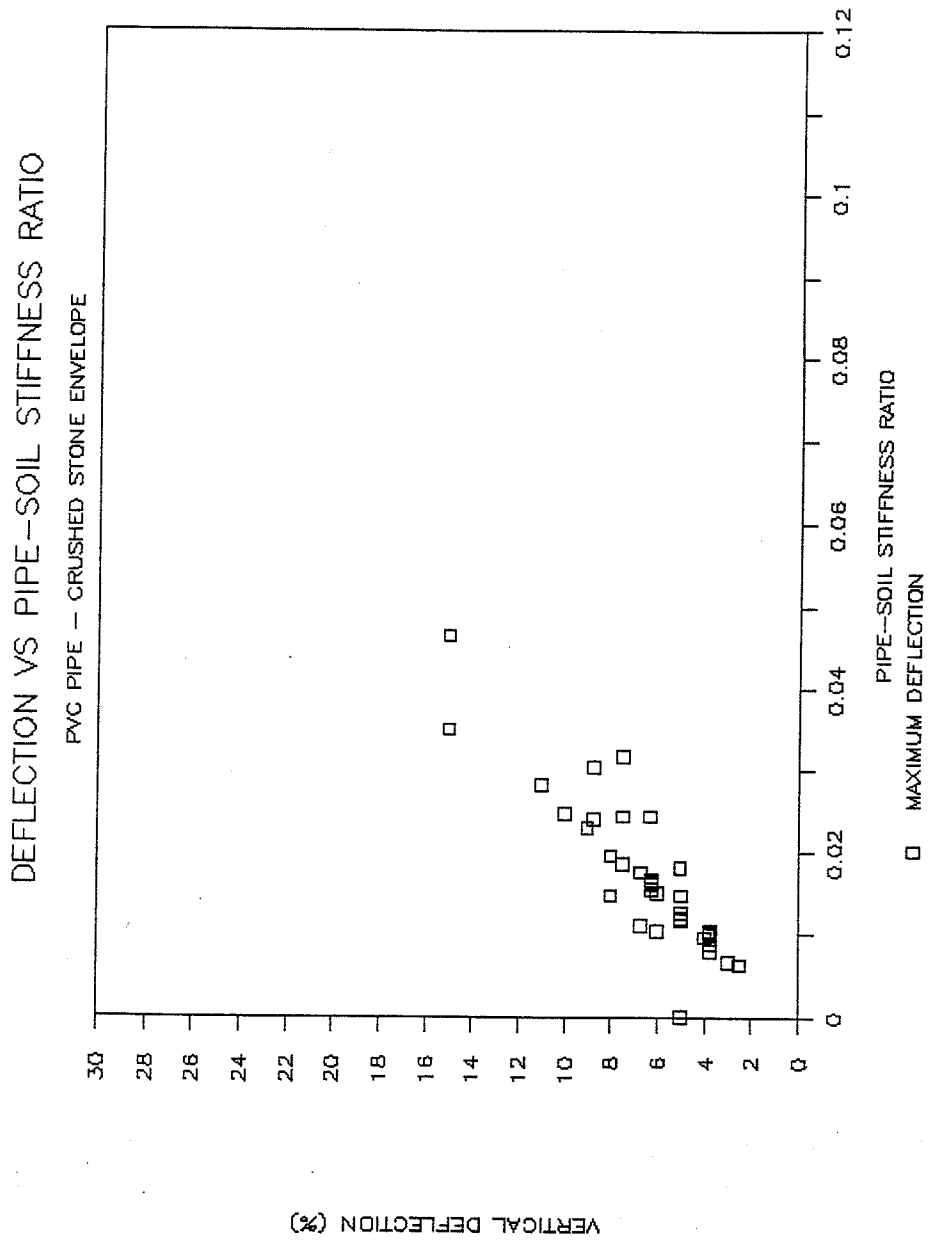


Figure 5.15 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection Crushed Stone Envelope. (Donahue & Associates Inc.)

VERTICAL DEFLECTION (%)

E' VS DEPTH OF COVER 8 INCH SDR35 PVC PIPE - SAND BEDDING

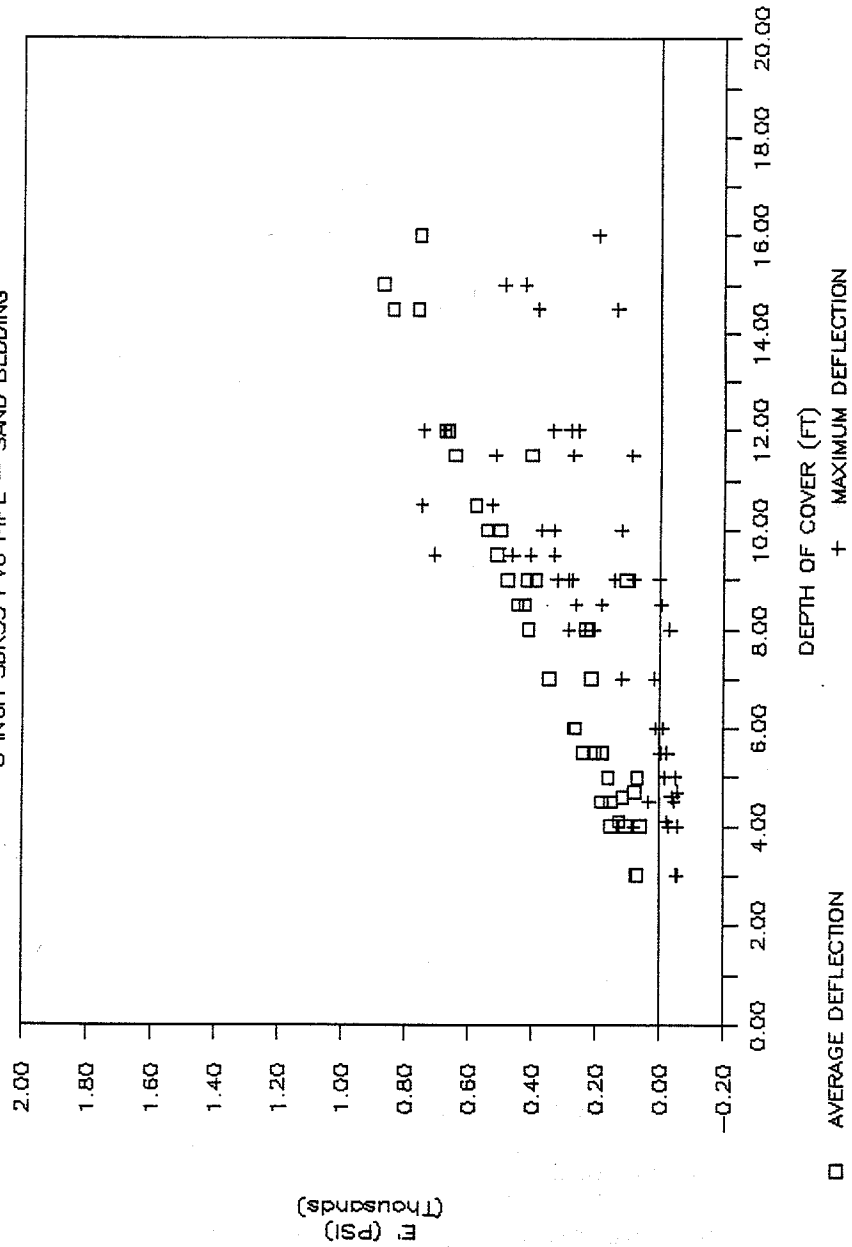


Figure 5.16 E' vs Depth of Cover
8 inch SDR35 PVC Pipe
Sand Bedding.
(National Clay Pipe Institute)

bedding classes were much higher for the truss pipe than for the SDR35 PVC pipe as may be seen in Figure 5.17. This supports the hypothesis that E' may also depend on the properties of the pipe.

The Donahue data presents some interesting trends. Several of the graphs resulted in correlations such as is shown in Figure 5.18 which include at least two well-defined linear correlations between E' and depth of cover. A review of the data base indicates that in many cases spot repairs were performed on the line in question, causing a decrease in average deflection, which would explain this phenomenon.

5.4.7 Variation of E' with Pipe-Soil Stiffness Ratio

The correlations between E' and the pipe-soil stiffness ratio are summarized in Figure 5.19. The trend is similar in all cases which is best described as a curve, asymptotic to both the x-axis and the y-axis. For a given pipe-soil stiffness ratio, the pipe with the greater pipe stiffness produces a greater E' . This tendency is apparent when comparing any of the different data sets. It also shows up in the graphs produced from the Donahue's data since more than one pipe stiffness was included. It should be noted that the values of negative E' were excluded since this is

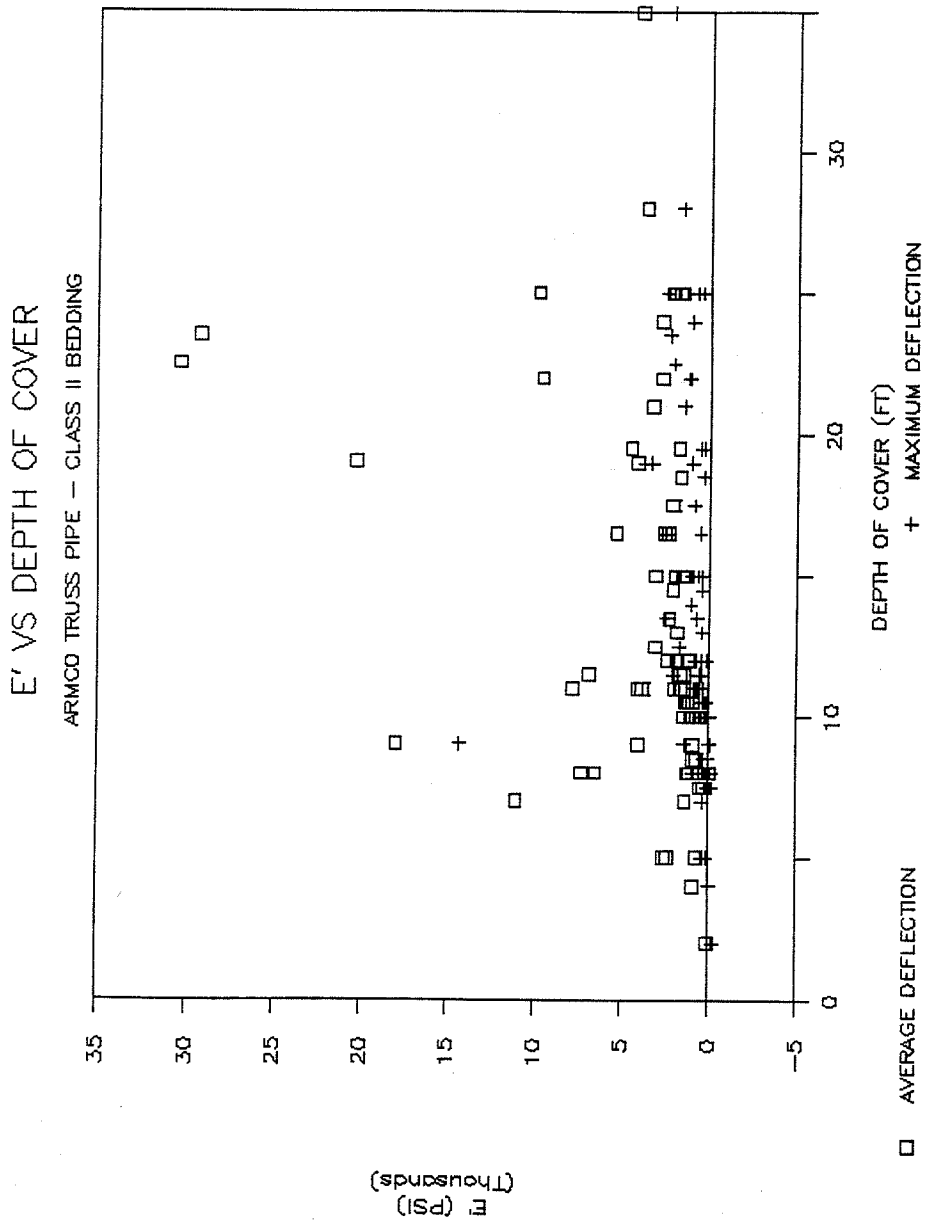


Figure 5.17 E' vs Depth of Cover
Truss Pipe - Class II Bedding.
(Contech Construction Products Inc.)

E' VS DEPTH OF COVER
8 INCH SDR42 PVC PIPE - STONE ENCASED

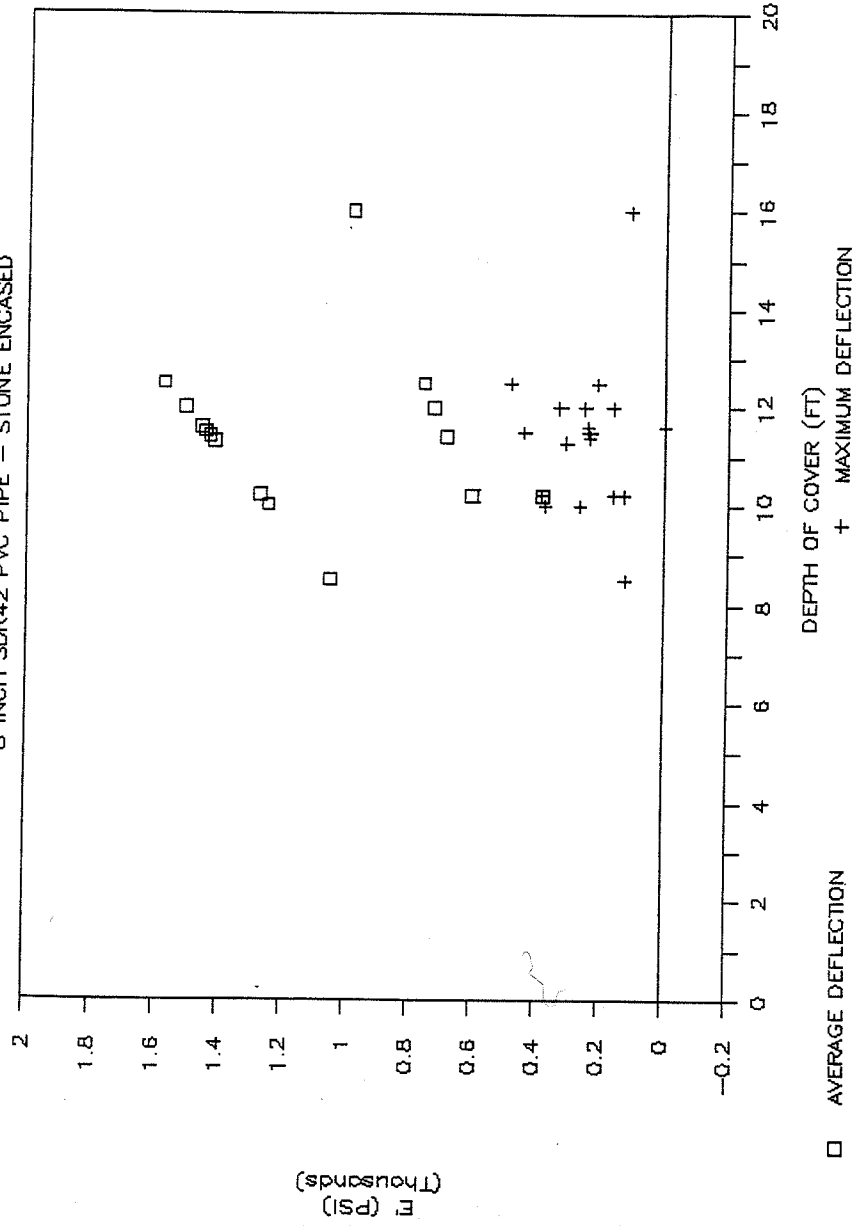


Figure 5.18 E' vs Depth of Cover
8 inch SDR42 PVC Pipe
Crushed Stone Envelope.
(Donahue & Associates Inc.)

not theoretically possible.

5.4.8 Variation of E' with Embedment Type

The variation of E' with the embedment type is shown in Figure 5.20. The Contech's data and the NCPI's data indicate that the greatest value for E' as well as the most variation is obtained using a class II bedding. This trend is not apparent in the Donahue's data where the greatest value for E' and the most variation is obtained using a class I bedding. This trend is shown in Figure 5.21. It is interesting to note that for a given bedding class, the value of E' will be greater for the truss pipe than for any of the PVC pipe.

5.4.9 Comparison of Observed Deflections with Spangler's Predictions

Ideally, if the theory were to predict what was occurring in the field, the graphs would show points scattered around a line set at 45 degrees. Unfortunately, this is not the case for this data as shown in Figures 5.22 - 5.24. Spangler's equation appears to underpredict the vertical average deflection for SDR35, SDR41, and SDR42 PVC pipes in the

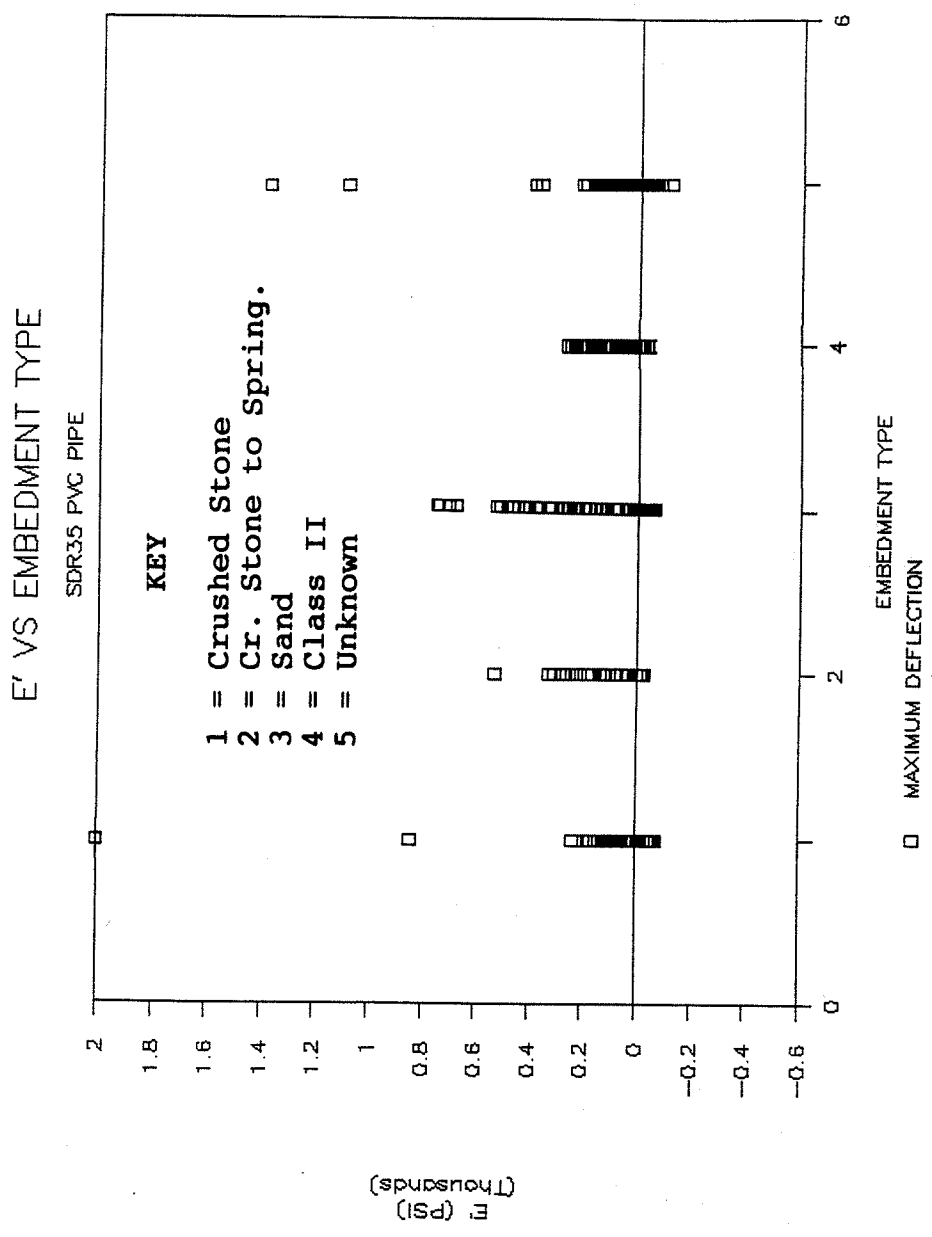
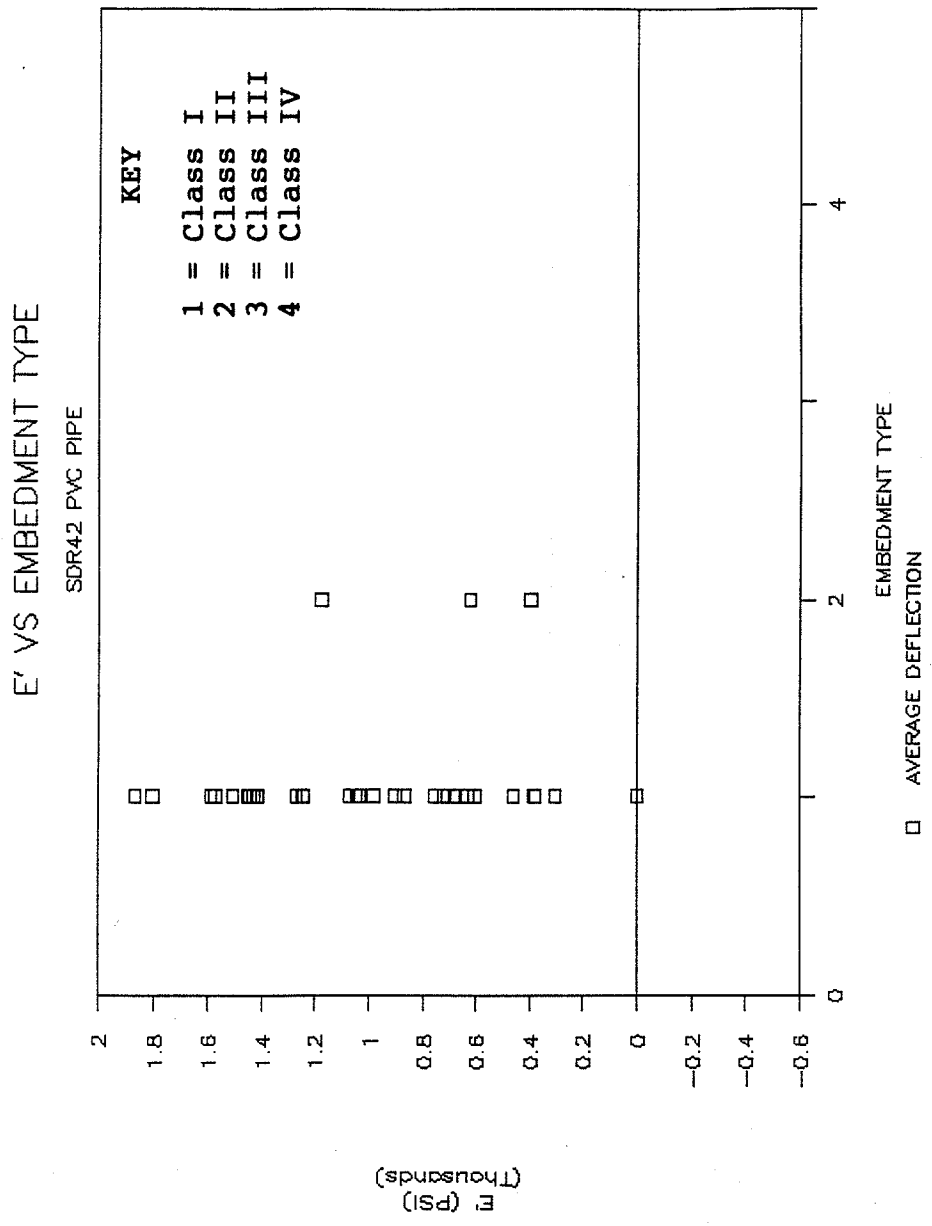


Figure 5.20 E' vs Embedment Type
SDR42 PVC Pipe
Maximum Deflection.
(National Clay Pipe Institute)



**Figure 5.21 E' vs Embedment Type
SDR42 PVC Pipe
Average Deflection.
(Donahue & Associates Inc.)**

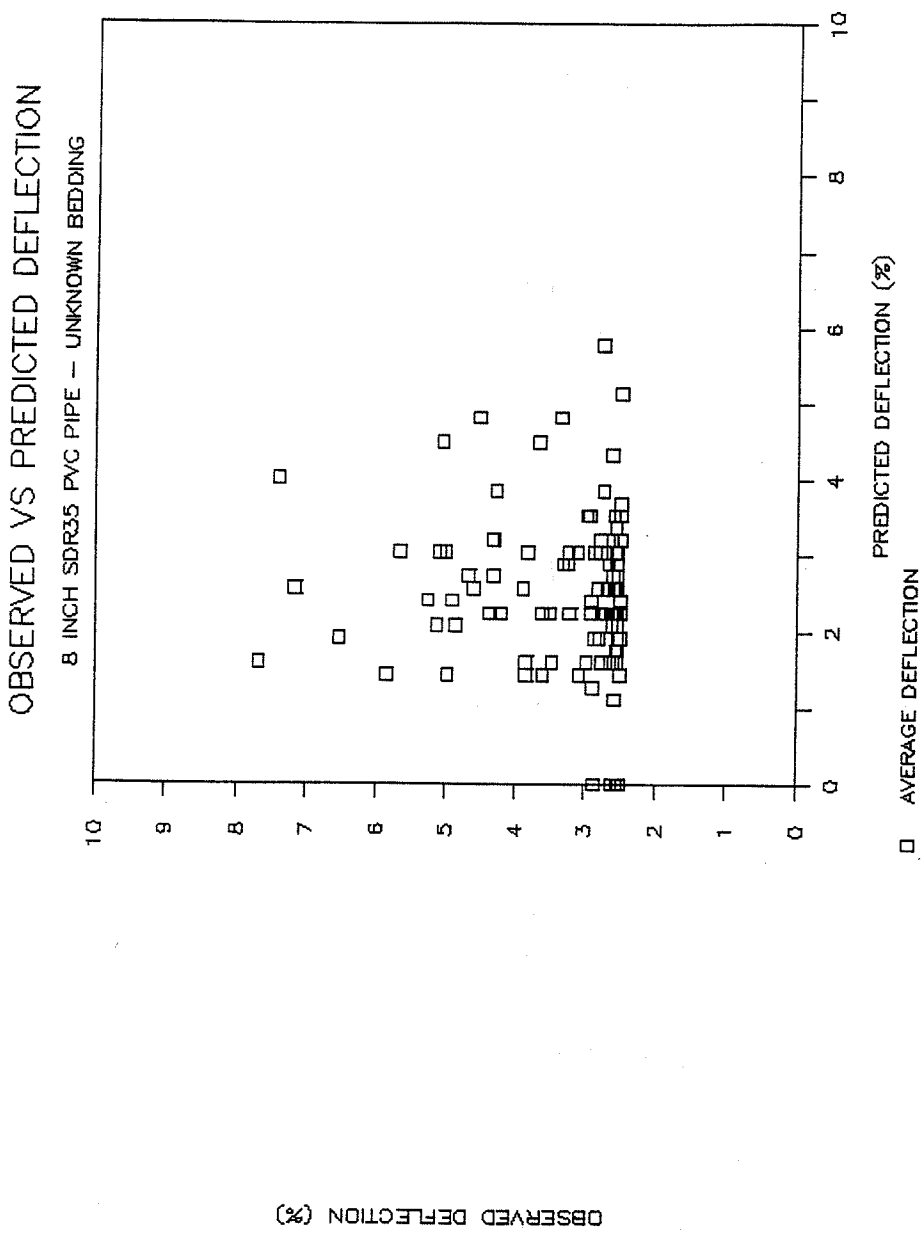
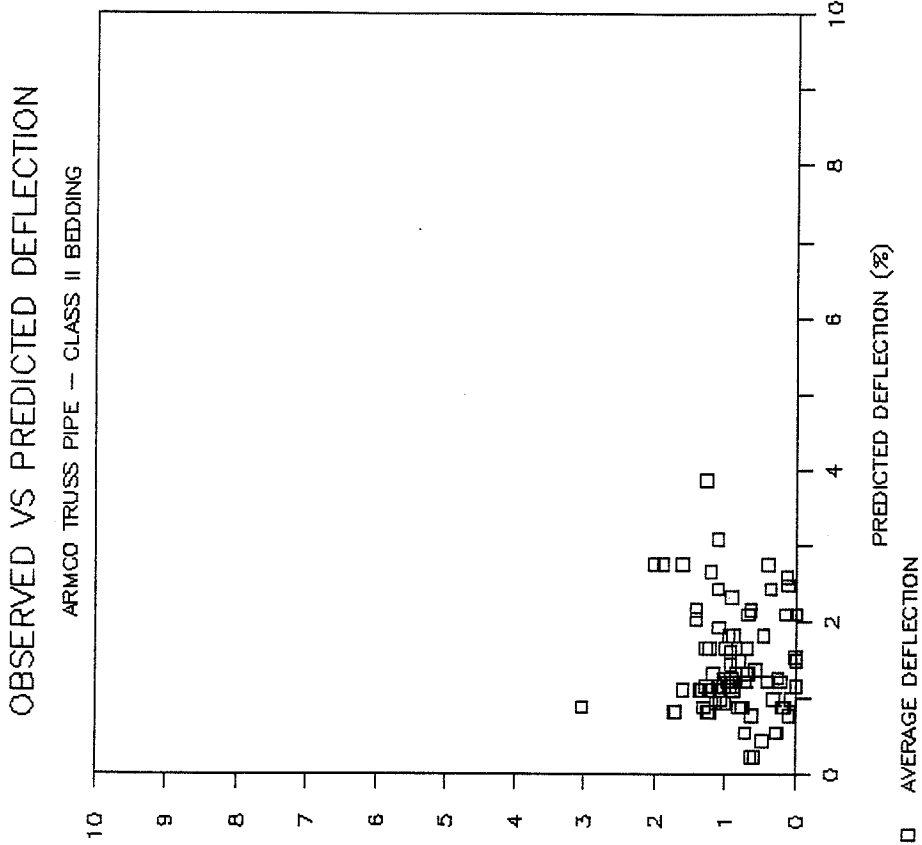
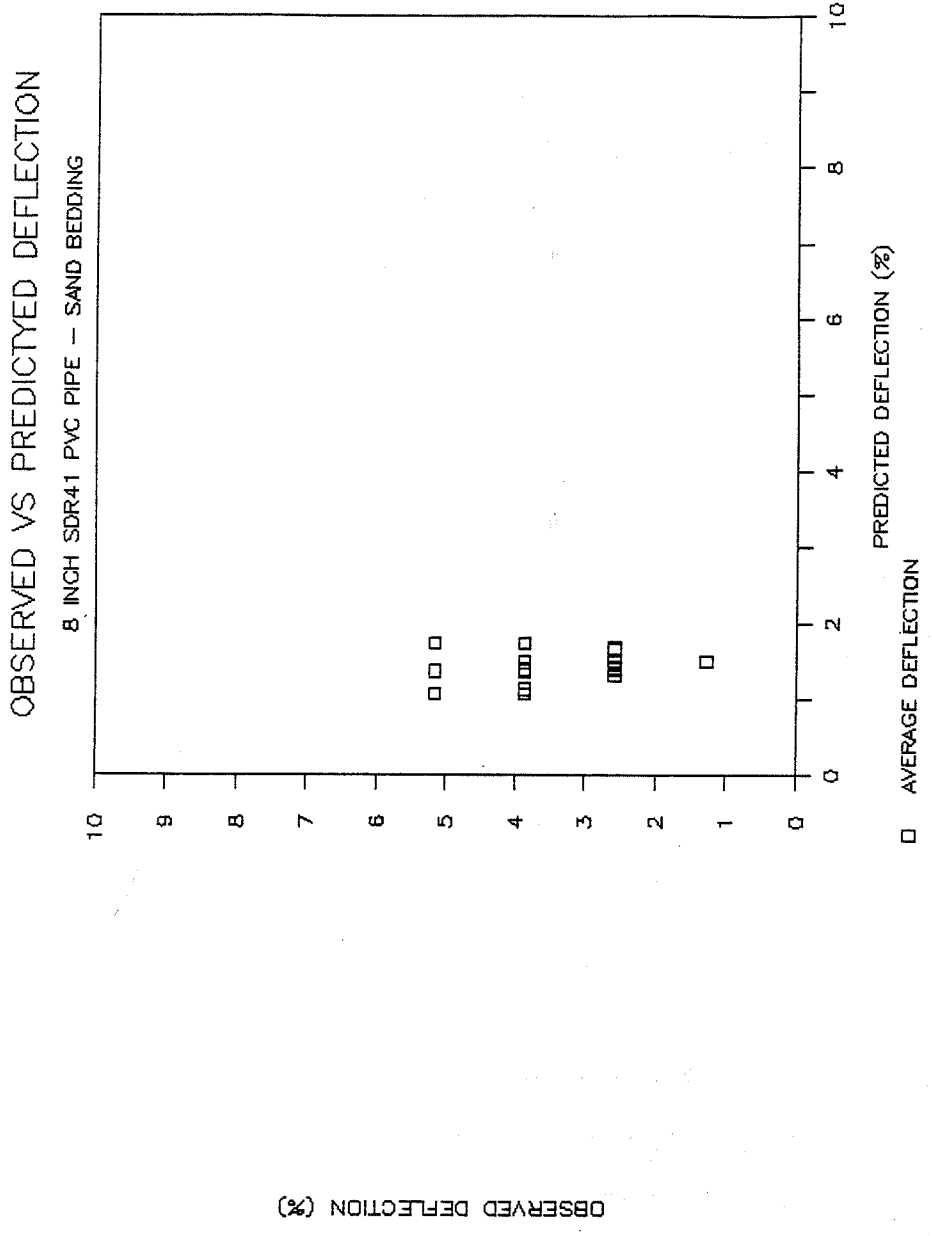


Figure 5.22 Observed vs Predicted Deflection
8 inch SDR35 PVC Pipe
Unknown Bedding.
(National Clay Pipe Institute)





**Figure 5.24 Observed vs Predicted Deflection
8 inch SDR41 PVC Pipe
Sand Bedding.
(Donahue & Associates Inc.)**

range of diameters and bedding conditions included in the study.

It may be argued that in the case of PVC pipe, the use of a lag factor which is larger than 1.2 would produce more favorable results. This lag factor was selected since it was thought to be representative of the average age of all of the lines included in the study. A review of the data contained in Tables 5.10 - 5.14, Tables 5.16 - 5.26 and Tables 5.28 - 5.33 shows that the average age of the pipelines found in the NCPI data is 2.39 years, in the Contech data is 1.52 years, and in the Donahue data is 1.59 years. Although Spangler (28) suggested the use of a lag factor of 1.5 for design to account for the final deflection, one should recall that these deflections were not attained until after the maximum load on the pipe was reached which occurred after the fill had been in place about 5 years. For this reason a lag factor of 1.2 is appropriate.

Another reason for the difference between the observed and the predicted deflection may have been caused by the application of a theory based on corrugated metal pipe behavior to that of a smooth walled thermoplastic pipe. The soil-structure interaction at the interface would not be expected to be equal since the different pipe materials as well as

their configuration would cause different frictional properties at the interface.

It is interesting to note that the Spangler's equation over predicts the deflection of the truss pipe. One explanation is that the pipe stiffness of the truss pipe (200 psi) is above the range of pipe stiffnesses used to develop the Spangler's equation (130 psi) so the truss pipe is no longer behaving as a flexible pipe.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 General

In this chapter, a summary of the conclusions which are drawn from this study are as well as a list of recommendations for further research are presented.

6.2 Conclusions

The following conclusions may be drawn from this research effort:

1. The average vertical deflection shows no correlation with the age of the line with the exception of the 8 inch SDR41 PVC pipe installed in sand. This is expected since the average age of the pipelines is too small to develop any correlation.

2. The upper bound as well as the average deflection increase with the depth of cover. A similar but less well-defined trend was present in the maximum deflection vs depth of cover data.

3. As pipe stiffness decreases the variability in the deflection of the installation as well as the magnitude of the average deflection of the line become increasingly more difficult to control.

4. The average vertical deflection increases with the pipe-soil stiffness ratio for a given pipe stiffness.

5. The value for E' increases with an increase in pipe stiffness for a given pipe-soil stiffness ratio.

6. Based on the parameter assumptions made in this analysis, the Spangler's equation, on one hand, tends to underpredict the average deflection of a PVC pipe under a trench installation with a pipe stiffness of between 26 and 46 psi by between 1.0 percent and 1.5 percent and, on the other hand, tends to overpredict the deflection of the truss pipe by about 0.5 percent.

7. The "typical" field installation of 8 inch SDR35 PVC pipe will result in 8 and 18 percent of the line exceeding 5 percent deflection and 1 and 5 percent exceeding 7.5 percent deflection depending on the embedment type.

6.3 Recommendations for Further Research

The author would like to make the following recommendations for future research:

1. A study should be performed to determine the deformed shape of the pipe in field installations to determine compliance or noncompliance with the assumed elliptical shape.
2. A statistical analysis should be performed on this data base and best-fit curves established to study the correlations more in depth.
3. The possible dependence of E' on the pipe stiffness should be investigated.
4. The data base should be enlarged to include pipes with stiffnesses in the range of from 46 psi to 200 psi to determine the extent of applicability of the Spangler's equation.
5. More data should be taken on the trench geometry to determine its influence on pipe deflection.

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APPENDIX A1

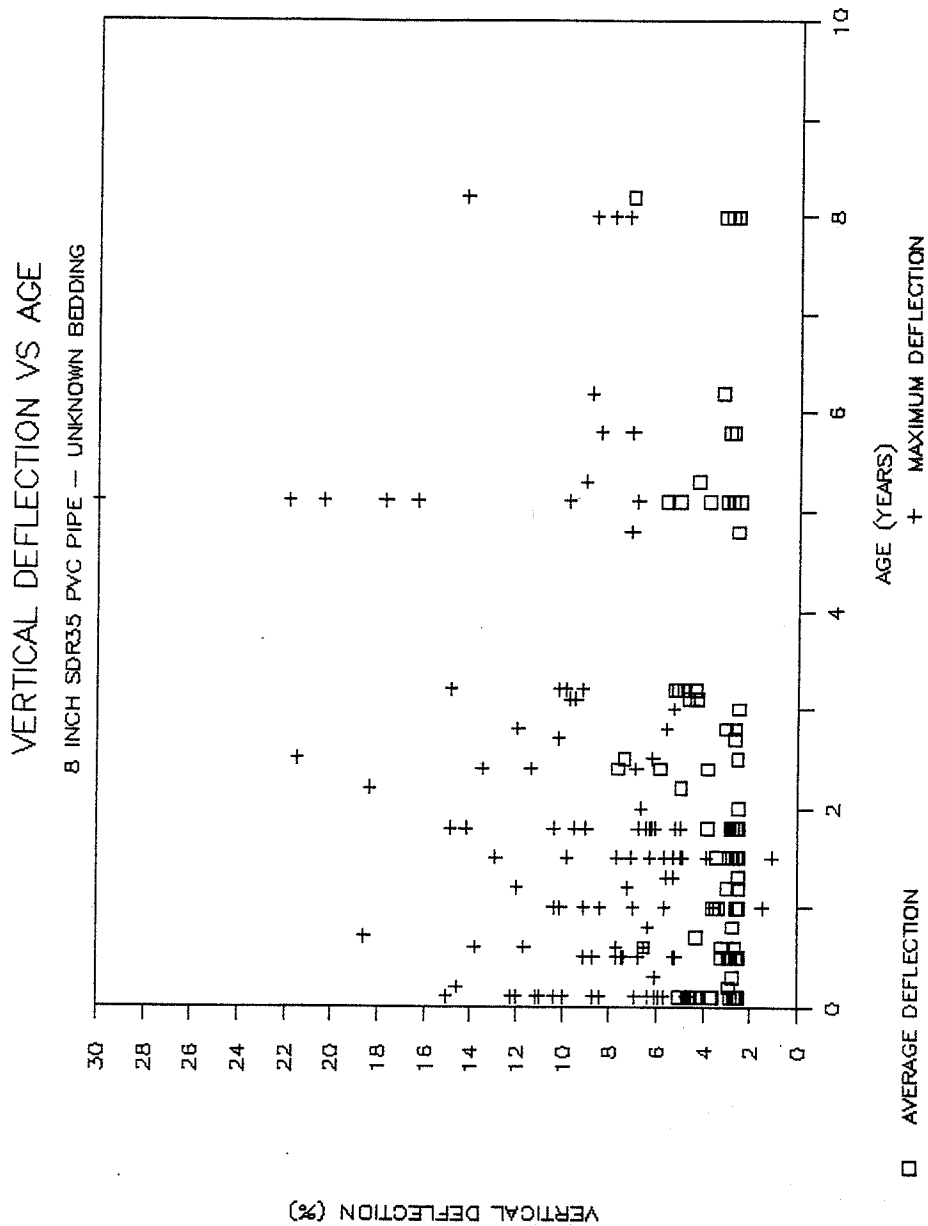


Figure A1.1 Vertical Deflection vs Age
8 inch SDR35 PVC Pipe - Unknown
Bedding Class.
(National Clay Pipe Institute)

VERTICAL DEFLECTION VS AGE
8 INCH SDR35 PVC PIPE- CLASS II BEDDING

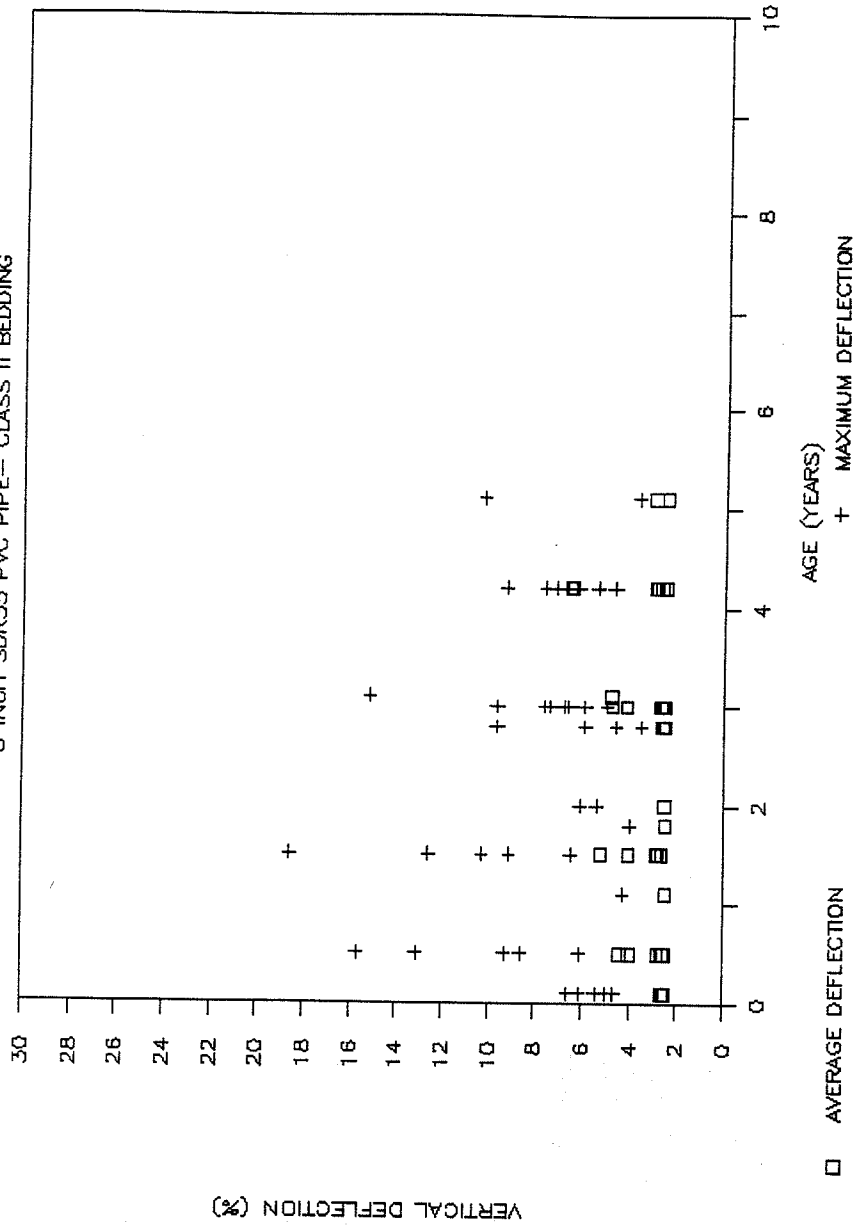


Figure A1.2 Vertical Deflection vs Age
8 inch SDR35 PVC Pipe - Class II Bedding.
(National Clay Pipe Institute)

VERTICAL DEFLECTION VS AGE
8 INCH SDR35 PVC PIPE - SAND BEDDING

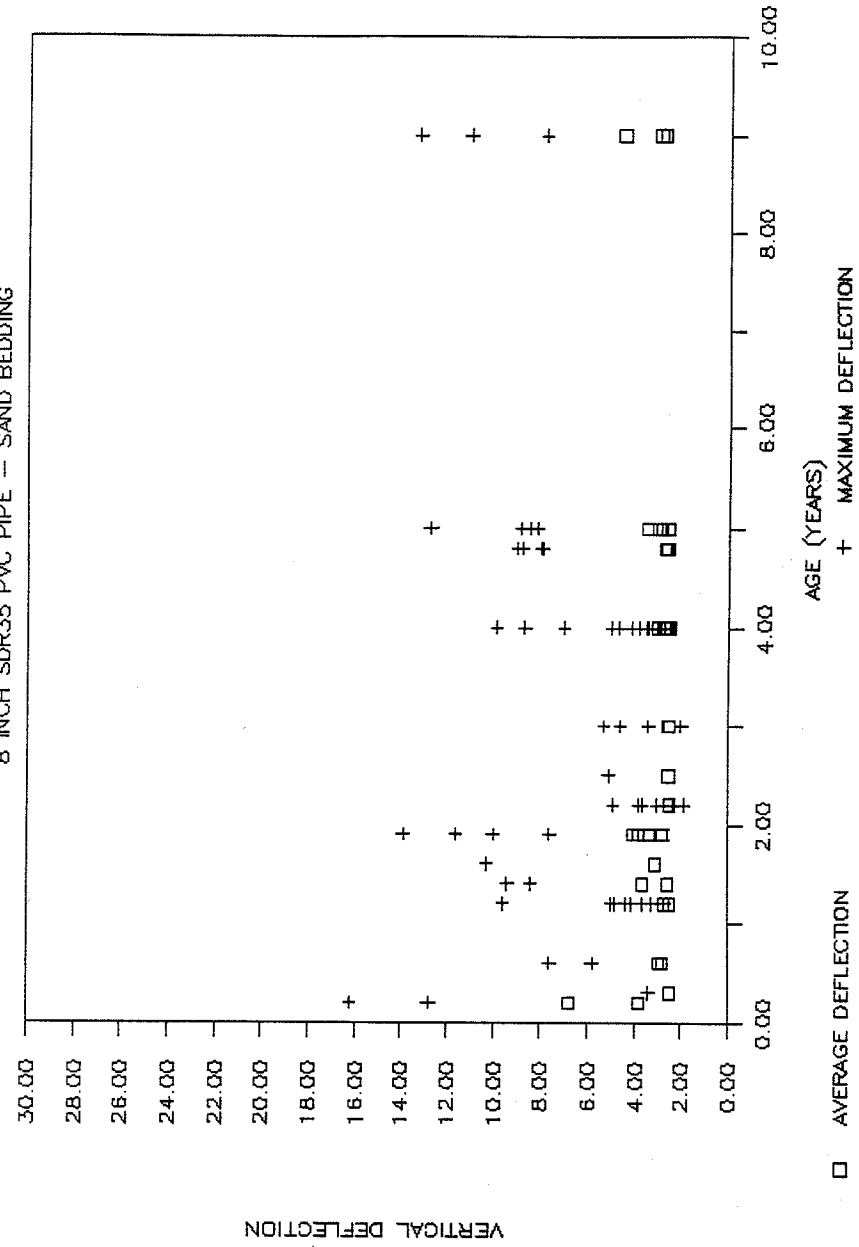


Figure A1.3 Vertical Deflection vs Age
8 inch SDR35 PVC Pipe - Sand
Bedding.
(National Clay Pipe Institute)

VERTICAL DEFLECTION VS AGE

8 INCH SDR35 PVC PIPE - STONE TO SPRING

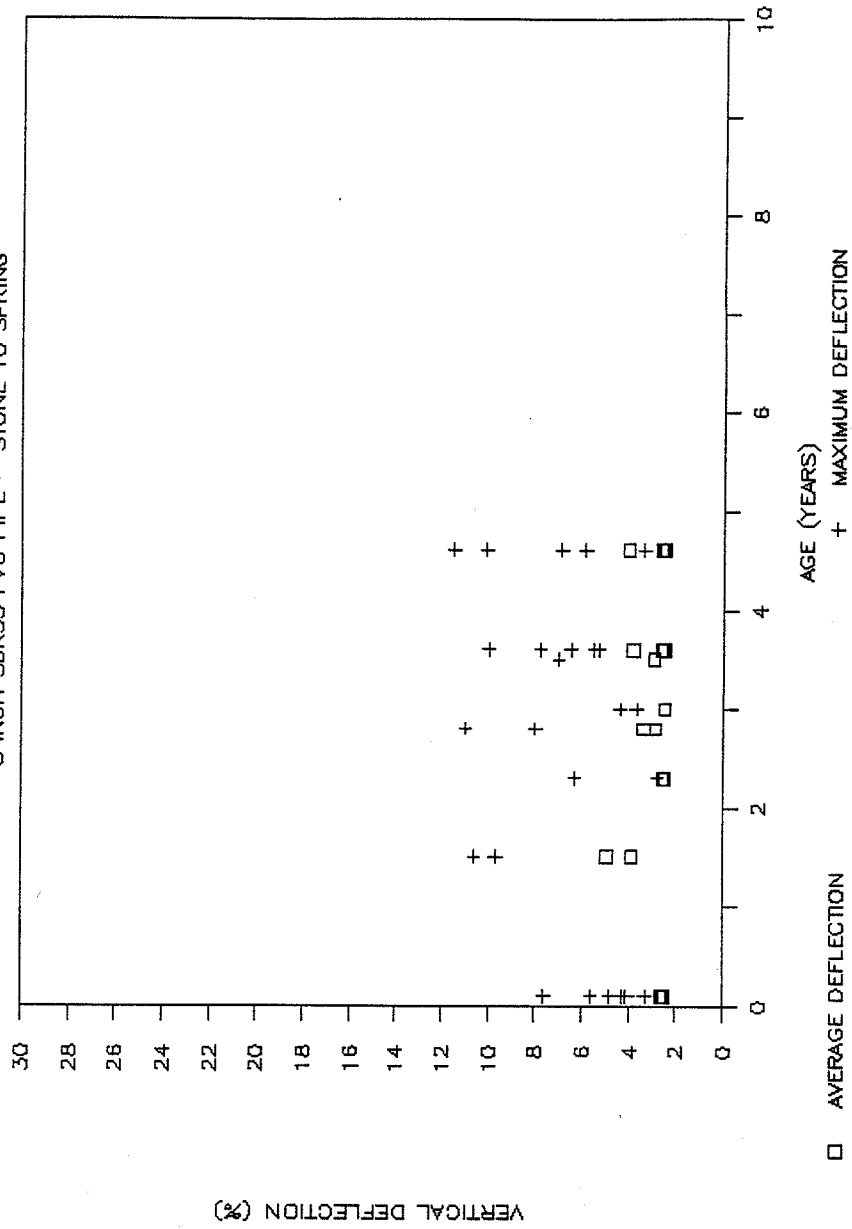


Figure A1.4 Vertical Deflection vs Age
8 inch SDR35 PVC Pipe - Crushed Stone to the Springline.
(National Clay Pipe Institute)

VERTICAL DEFLECTION VS AGE
8 INCH SDR35 PVC PIPE -- STONE ENCASED

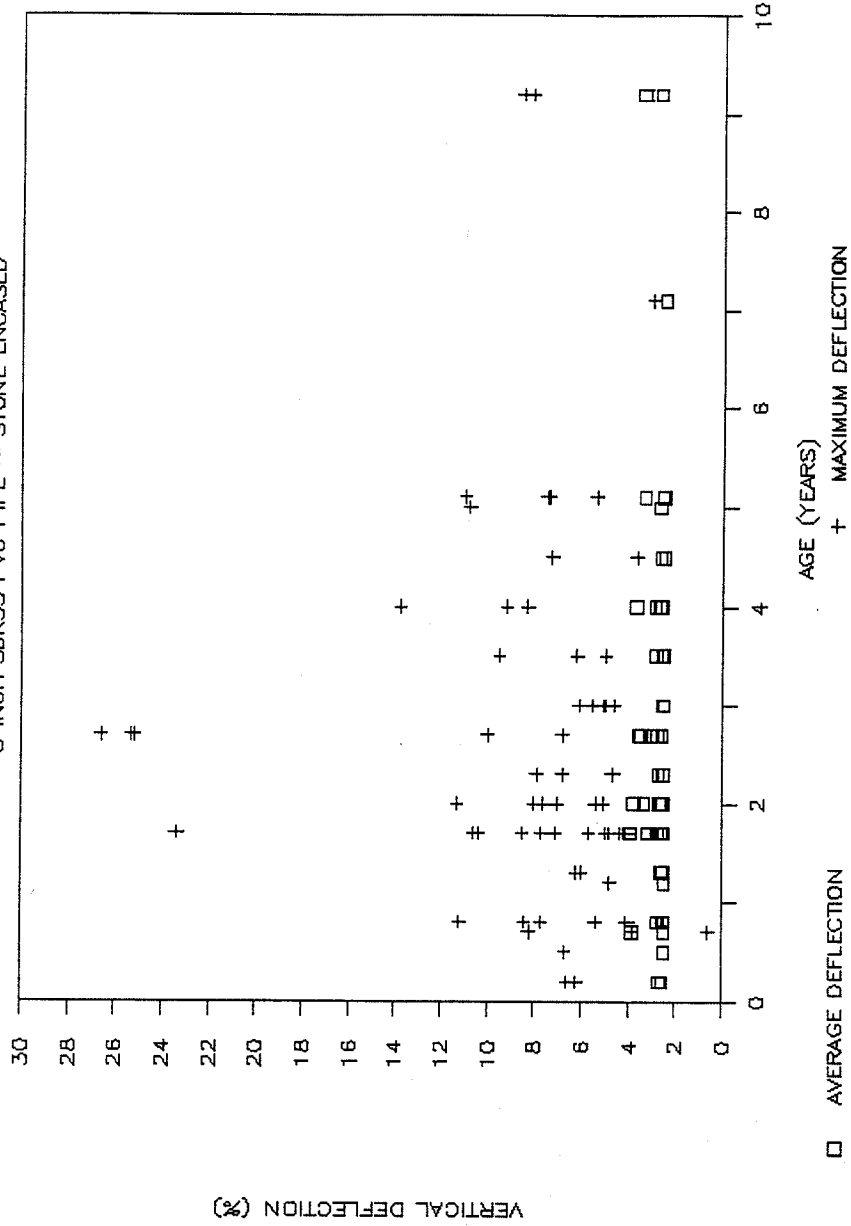


Figure A1.5 Vertical Deflection vs Age
8 inch SDR35 PVC Pipe - Crushed
Stone Envelope.
(National Clay Pipe Institute)

VERTICAL DEFLECTION VS AGE
ARMCO TRUSS PIPE - CLASS I BEDDING

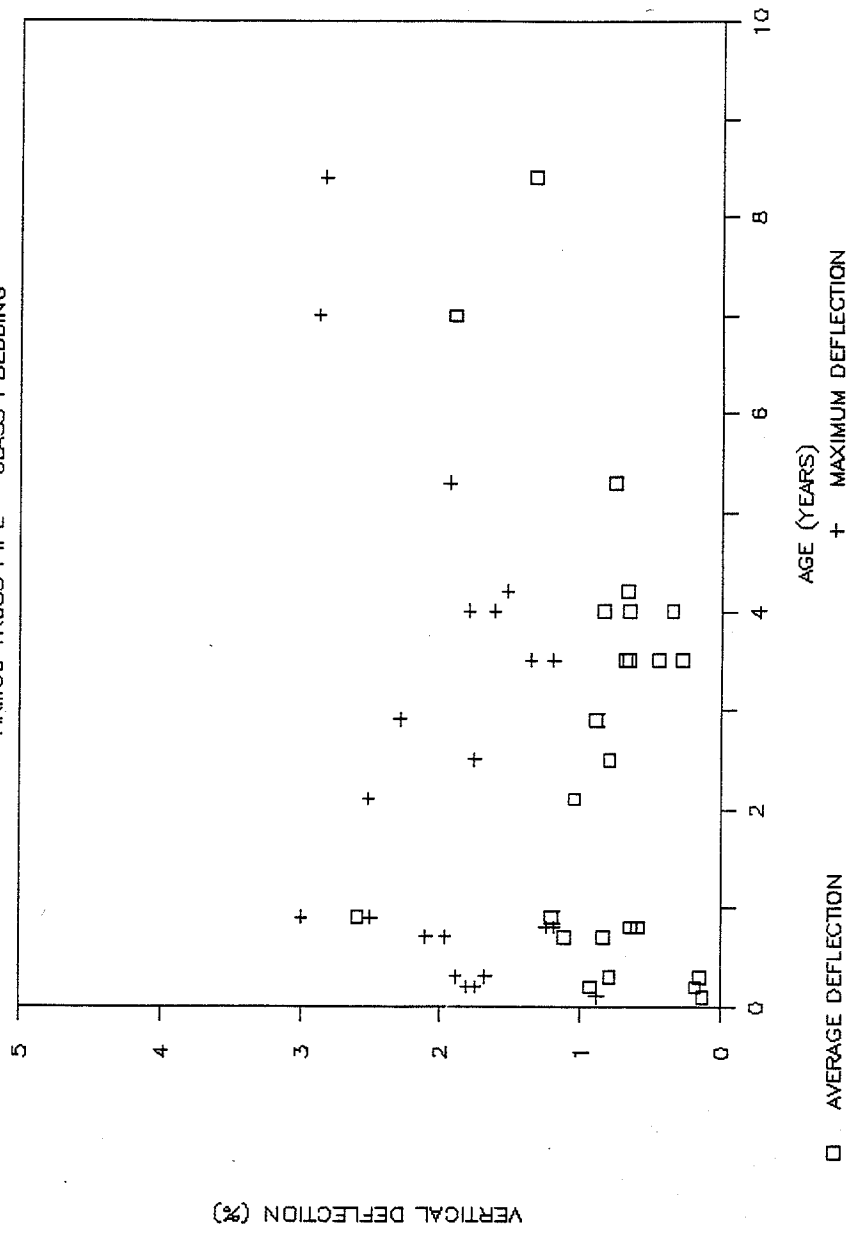


Figure A1.6 Vertical Deflection vs Age
Truss Pipe - All Diameters
Class I Bedding.
(Contech Construction Products Inc.)

VERTICAL DEFLECTION VS AGE
ARMCO TRUSS PIPE - CLASS II BEDDING

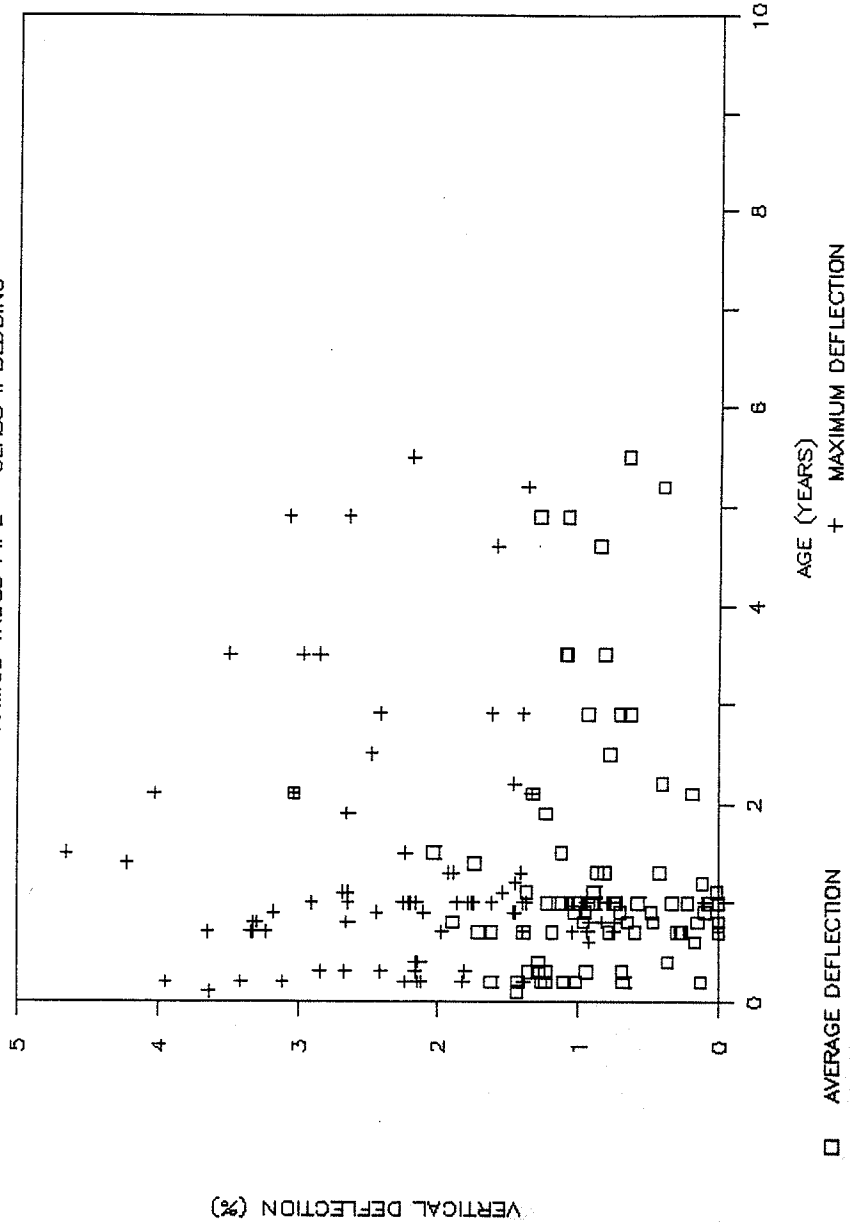


Figure A1.7 Vertical Deflection vs Age
Truss Pipe - All Diameters
Class II Bedding.
(Contech Construction Products Inc.)

VERTICAL DEFLECTION VS AGE
ARMCO TRUSS PIPE - CLASS III BEDDING

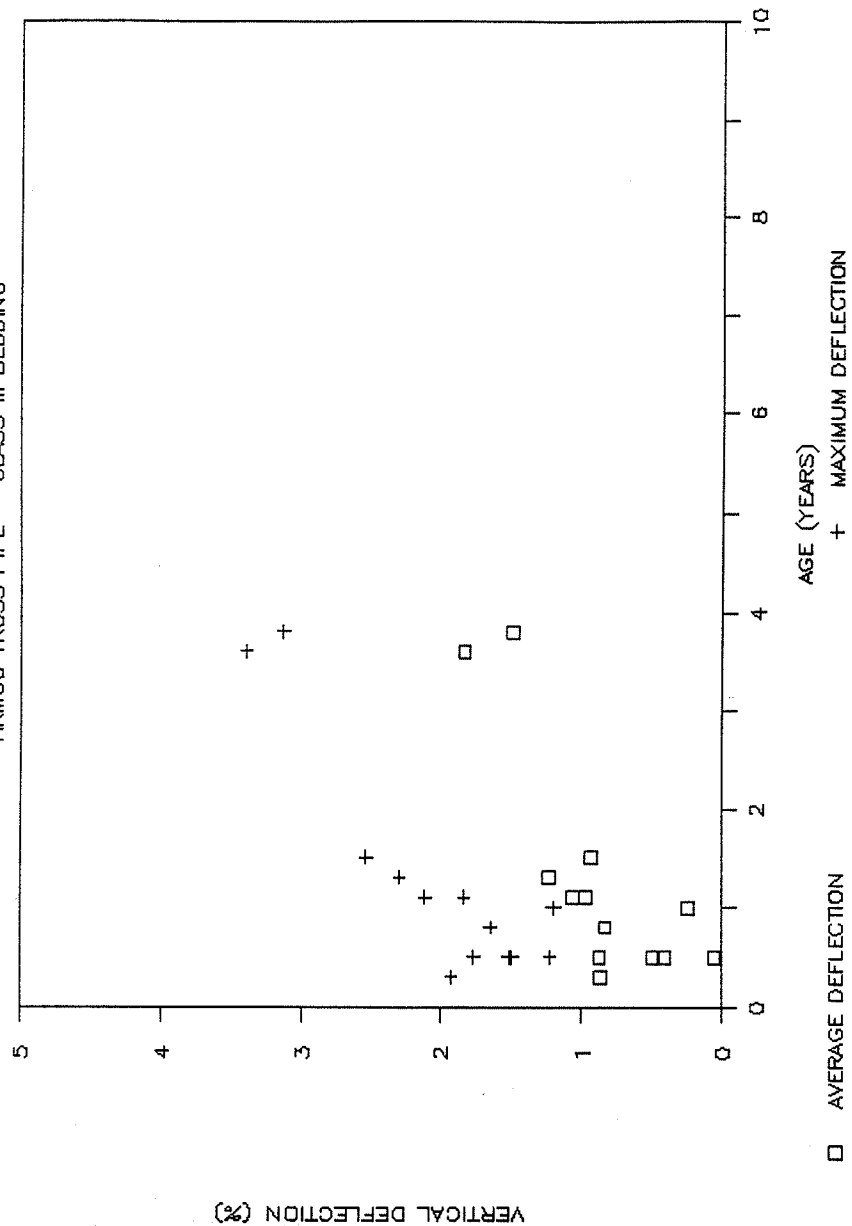


Figure A1.8 Vertical Deflection vs Age
Truss Pipe - All Diameters
Class III Bedding.
(Contech Construction Products Inc.)

VERTICAL DEFLECTION VS AGE
 ARMCO TRUSS PIPE - CLASS IV BEDDING

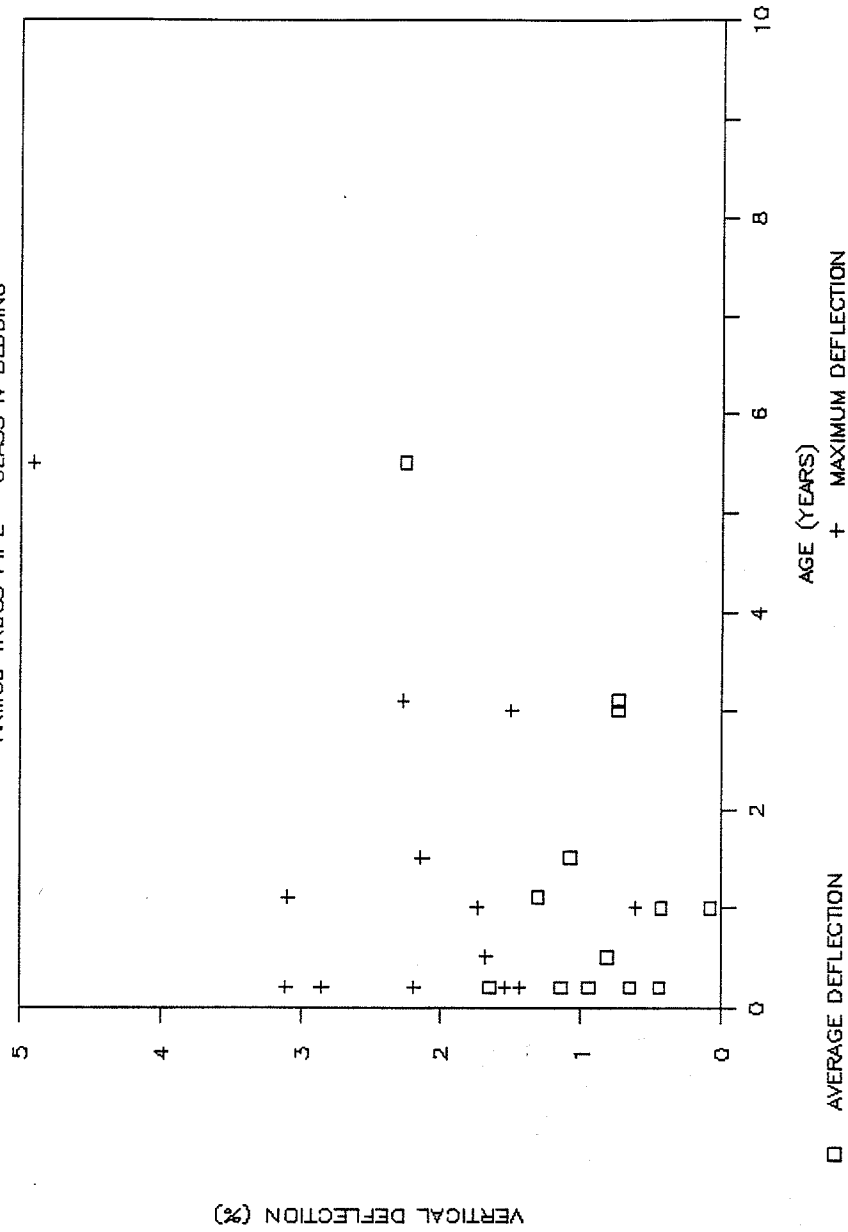


Figure A1.9 Vertical Deflection vs Age
 Truss Pipe - All Diameters
 Class IV Bedding.
 (Contech Construction Products Inc.)

VERTICAL DEFLECTION VS AGE
8 INCH SDR35 PVC PIPE - STONE ENCASED

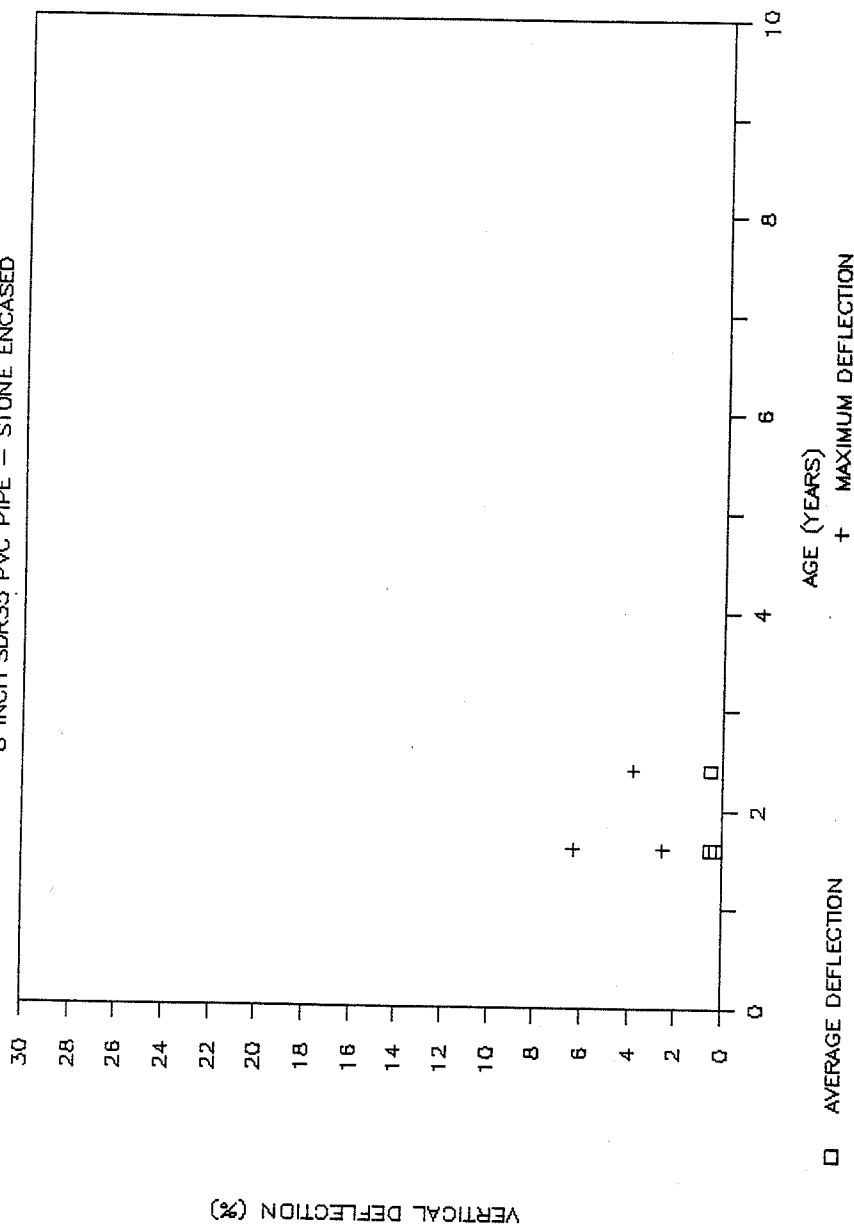


Figure A1.10 Vertical Deflection vs Age
8 inch SDR35 PVC Pipe - Crushed
Stone Envelope.
(Donahue & Associates Inc.)

VERTICAL DEFLECTION VS AGE
8 INCH SDR41 PVC PIPE - SAND BEDDING

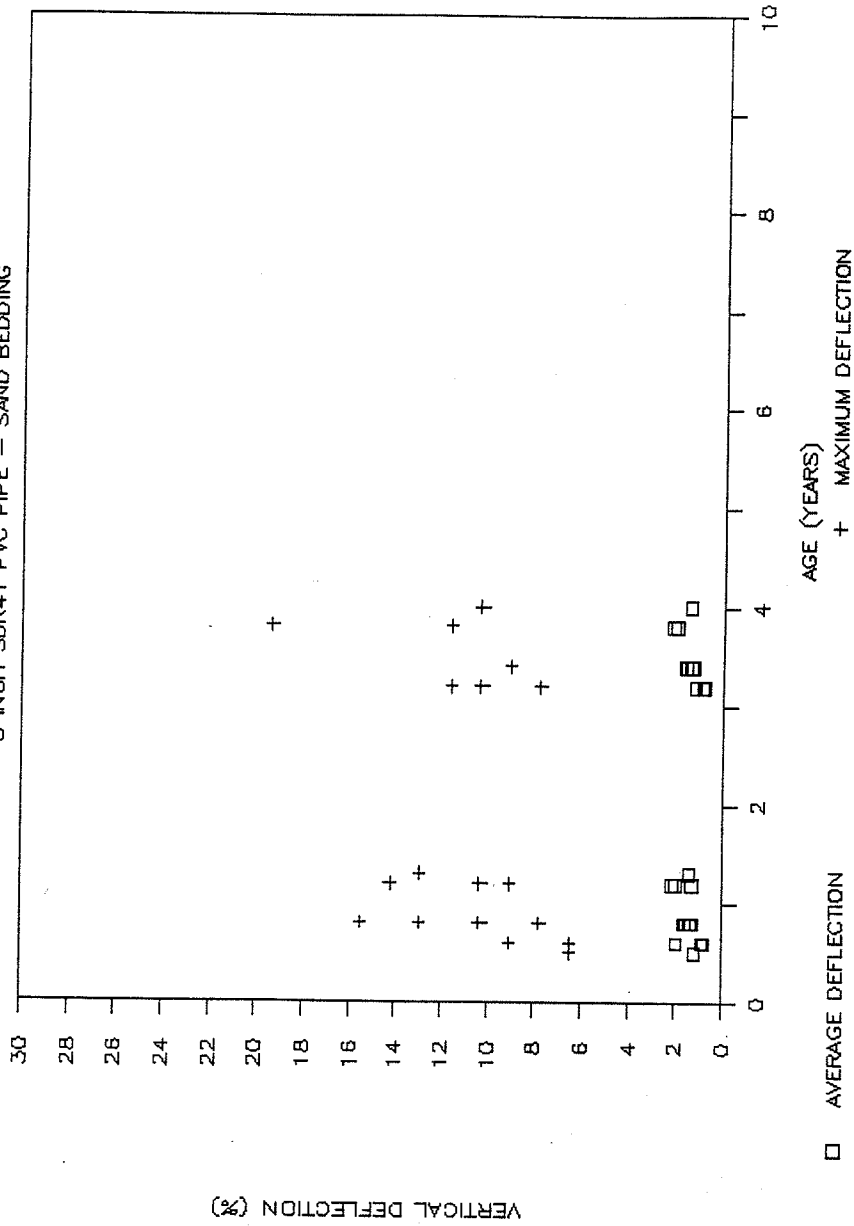


Figure A1.11 Vertical Deflection vs Age
8 inch SDR41 PVC Pipe - Sand Bedding.
(Donahue & Associates Inc.)

VERTICAL DEFLECTION VS AGE

8 INCH SDR42 PIPE - SAND BEDDING

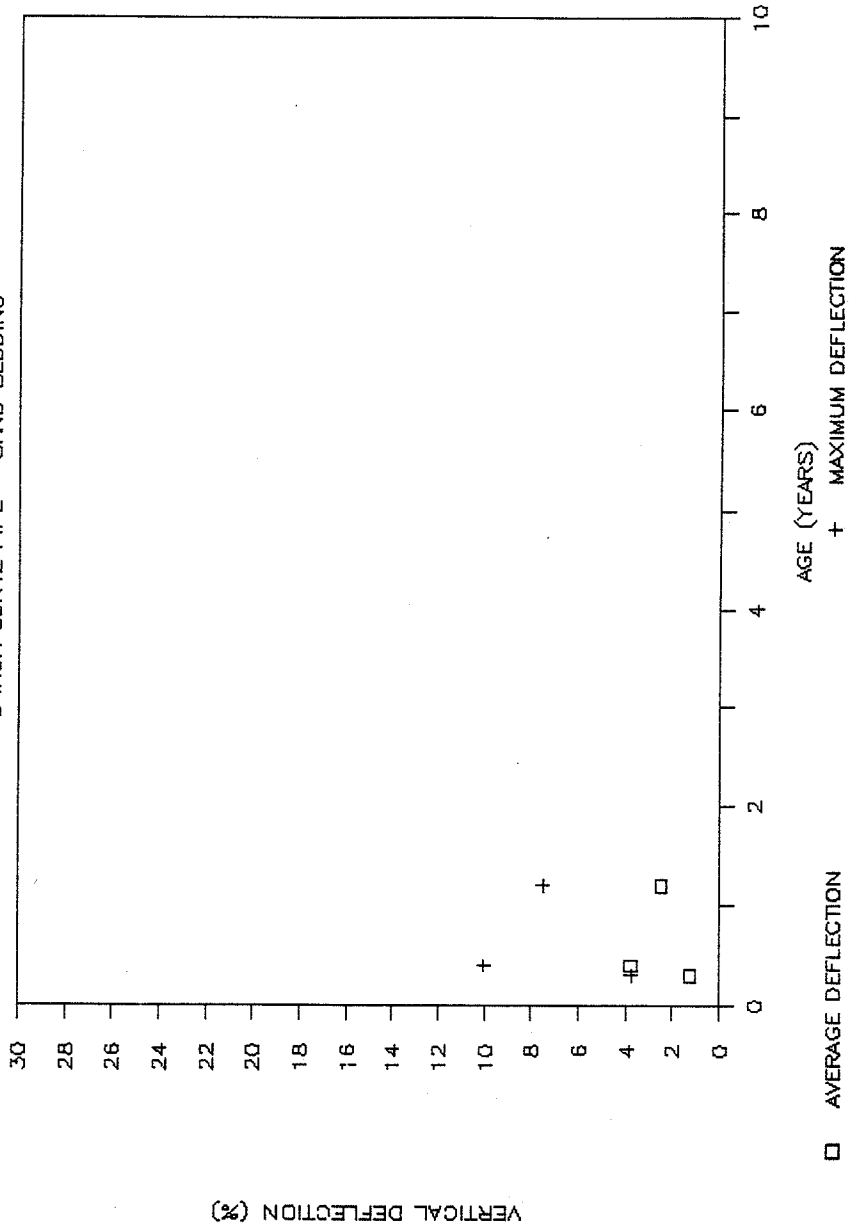


Figure A1.12 Vertical Deflection vs Age
8 inch SDR42 PVC Pipe - Sand
Bedding.
(Donahue & Associates Inc.)

VERTICAL DEFLECTION VS DEPTH OF COVER

8 INCH SDR35 PVC PIPE - UNKNOWN BEDDING

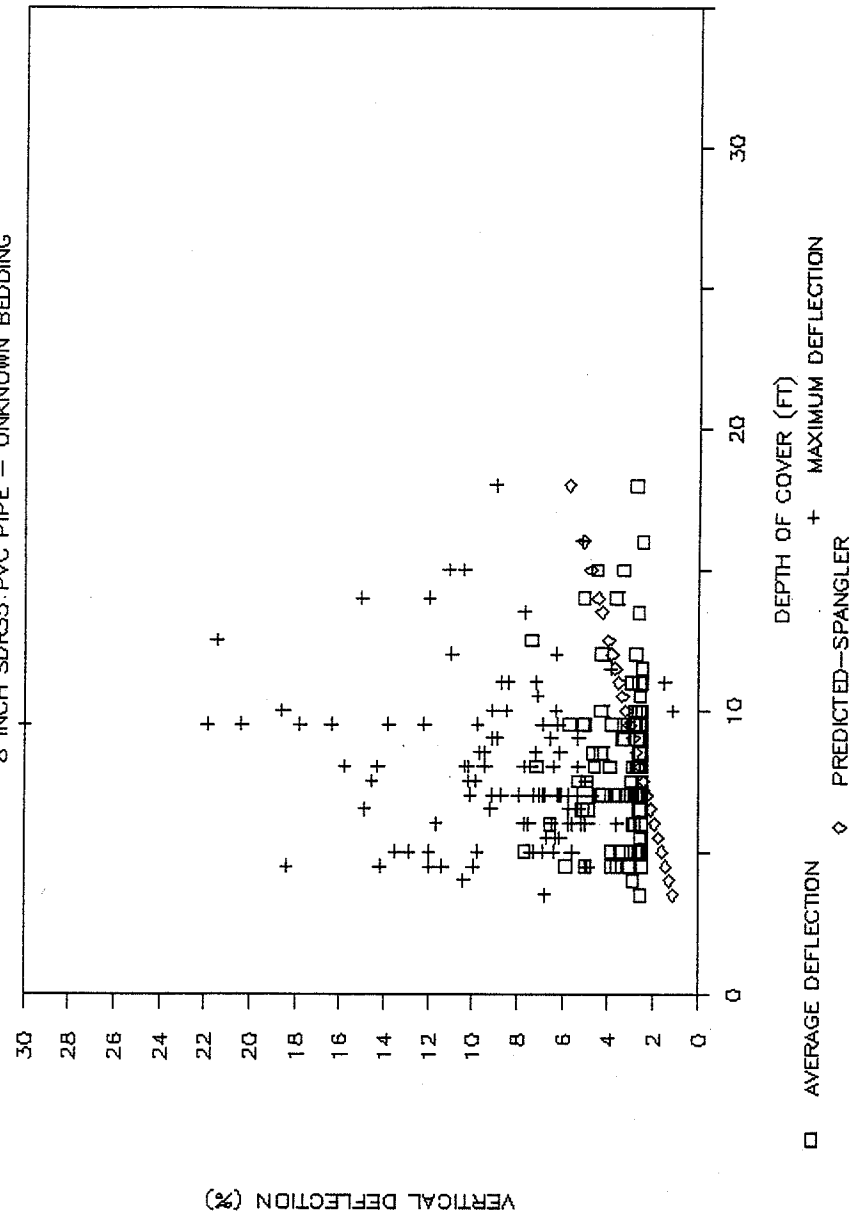


Figure A1.14 Vertical Deflection vs Depth of Cover
8 inch SDR35 PVC Pipe - Unknown
Bedding Class.
(National Clay Pipe Institute)

VERTICAL DEFLECTION VS DEPTH OF COVER

8 INCH SDR35 PVC PIPE - CLASS II

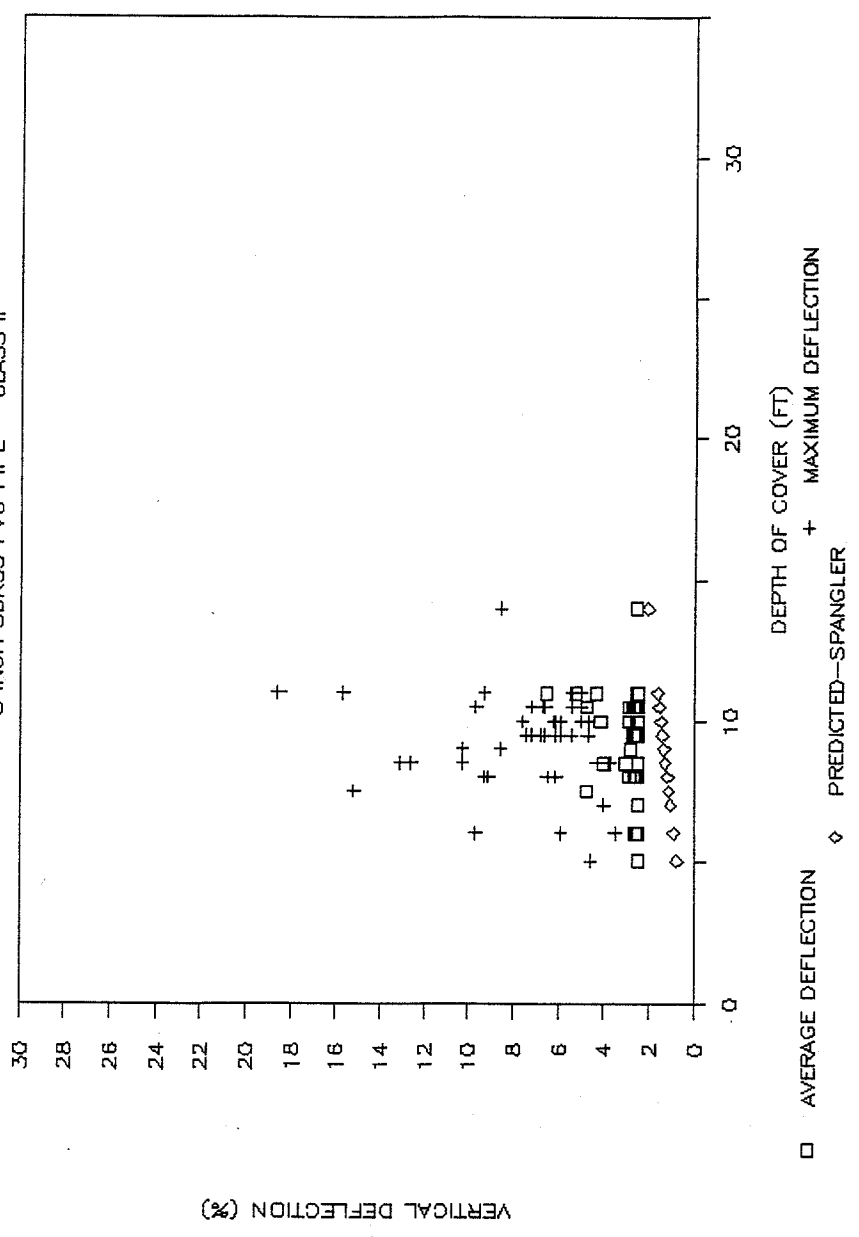


Figure A1.15 Vertical Deflection vs Depth of Cover
8 inch SDR35 PVC Pipe - Class II Bedding.
(National Clay Pipe Institute)

VERTICAL DEFLECTION VS DEPTH OF COVER

8 INCH SDR35 PVC PIPE - SAND BEDDING

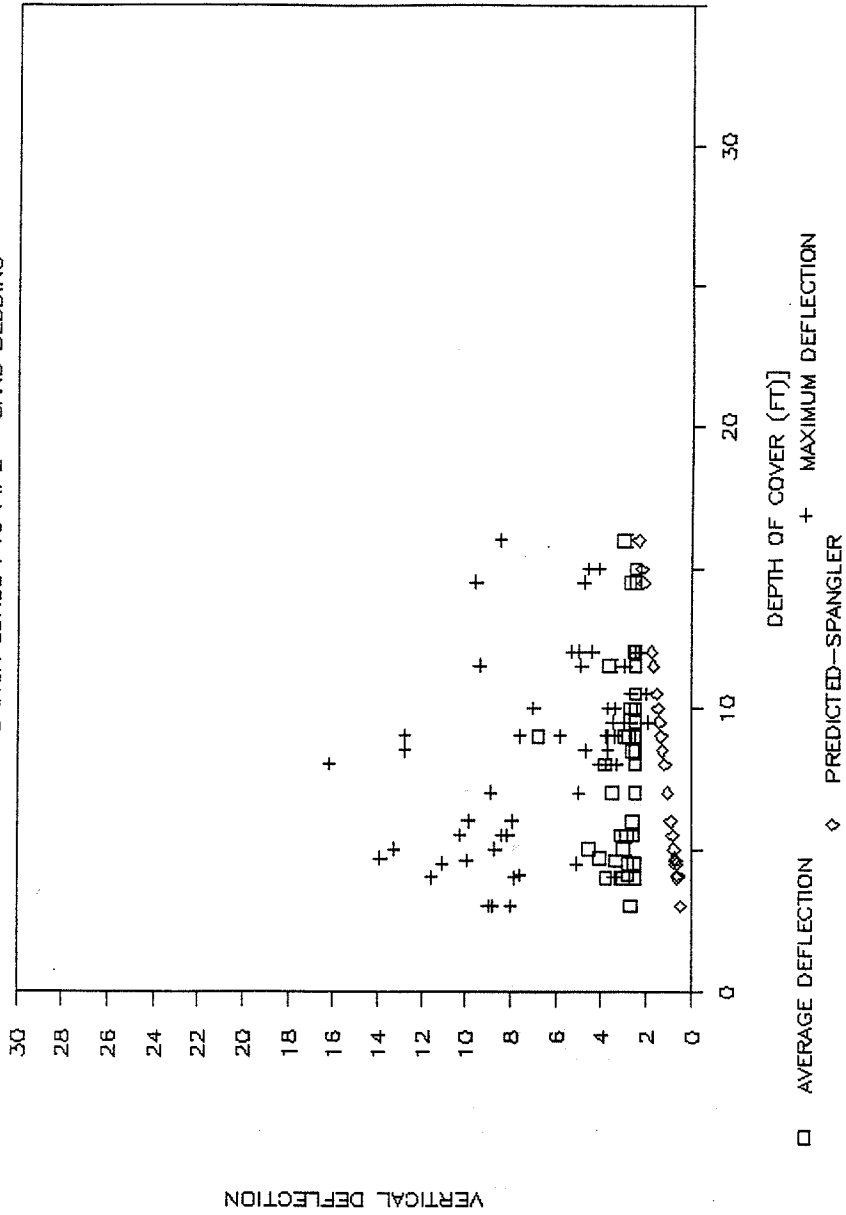


Figure A1.16 Vertical Deflection vs Depth of Cover
8 inch SDR35 PVC Pipe - Sand Bedding.
(National Clay Pipe Institute)

VERTICAL DEFLECTION VS DEPTH OF COVER

8 INCH SDR35 PVC PIPE - STONE TO SPRING

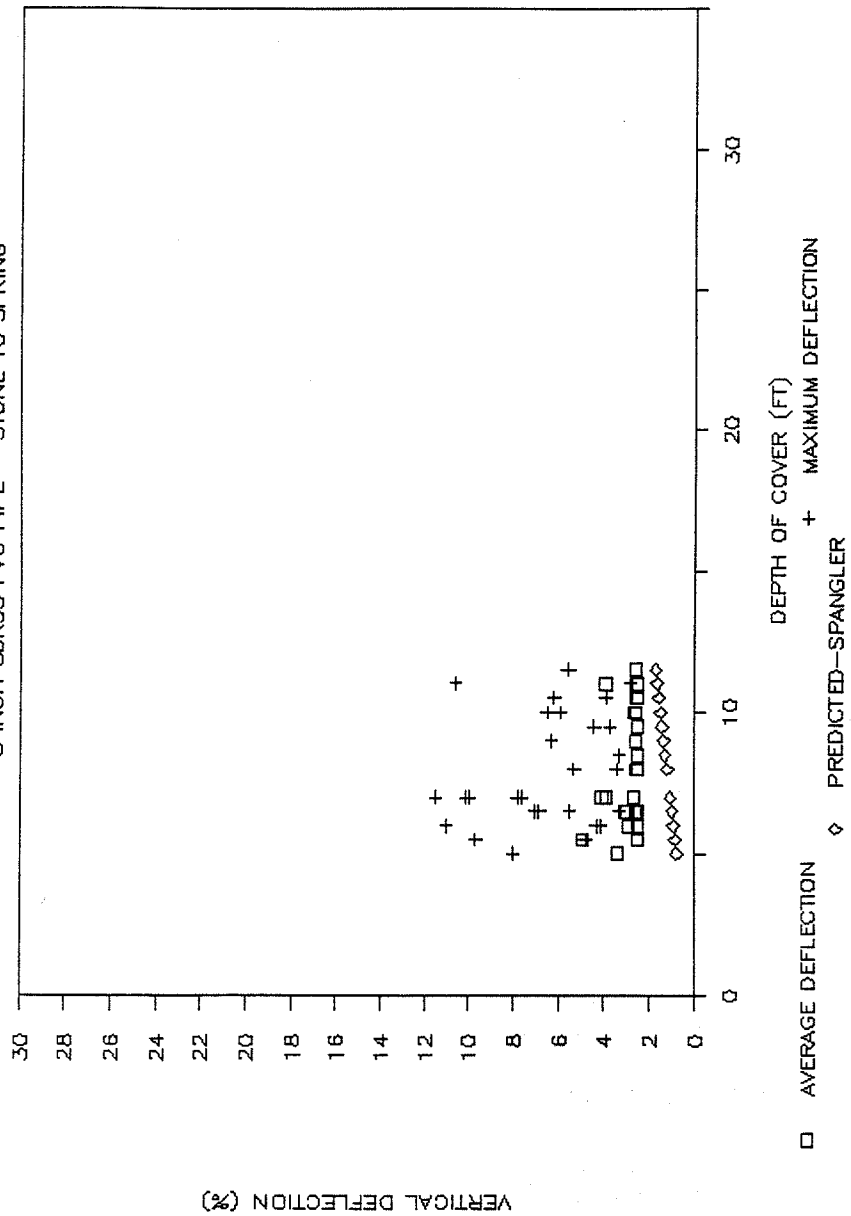
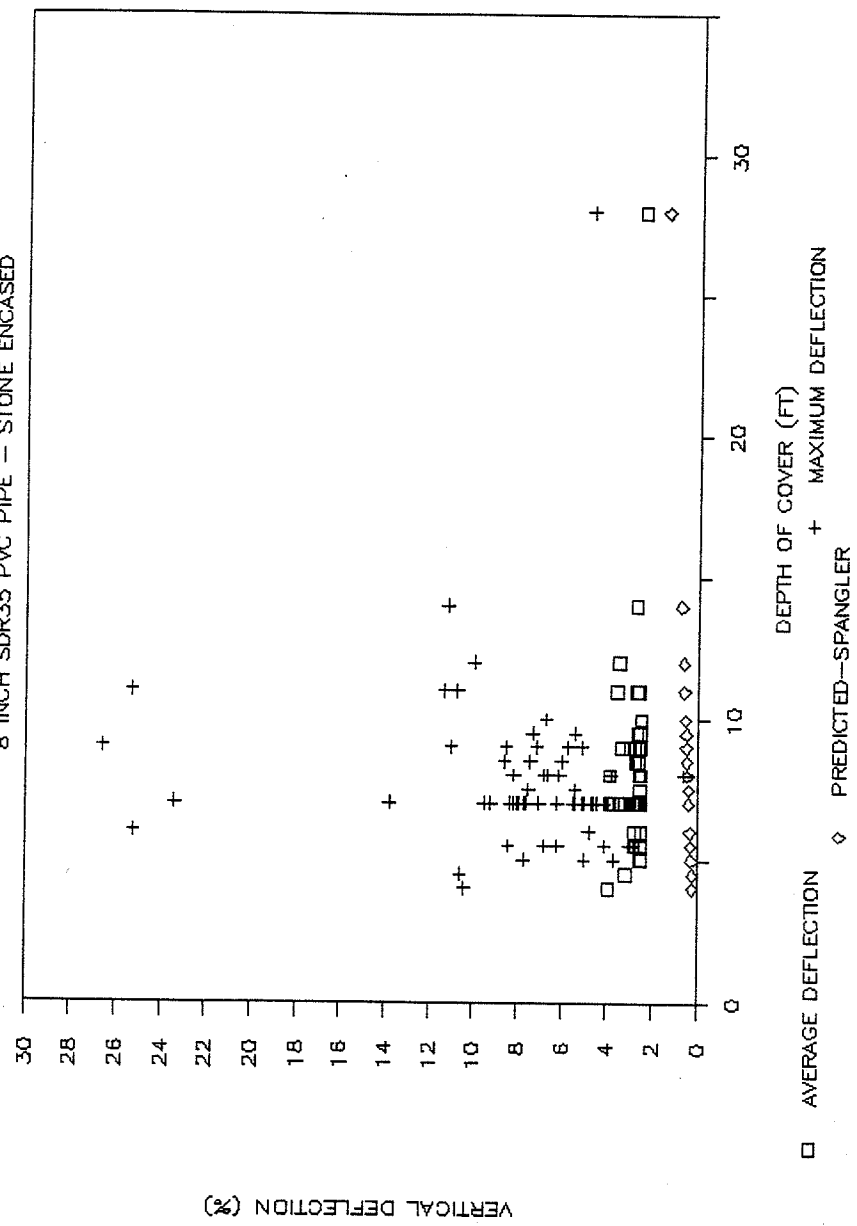


Figure A1.17 Vertical Deflection vs Depth of Cover
8 inch SDR35 PVC Pipe - Crushed Stone to the Springline.
(National Clay Pipe Institute)

VERTICAL DEFLECTION VS DEPTH OF COVER

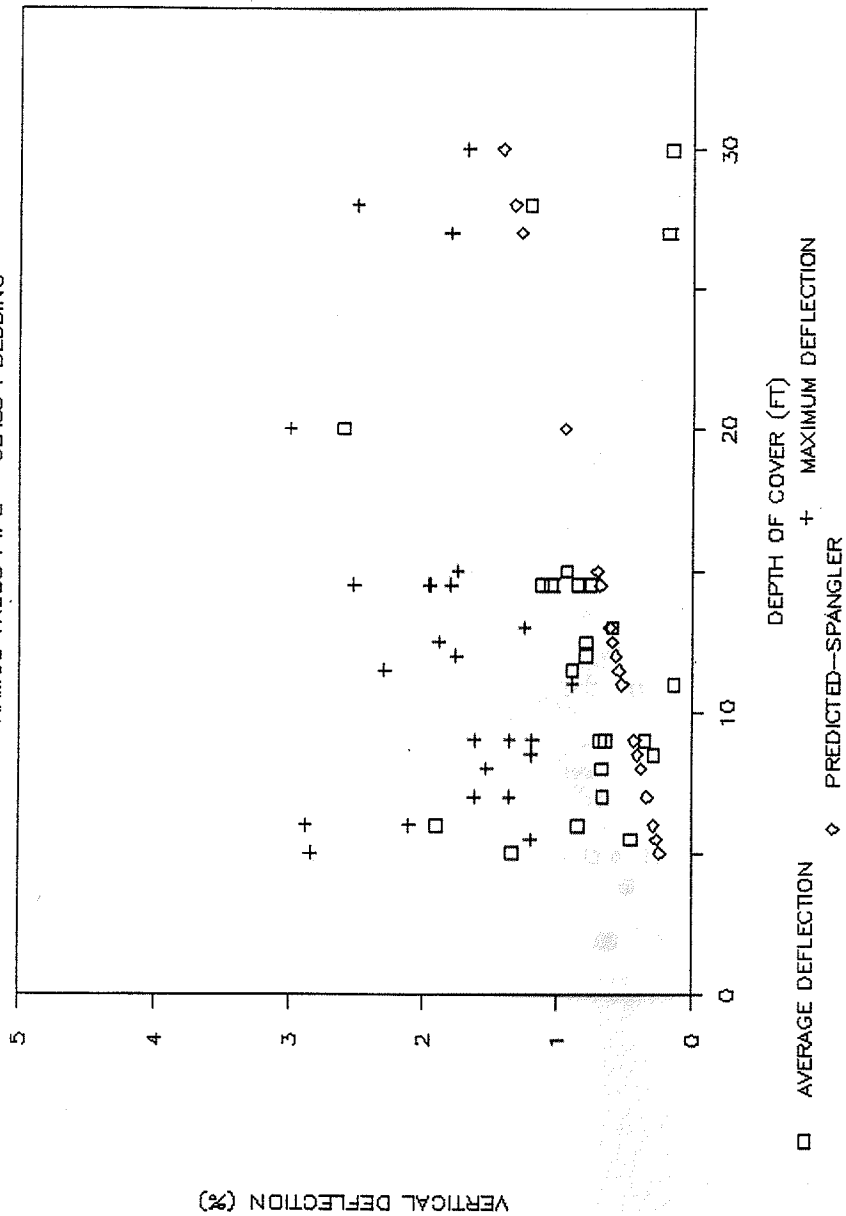
8 INCH SDR35 PVC PIPE - STONE ENCASED



**Figure A1.18 Vertical Deflection vs Depth of Cover
8 inch SDR35 PVC Pipe - Crushed
Stone Envelope.
(National Clay Pipe Institute)**

VERTICAL DEFLECTION VS DEPTH OF COVER

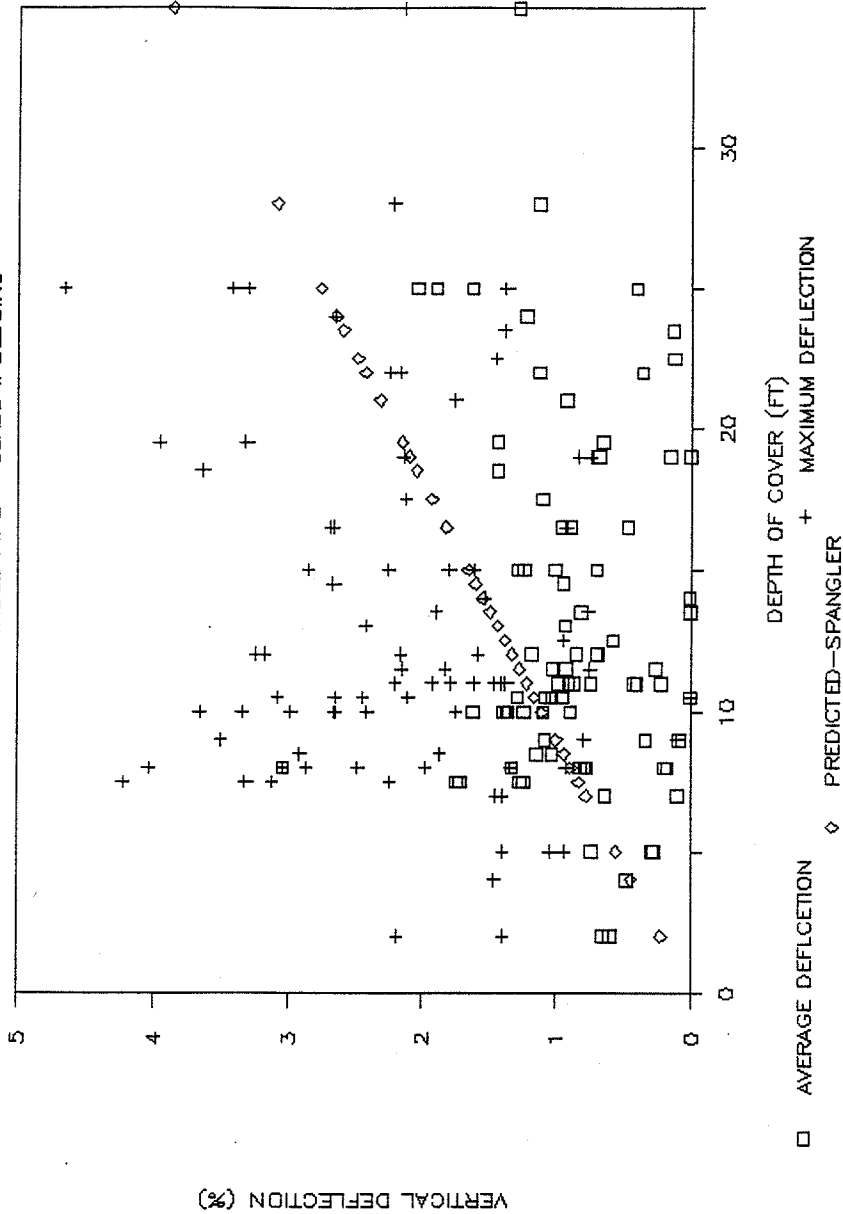
ARMCO TRUSS PIPE - CLASS I BEDDING



**Figure A1.19 Vertical Deflection vs Depth of Cover
Truss Pipe - All Diameters
Class I Bedding.
(Contech Construction Products Inc.)**

VERTICAL DEFLECTION VS DEPTH OF COVER

ARMCO TRUSS PIPE - CLASS II BEDDING



**Figure A1.20 Vertical Deflection vs Depth of Cover
Truss Pipe - All Diameters
Class II Bedding.
(Contech Construction Products Inc.)**

VERTICAL DEFLECTION VS DEPTH OF COVER

ARMCO TRUSS PIPE - CLASS III BEDDING

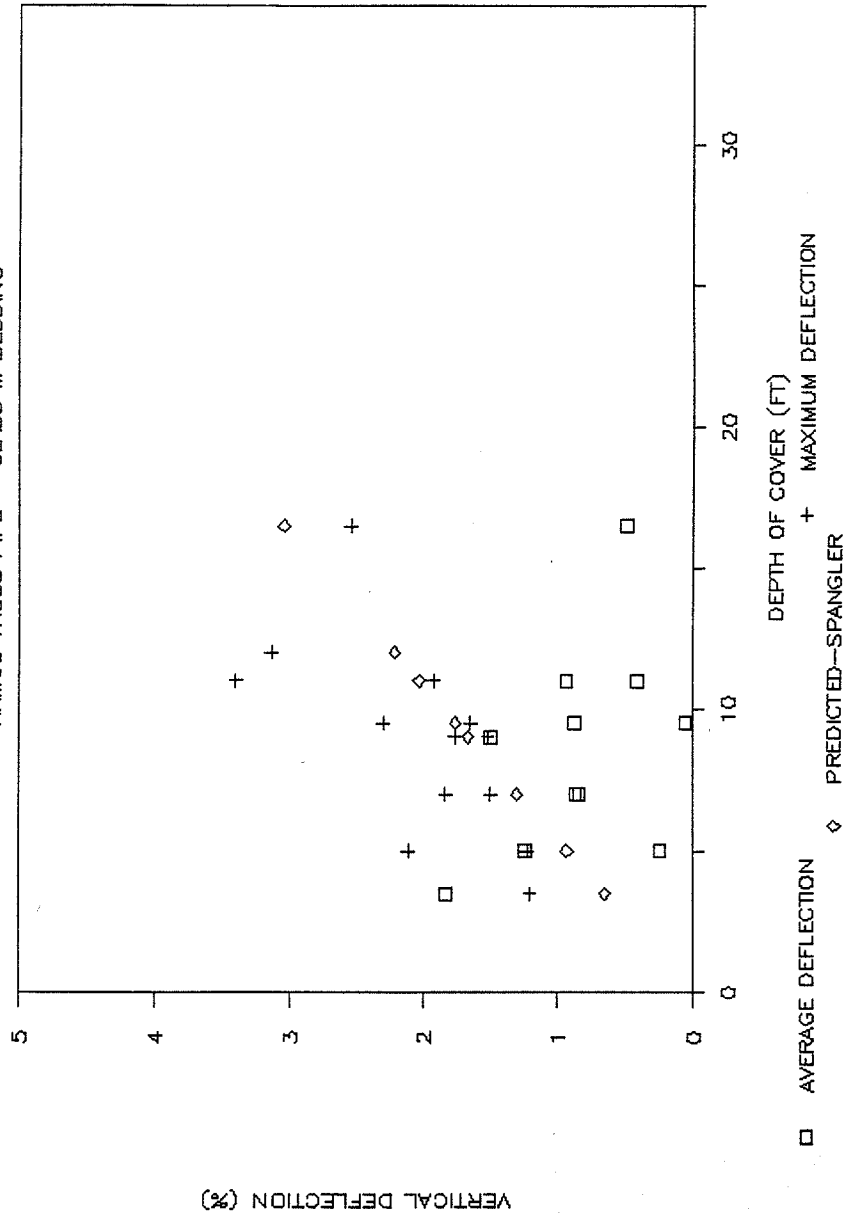
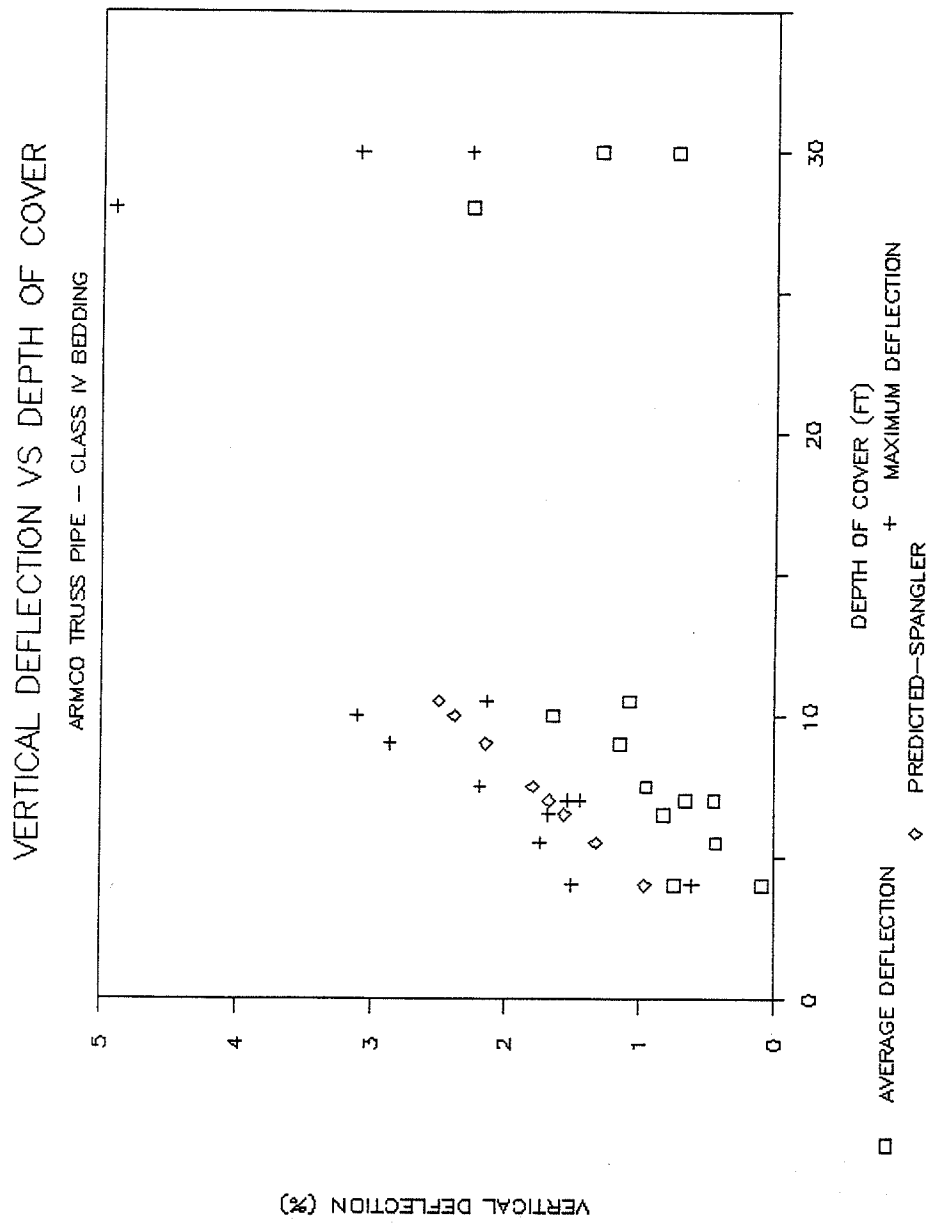


Figure A1.21 Vertical Deflection vs Depth of Cover
 Truss Pipe - All Diameters
 Class III Bedding.
 (Contech Construction Products Inc.)



**Figure A1.22 Vertical Deflection vs Depth of Cover
Truss Pipe - All Diameters
Class IV Bedding.
(Contech Construction Products Inc.)**

VERTICAL DEFLECTION VS DEPTH OF COVER

8 INCH SDR35 PVC PIPE - STONE ENCASED

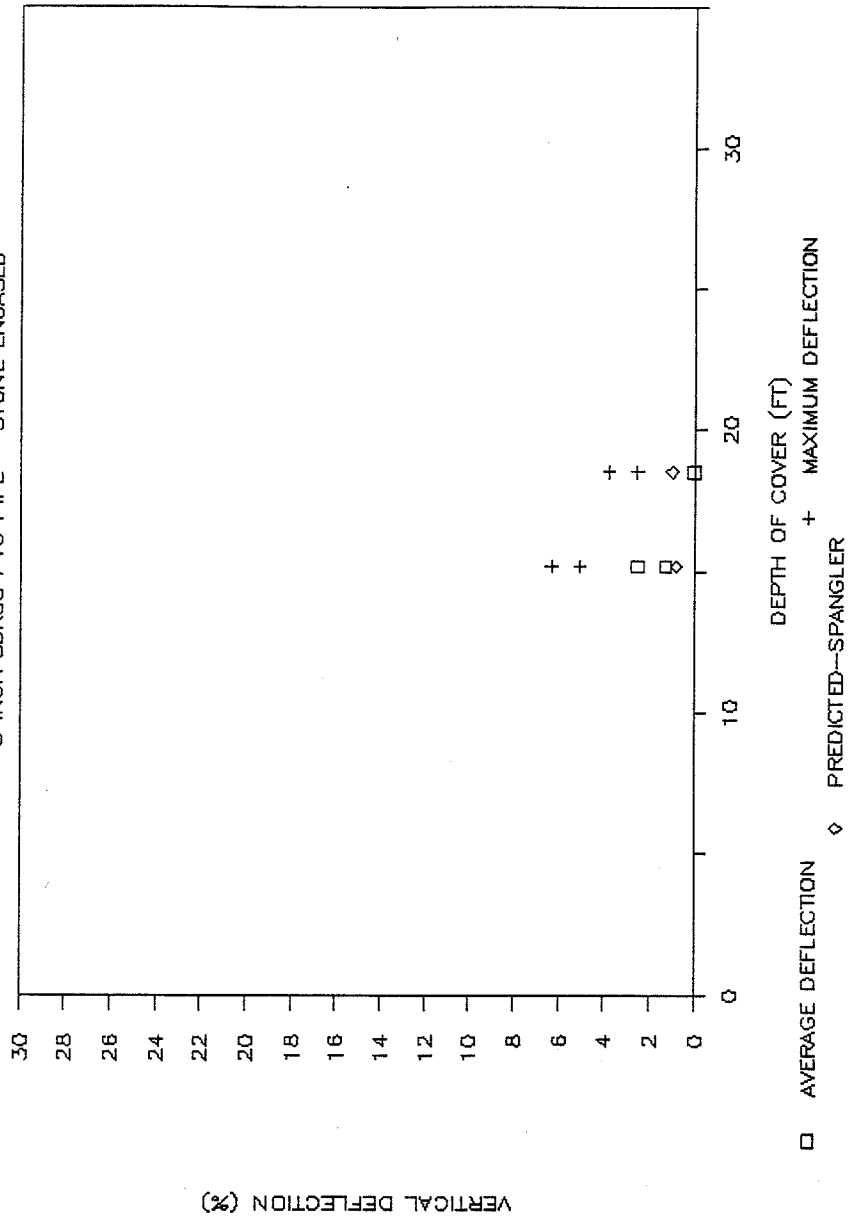


Figure A1.23 Vertical Deflection vs Depth of Cover
8 inch SDR35 PVC Pipe - Crushed Stone Envelope.
(Donahue & Associates Inc.)

VERTICAL DEFLECTION VS DEPTH OF COVER

8 INCH SDR41 PVC PIPE - SAND BEDDING

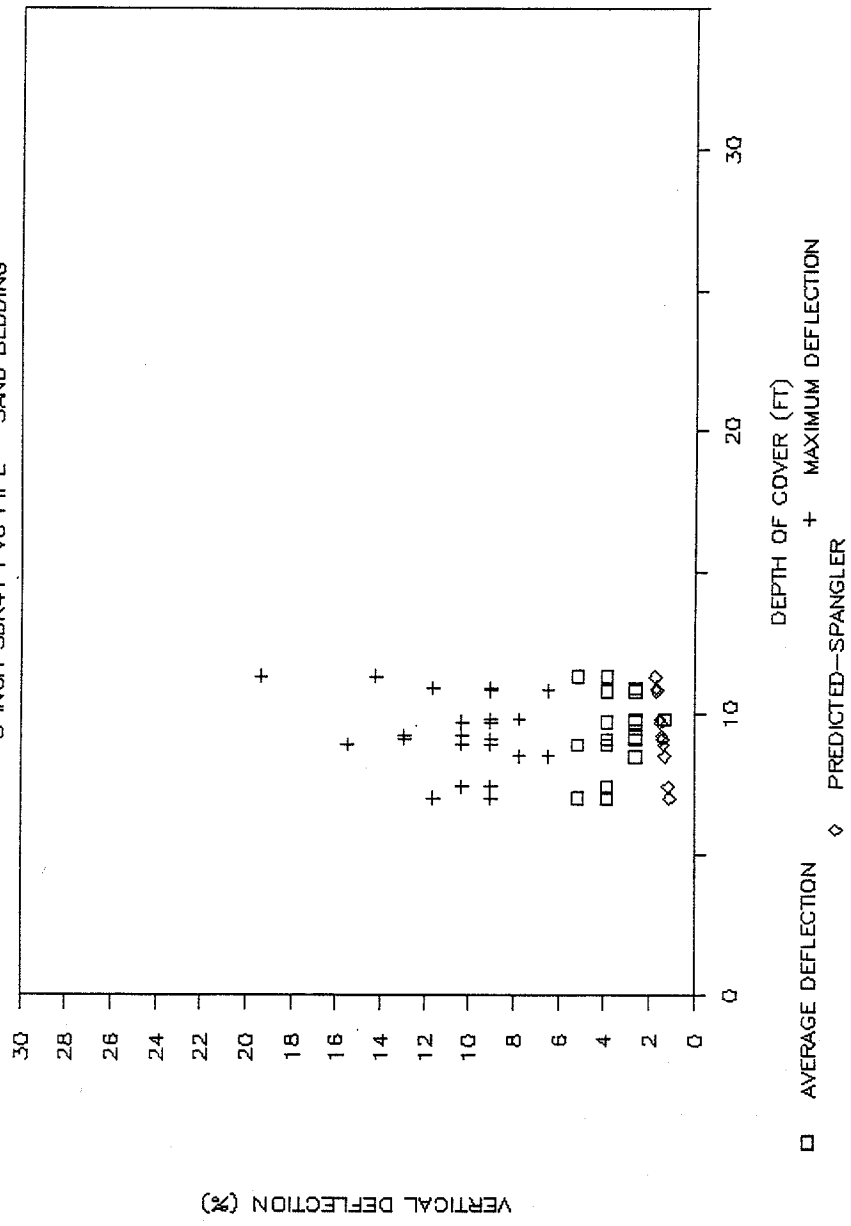
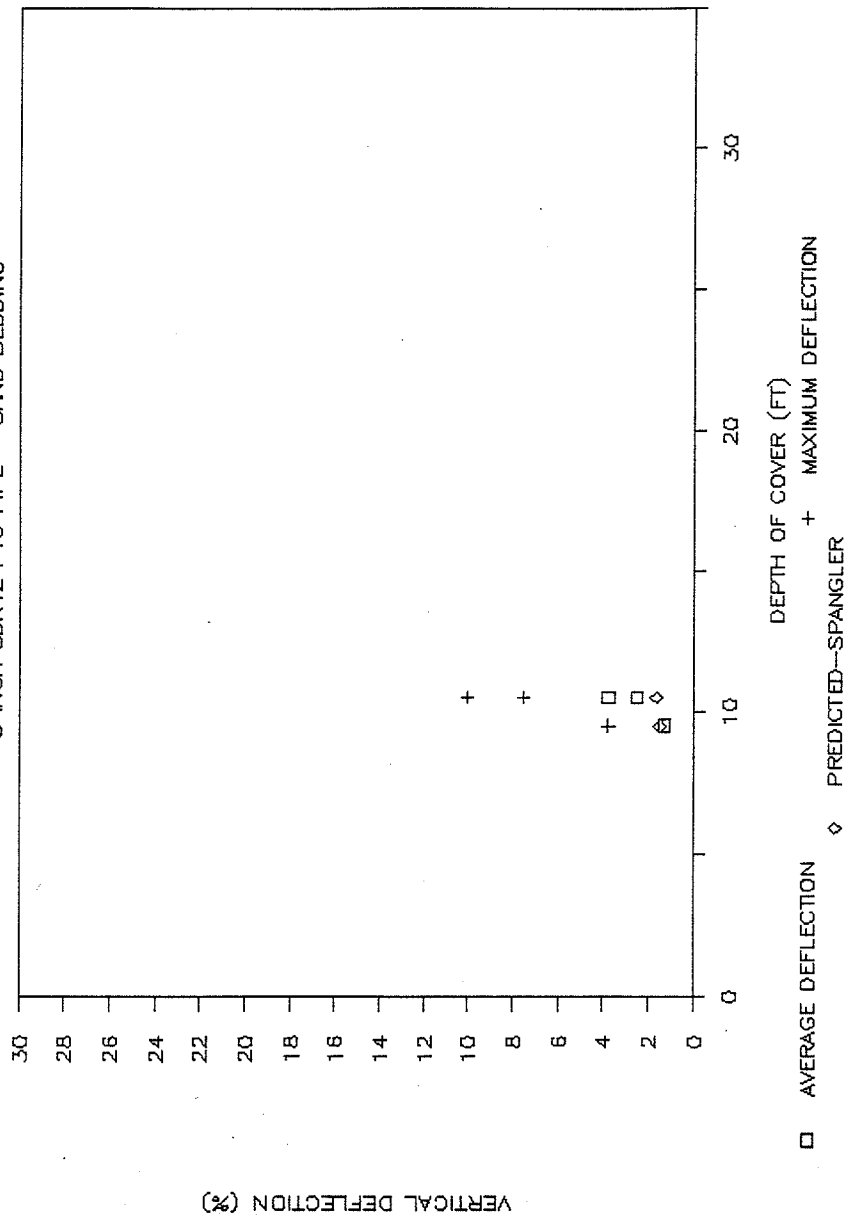


Figure A1.24 Vertical Deflection vs Depth of Cover
8 inch SDR41 PVC Pipe - Sand Bedding.
(Donahue & Associates Inc.)

VERTICAL DEFLECTION VS DEPTH OF COVER

8 INCH SDR42 PVC PIPE - SAND BEDDING



**Figure A1.25 Vertical Deflection vs Depth of Cover
8 inch SDR42 PVC Pipe - Sand
Bedding.
(Donahue & Associates Inc.)**

VERTICAL DEFLECTION VS DEPTH OF COVER

SDR42 PVC PIPE - STONE ENCASED

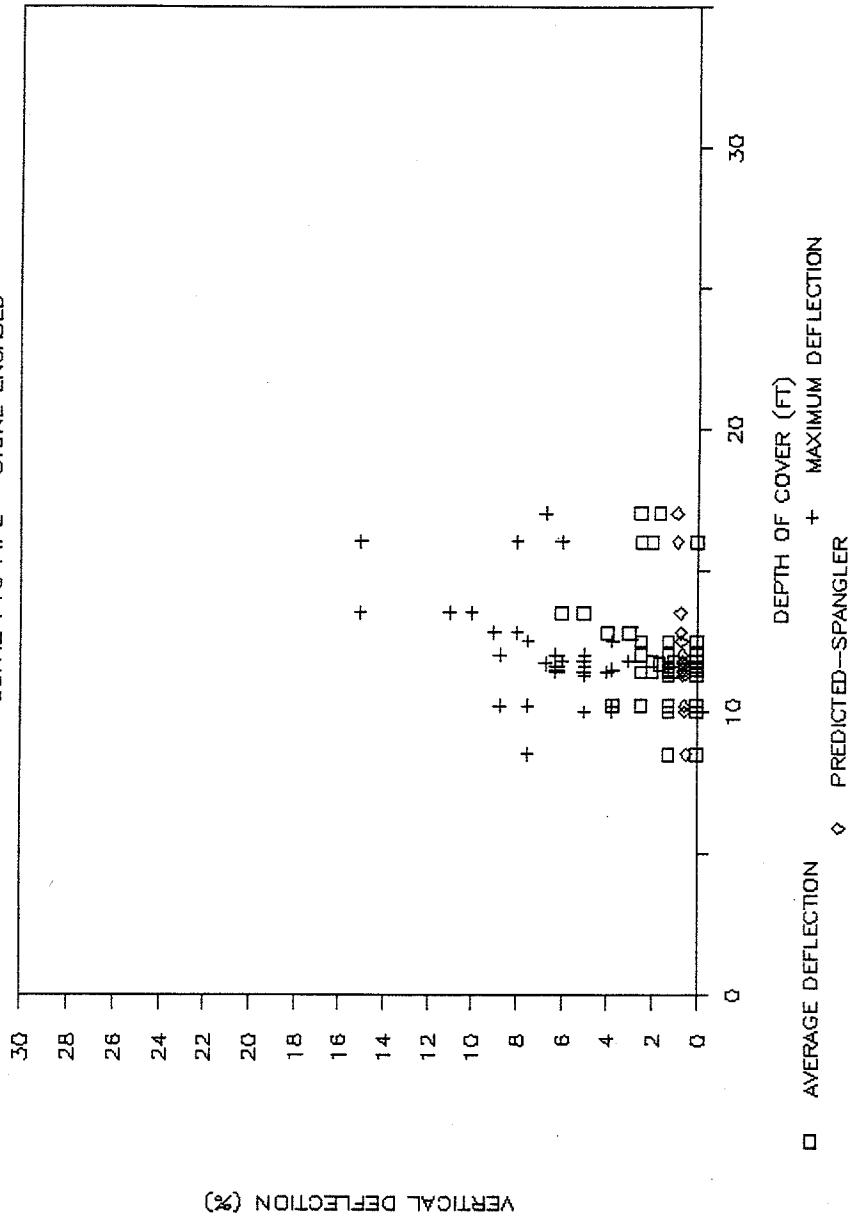


Figure A1.26 Vertical Deflection vs Depth of Cover
SDR42 PVC Pipe - All Diameters
Crushed Stone Envelope.
(Donahue & Associates Inc.)

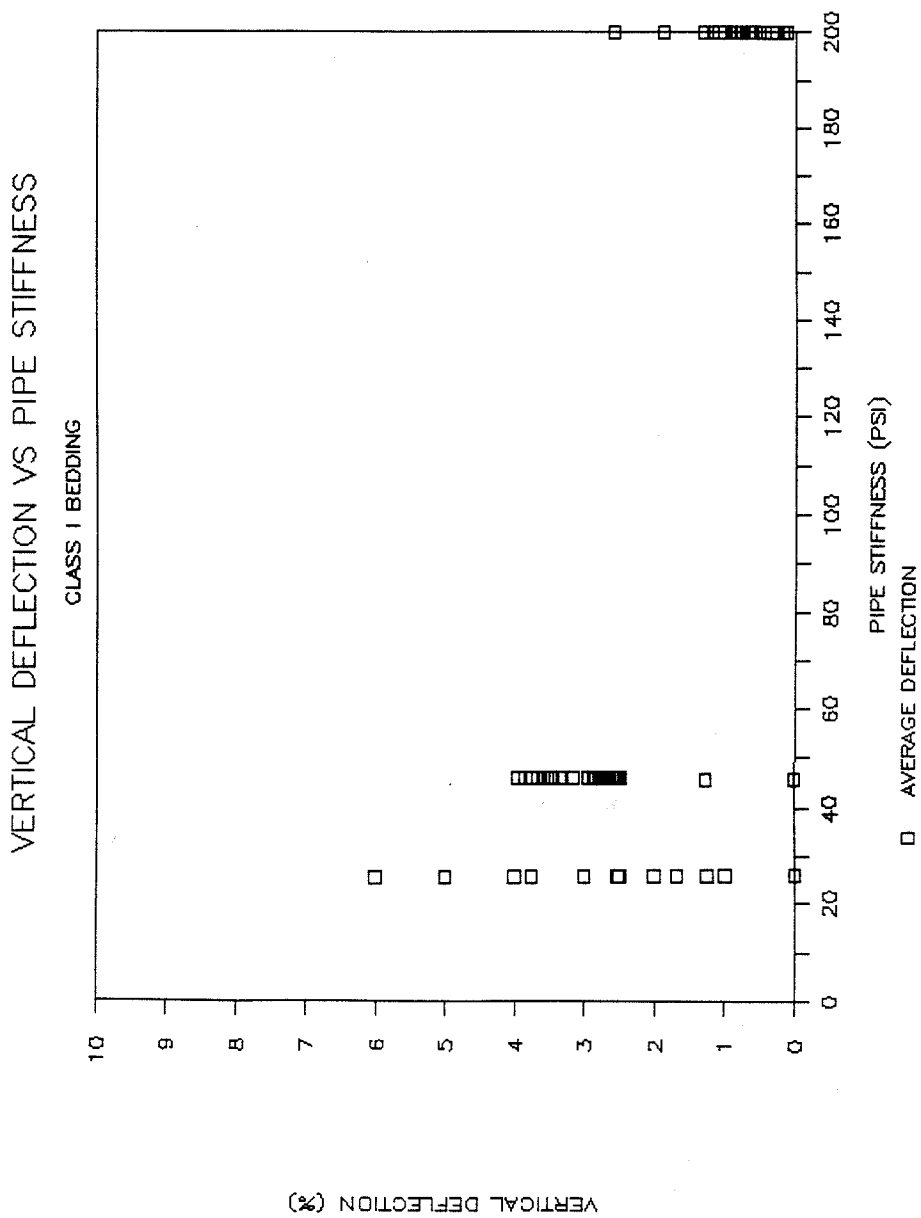


Figure A1.27 Vertical Deflection vs Pipe Stiffness
Average Deflection - Class I Bedding.

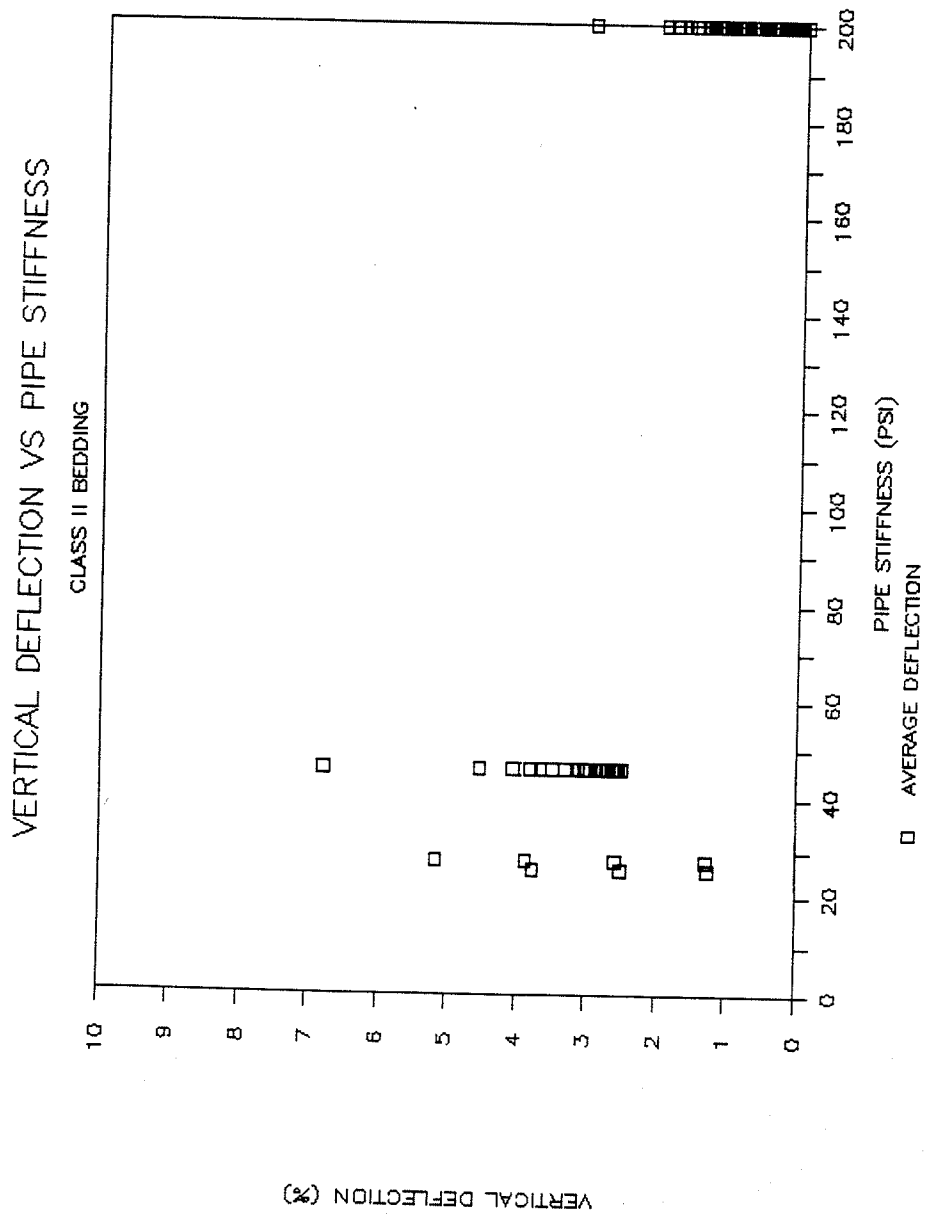


Figure A1.28 Vertical Deflection vs Pipe Stiffness
Average Deflection - Class II Bedding.

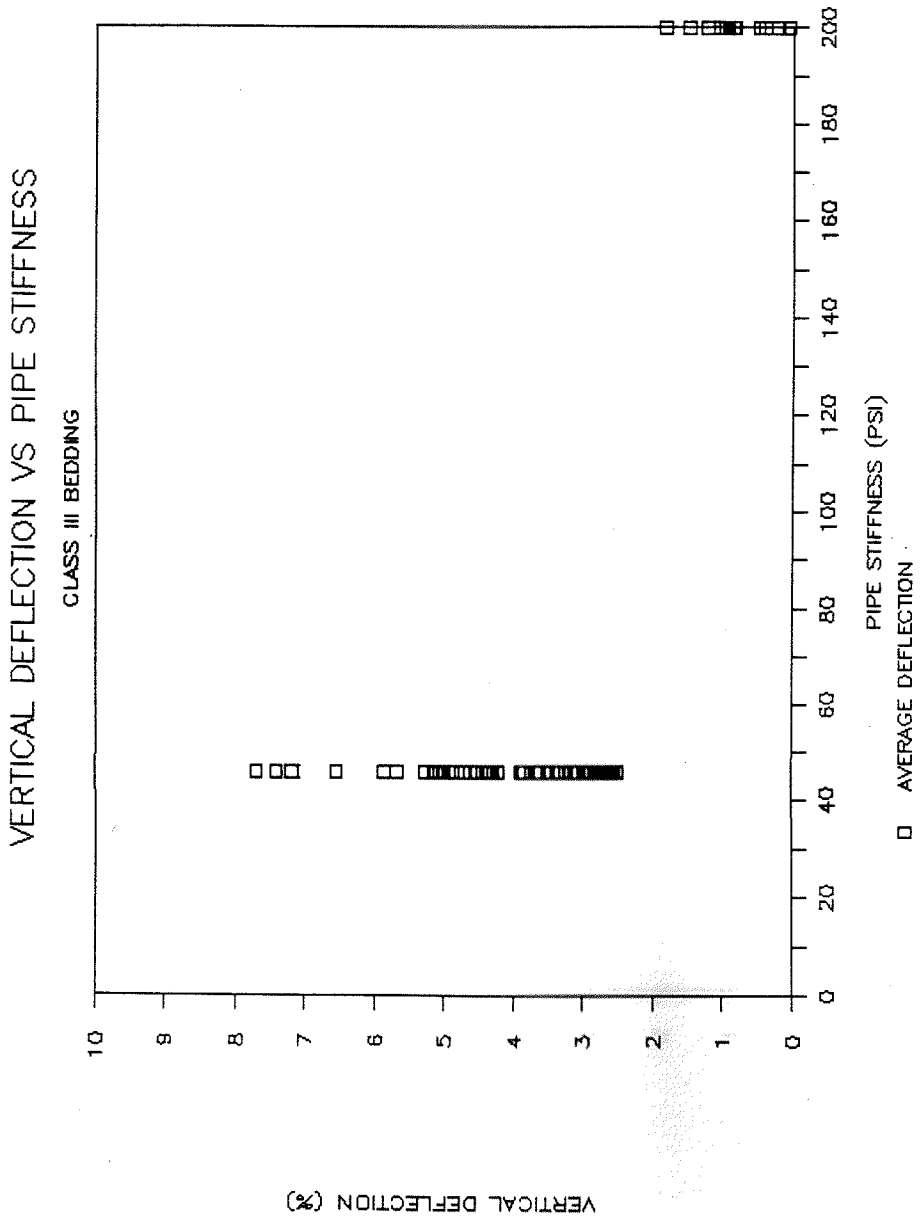
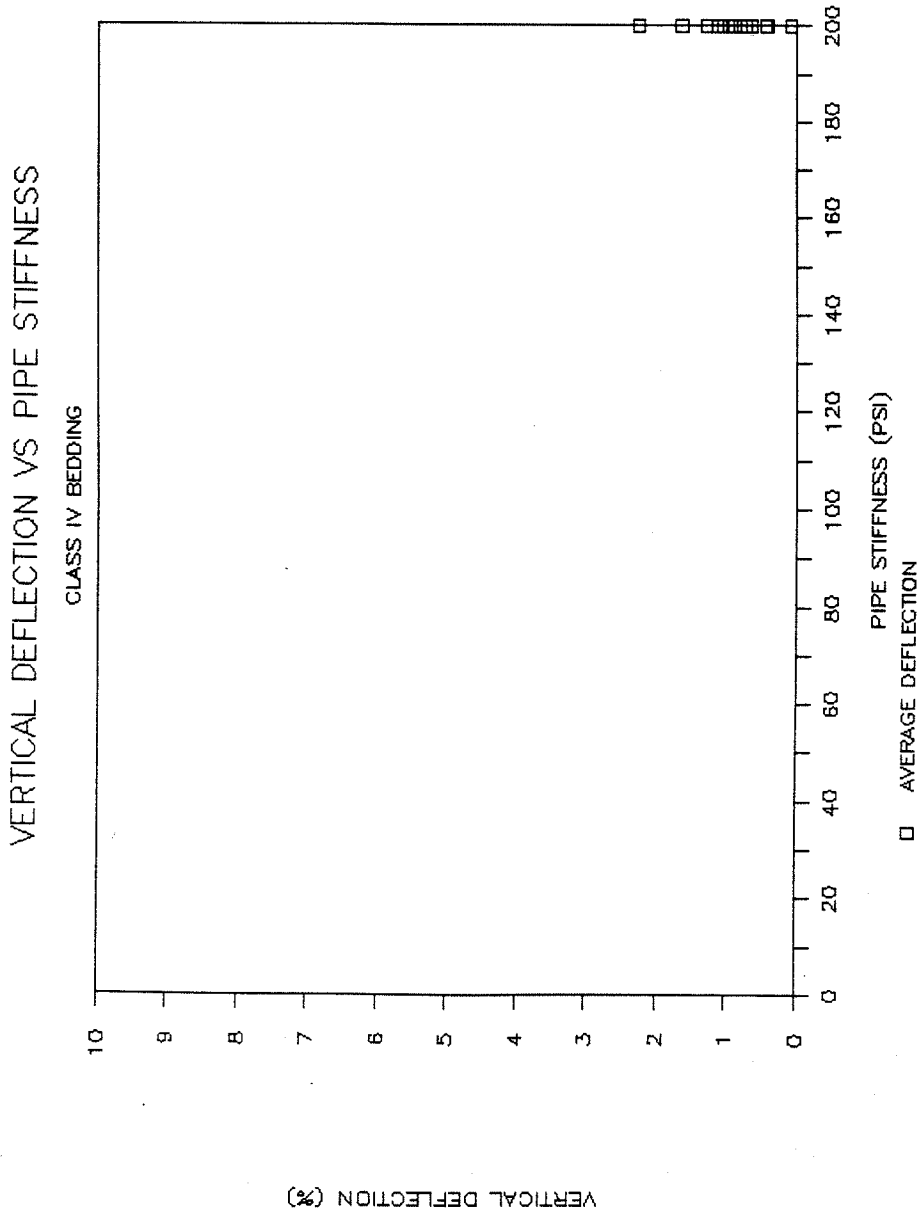


Figure A1.29 Vertical Deflection vs Pipe Stiffness
Average Deflection - Class III Bedding.



**Figure A1.30 Vertical Deflection vs Pipe Stiffness
Average Deflection - Class IV Bedding.**

VERTICAL DEFLECTION VS PIPE STIFFNESS

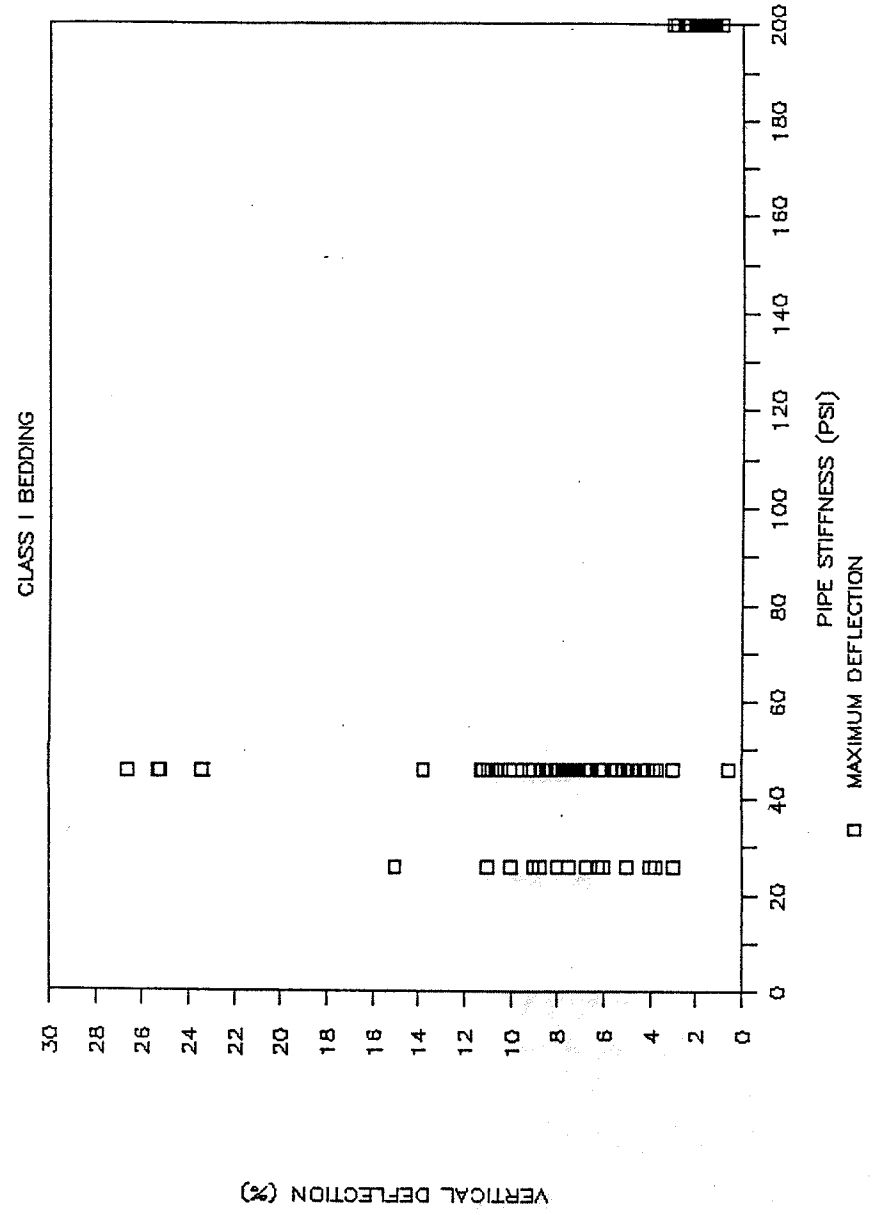


Figure A1.31 Vertical Deflection vs Pipe Stiffness
Maximum Deflection - Class I Bedding.

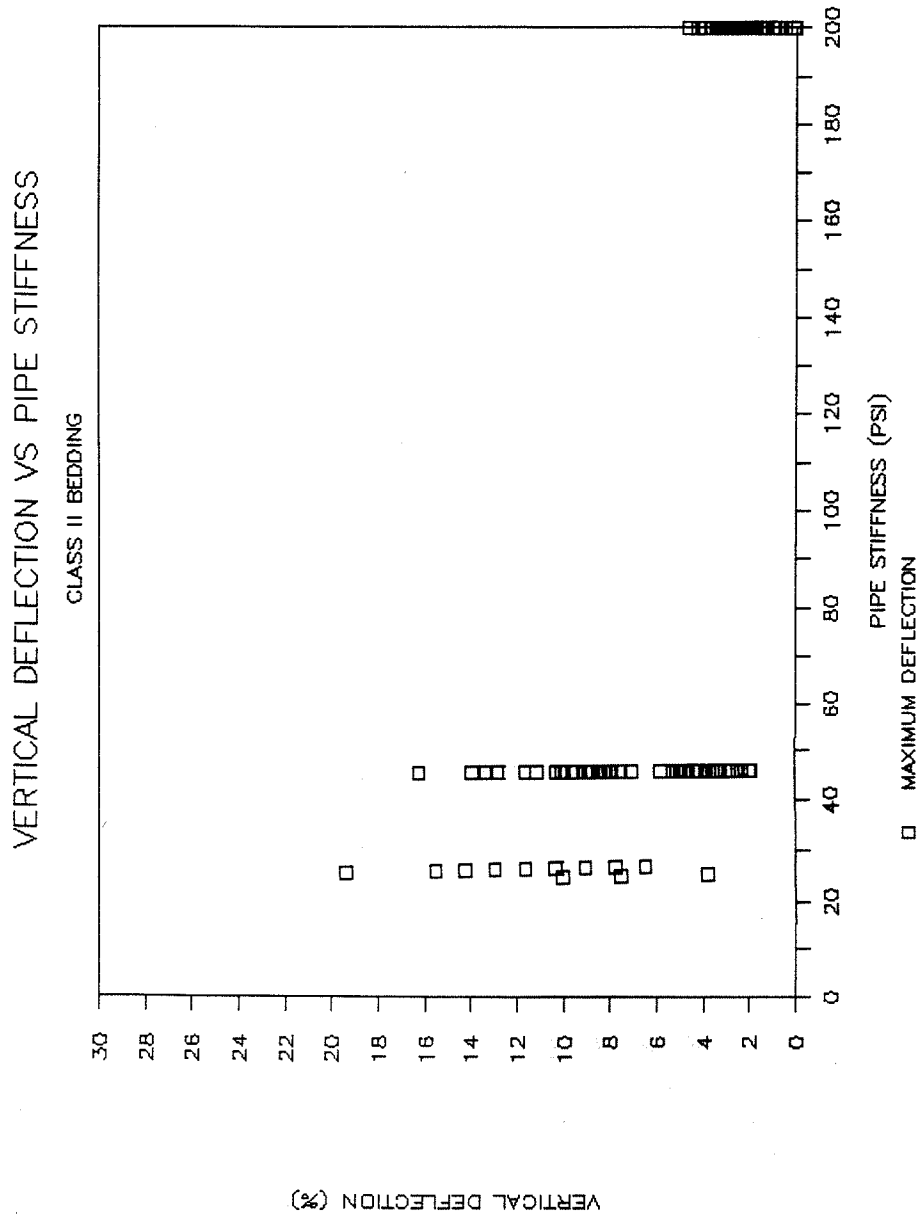
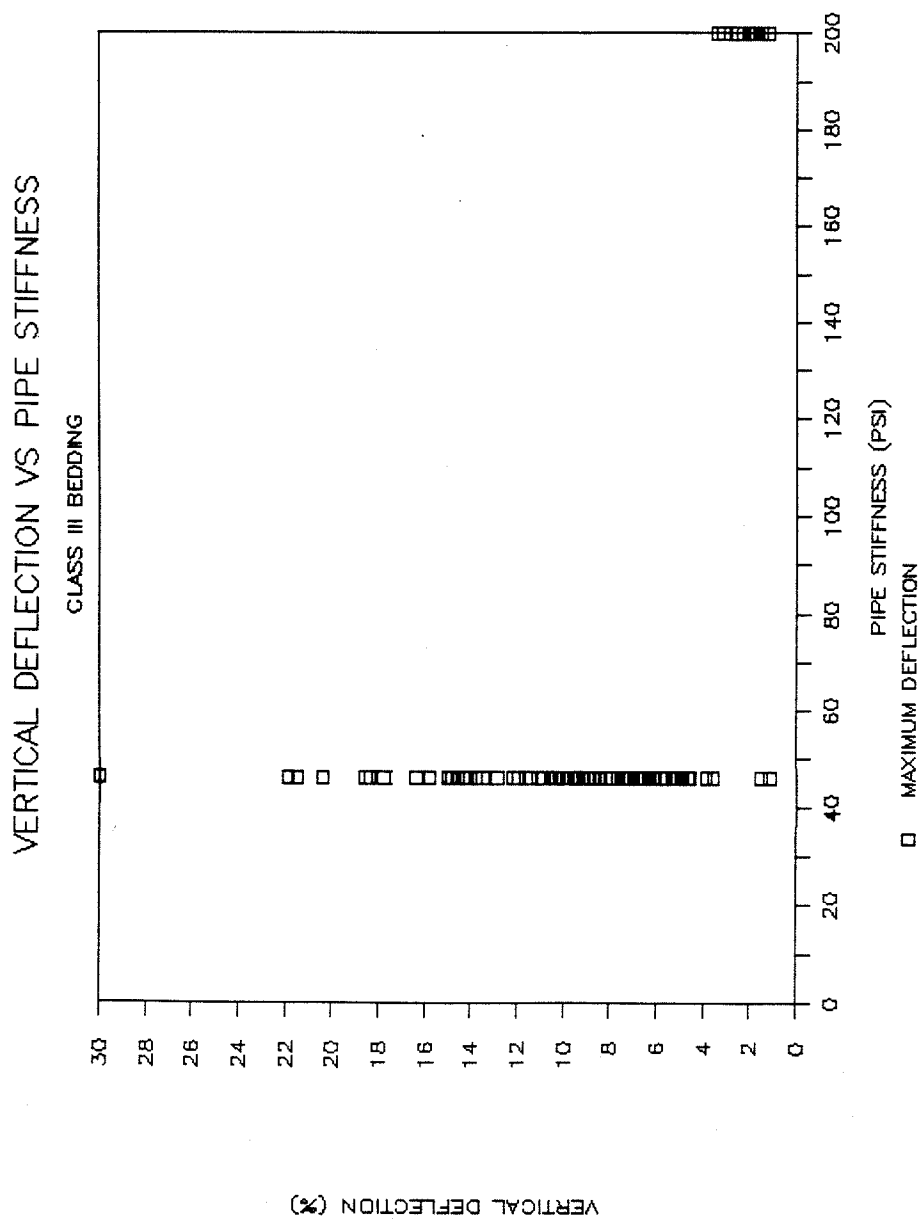
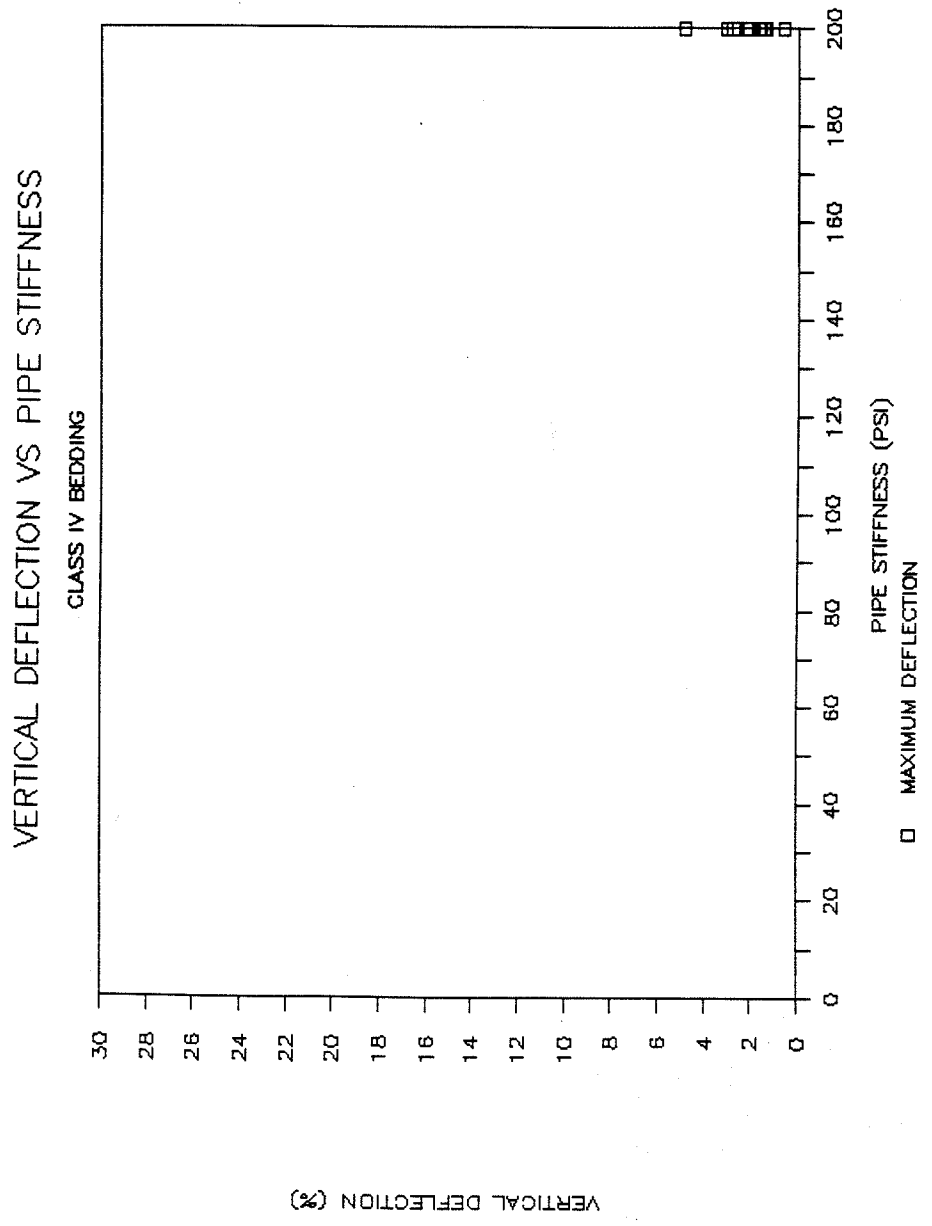


Figure A1.32 Vertical Deflection vs Pipe Stiffness
Maximum Deflection - Class II Bedding.



**Figure A1.33 Vertical Deflection vs Pipe Stiffness
Maximum Deflection - Class III Bedding.**



**Figure A1.34 Vertical Deflection vs Pipe Stiffness
Maximum Deflection - Class IV Bedding.**

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - UNKNOWN BEDDING

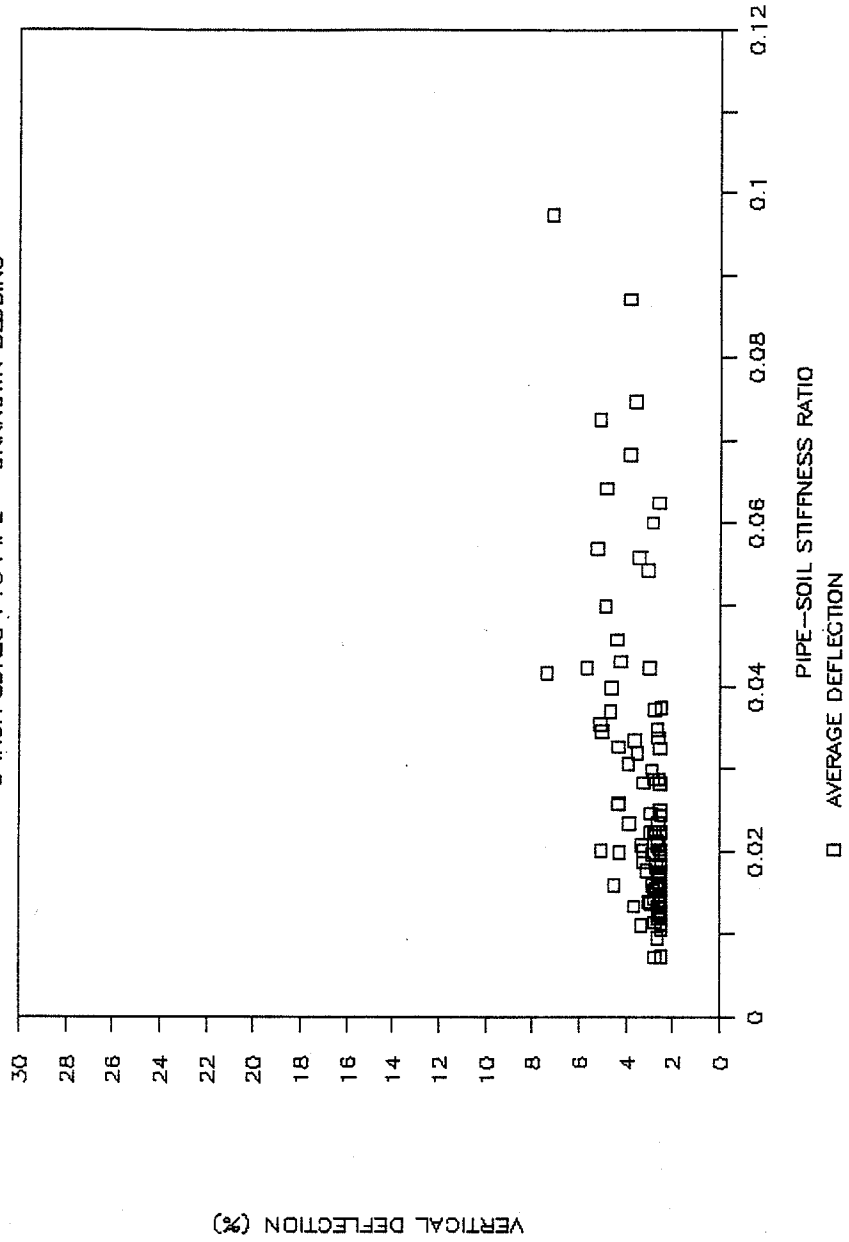


Figure A1.35 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection SDR35 PVC Pipe - Unknown Bedding. (National Clay Pipe Institute)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE-CLASS II BEDDING

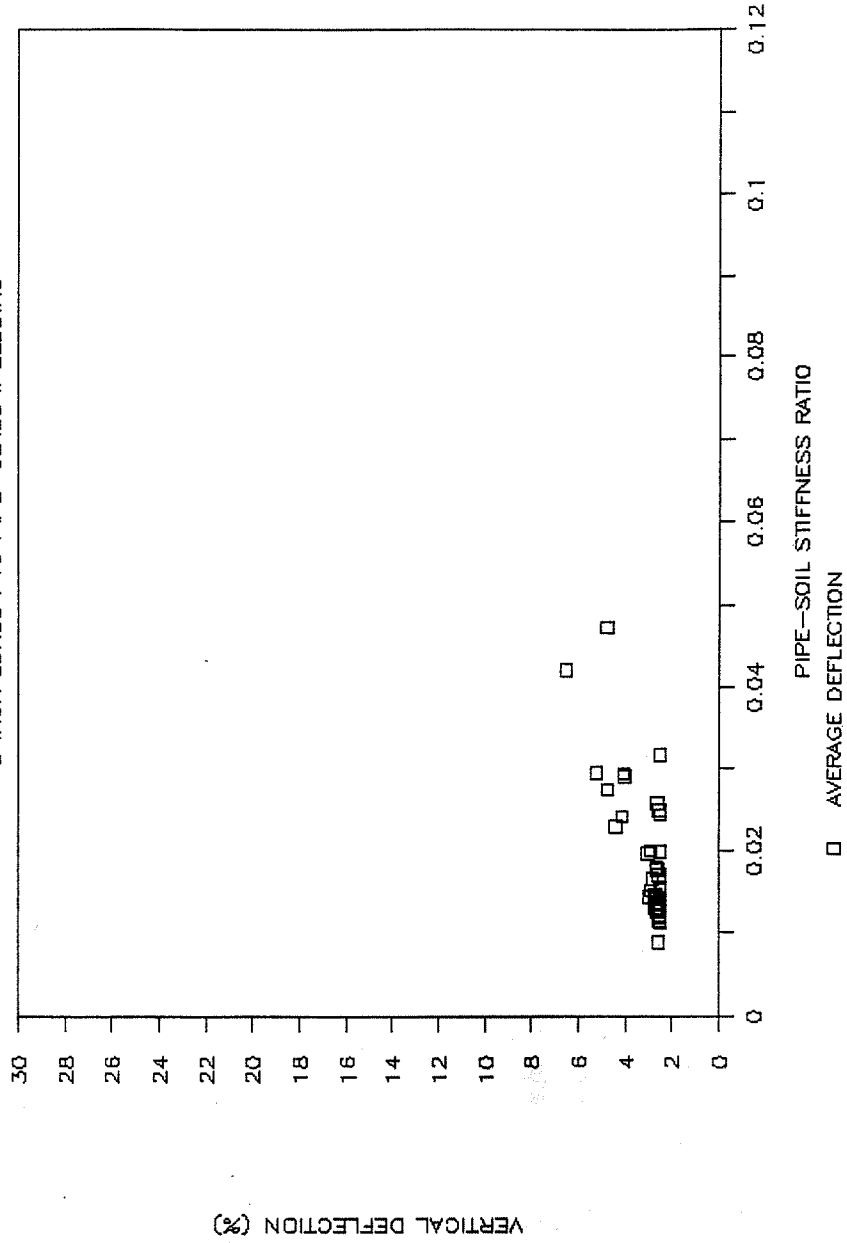


Figure A1.36 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection SDR35 PVC Pipe - Class II Bedding. (National Clay Pipe Institute)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - SAND BEDDING

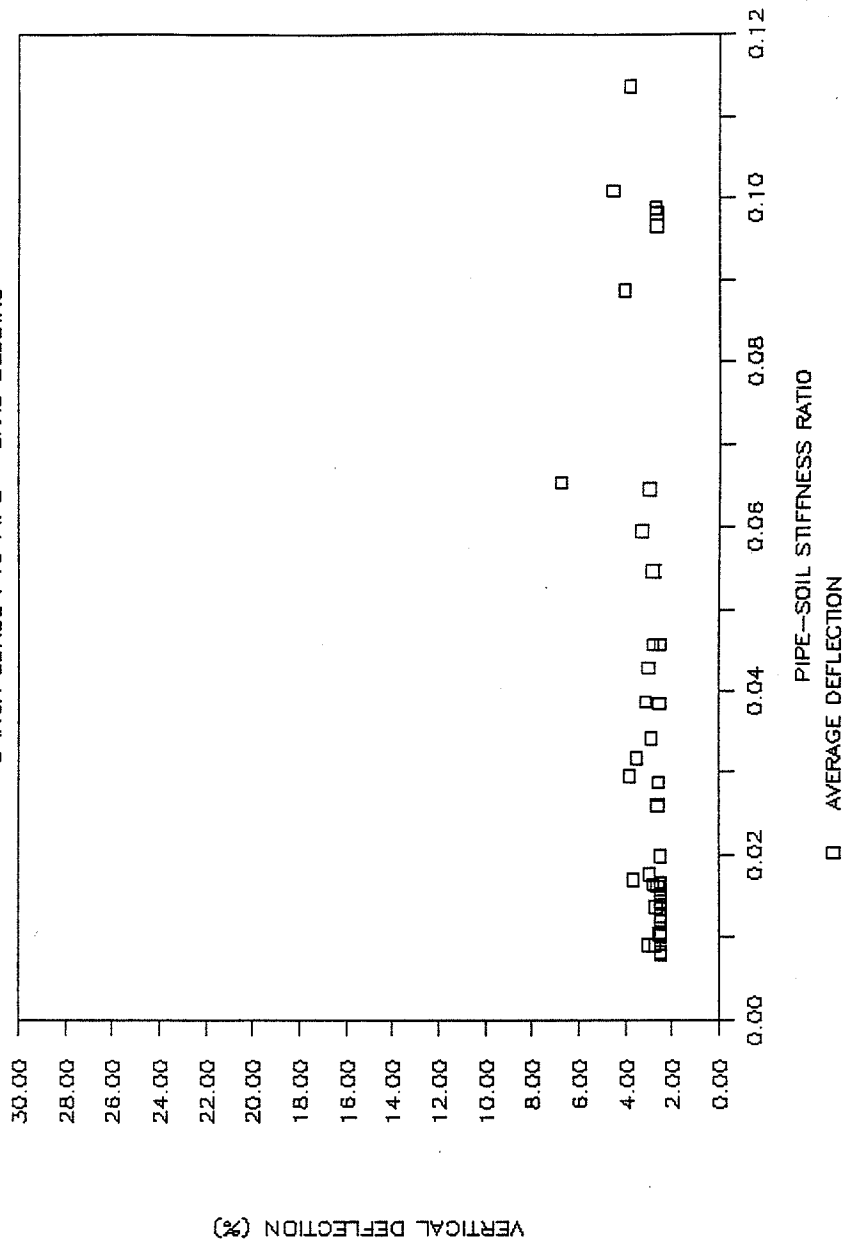


Figure A1.37 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection SDR35 PVC Pipe - Sand Bedding. (National Clay Pipe Institute)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - STONE TO SPRING

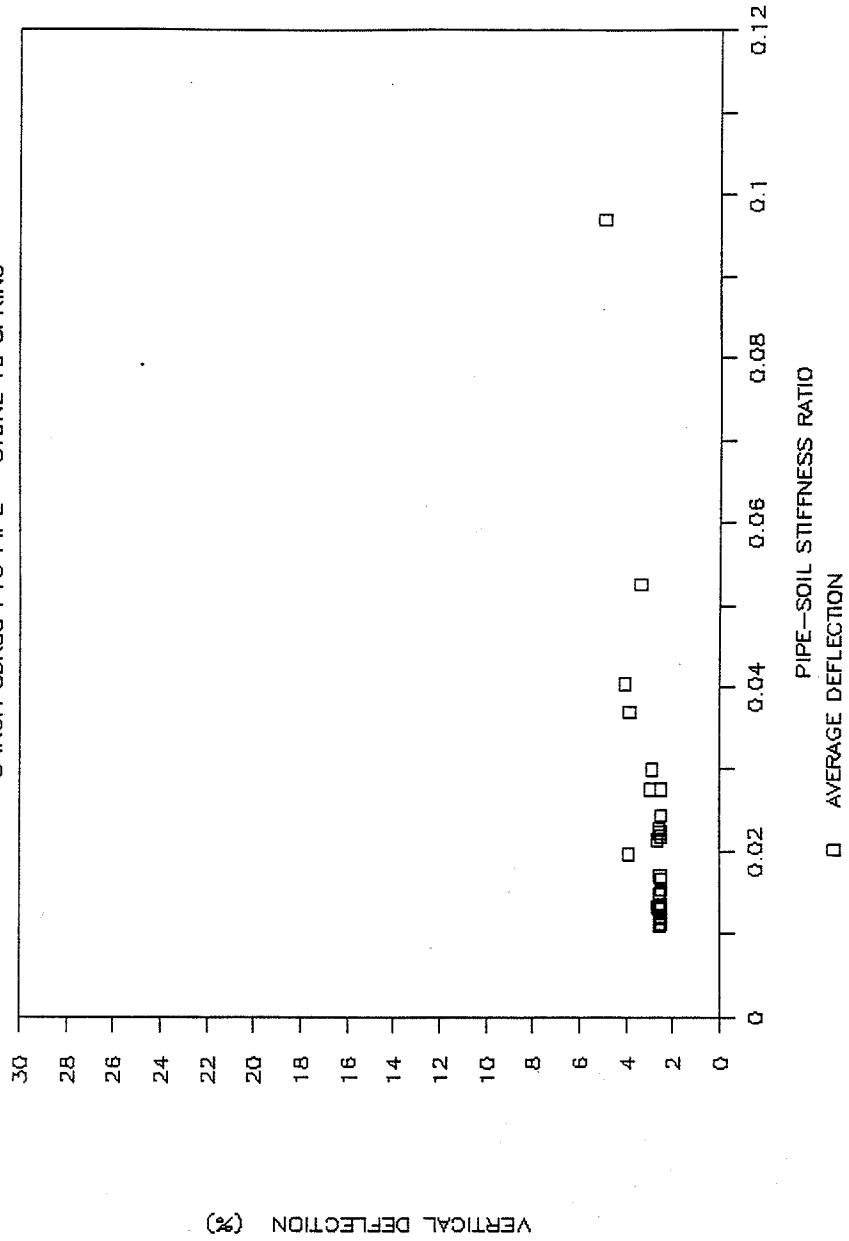


Figure A1.38 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection SDR35 PVC Pipe - Stone to Springline. (National Clay Pipe Institute)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - STONE ENCASED

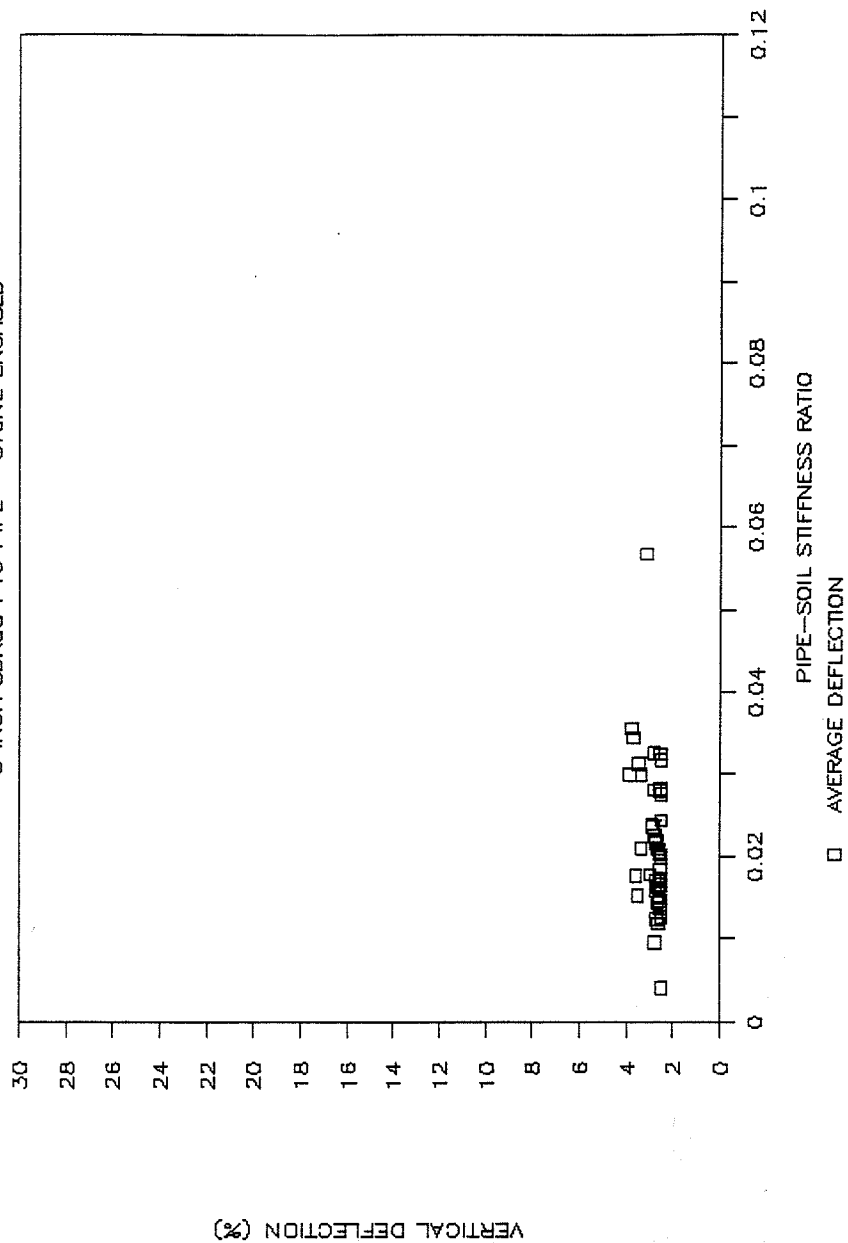


Figure A1.39 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection SDR35 PVC Pipe - Crushed Stone Envelope. (National Clay Pipe Institute)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - UNKNOWN BEDDING

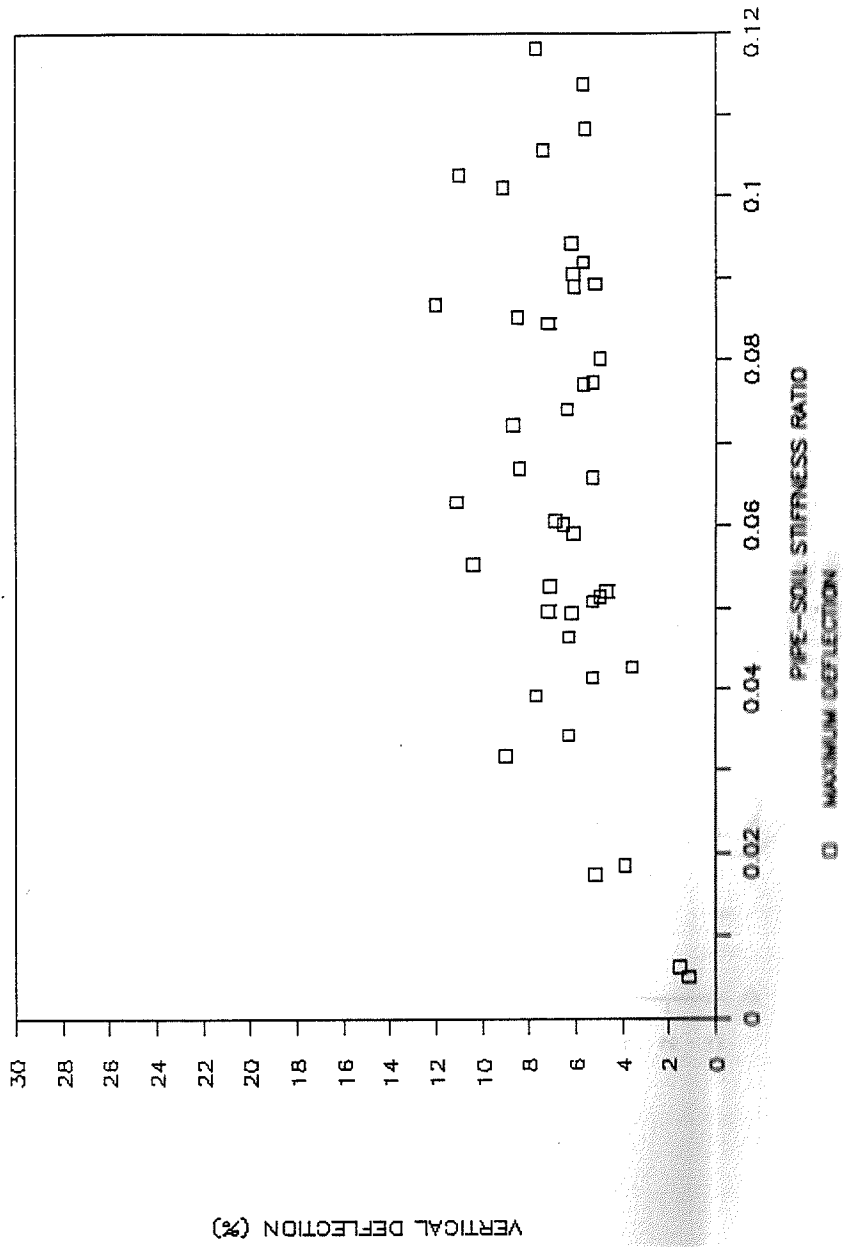


Figure A1.40 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection SDR35 PVC Pipe - Unknown Bedding. (National Clay Pipe Institute)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE-CLASS II BEDDING

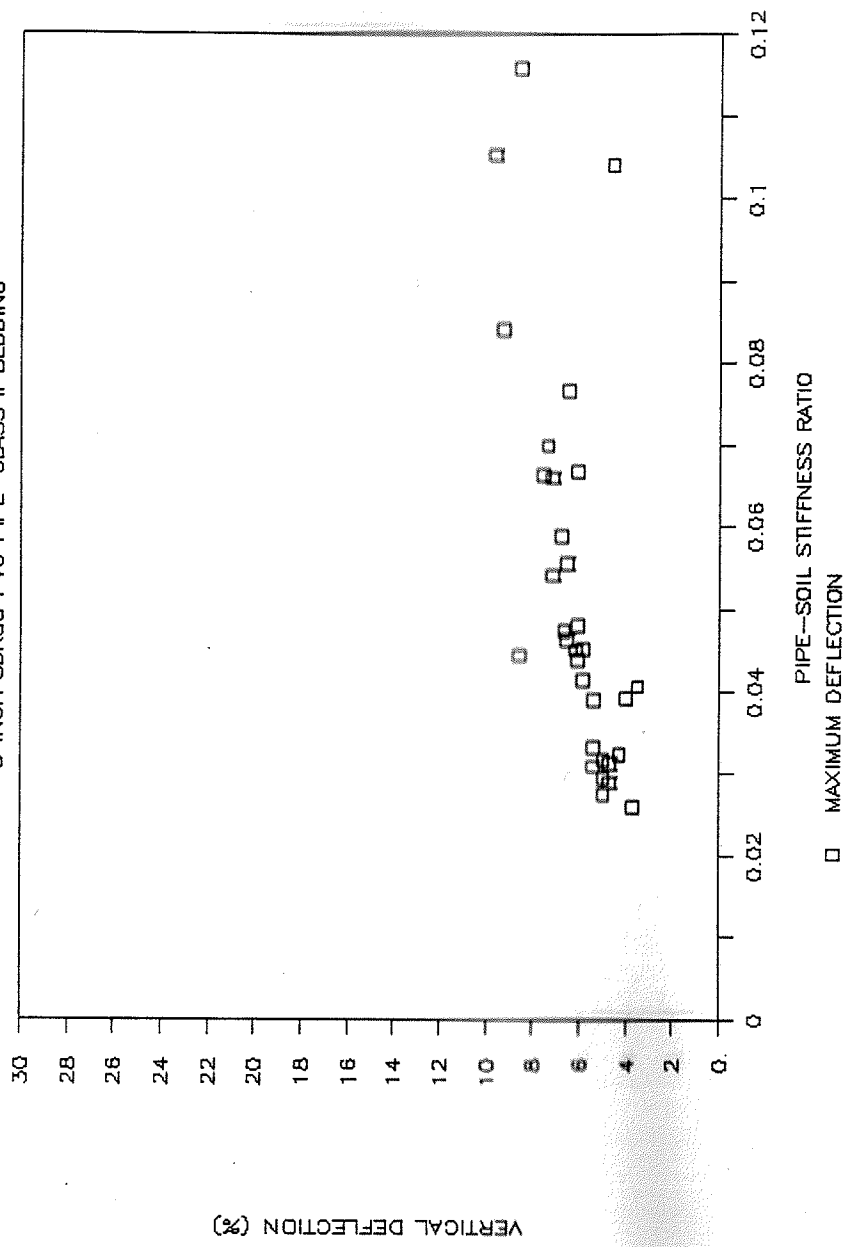


Figure A1.41 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection SDR35 PVC Pipe - Class II Bedding. (National Clay Pipe Institute)

VERTICAL DEFLECTION (%)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR41 PVC PIPE - SAND BEDDING

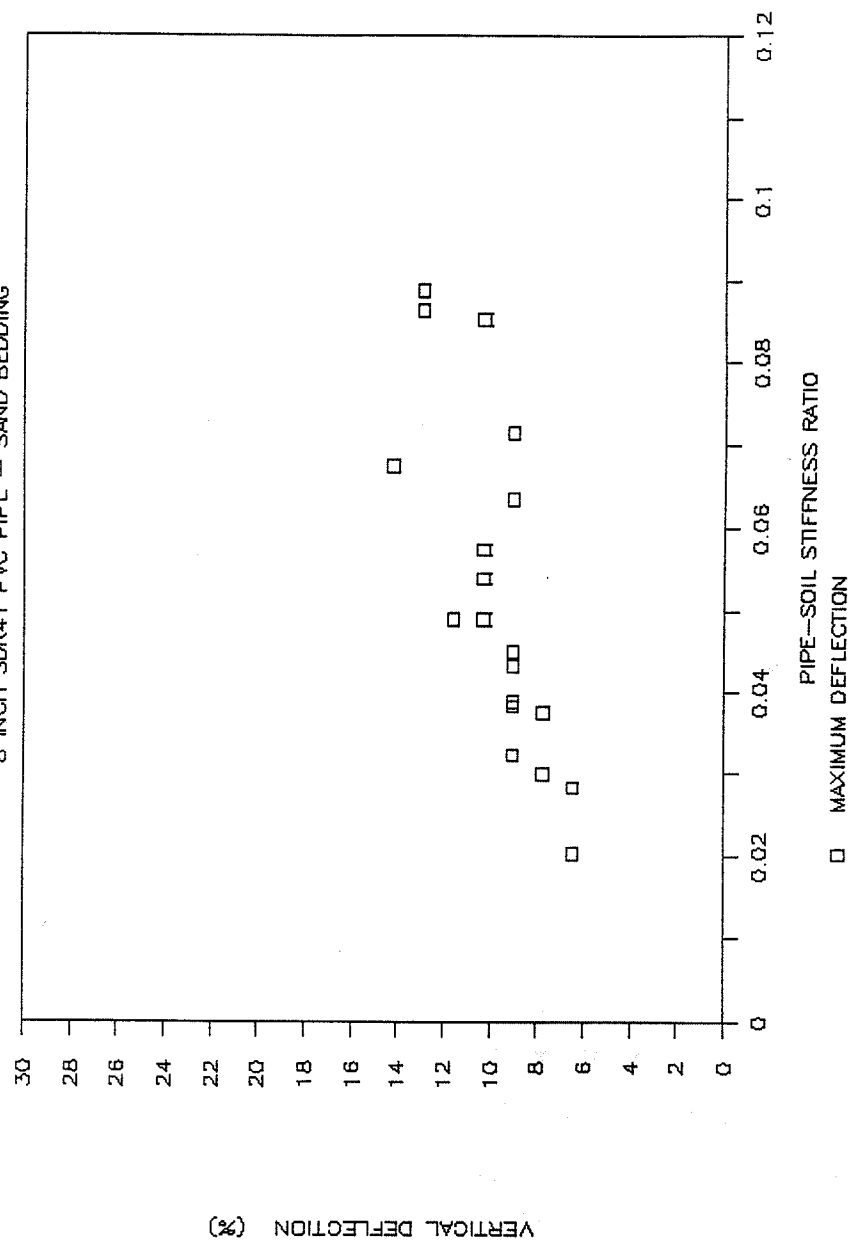


Figure A1.42 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection SDR35 PVC Pipe - Sand Bedding. (National Clay Pipe Institute)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - STONE TO SPRING

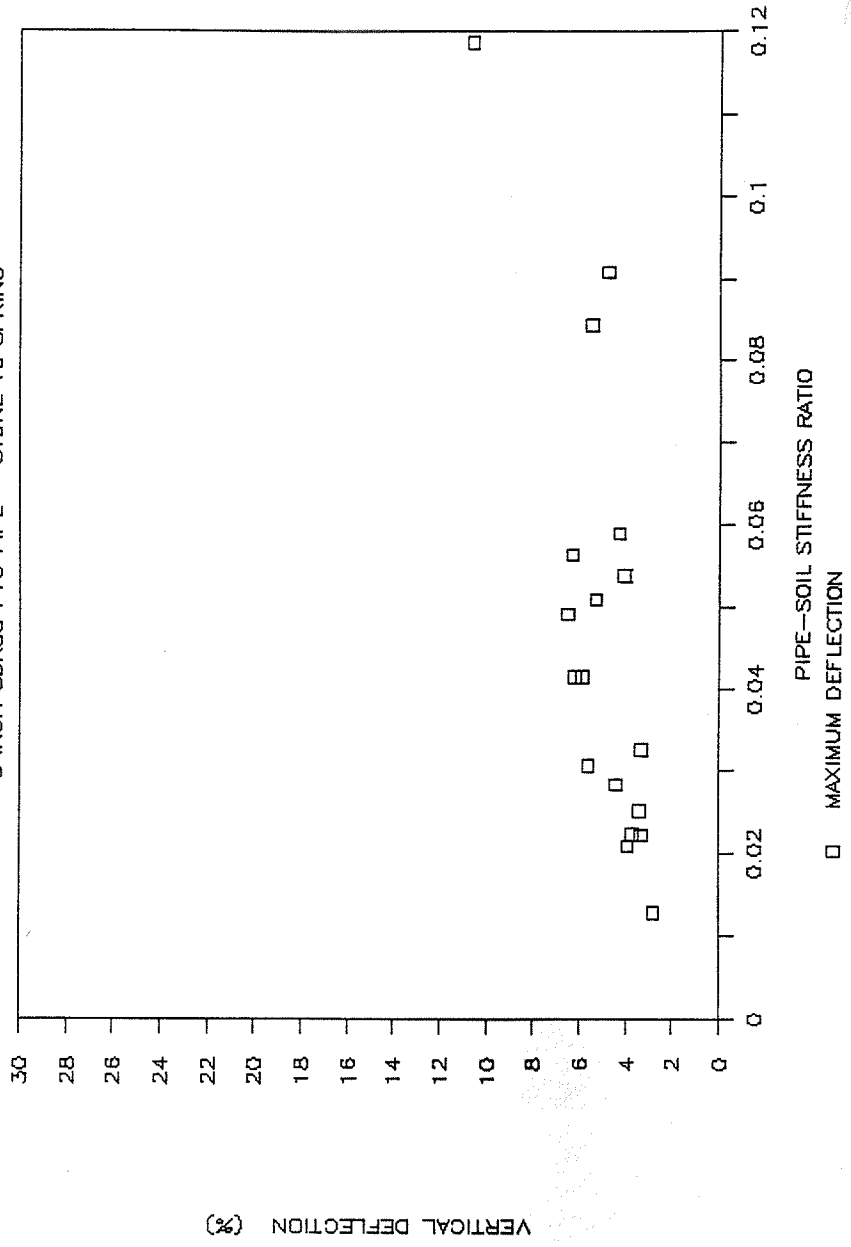


Figure A1.43 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection SDR35 PVC Pipe - Stone to Springline. (National Clay Pipe Institute)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - STONE ENCASED

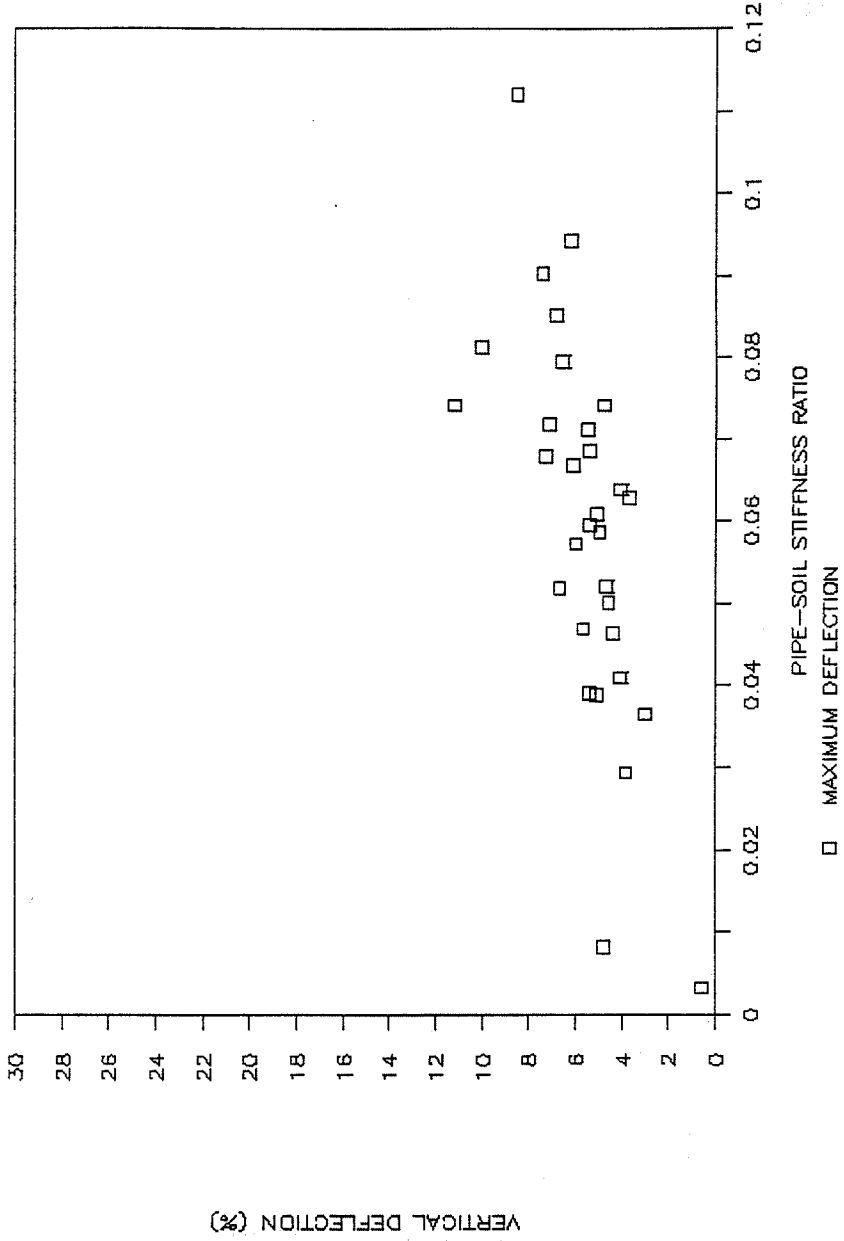


Figure A1.44 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection SDR35 PVC Pipe - Crushed Stone Envelope. (National Clay Pipe Institute)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS I BEDDING

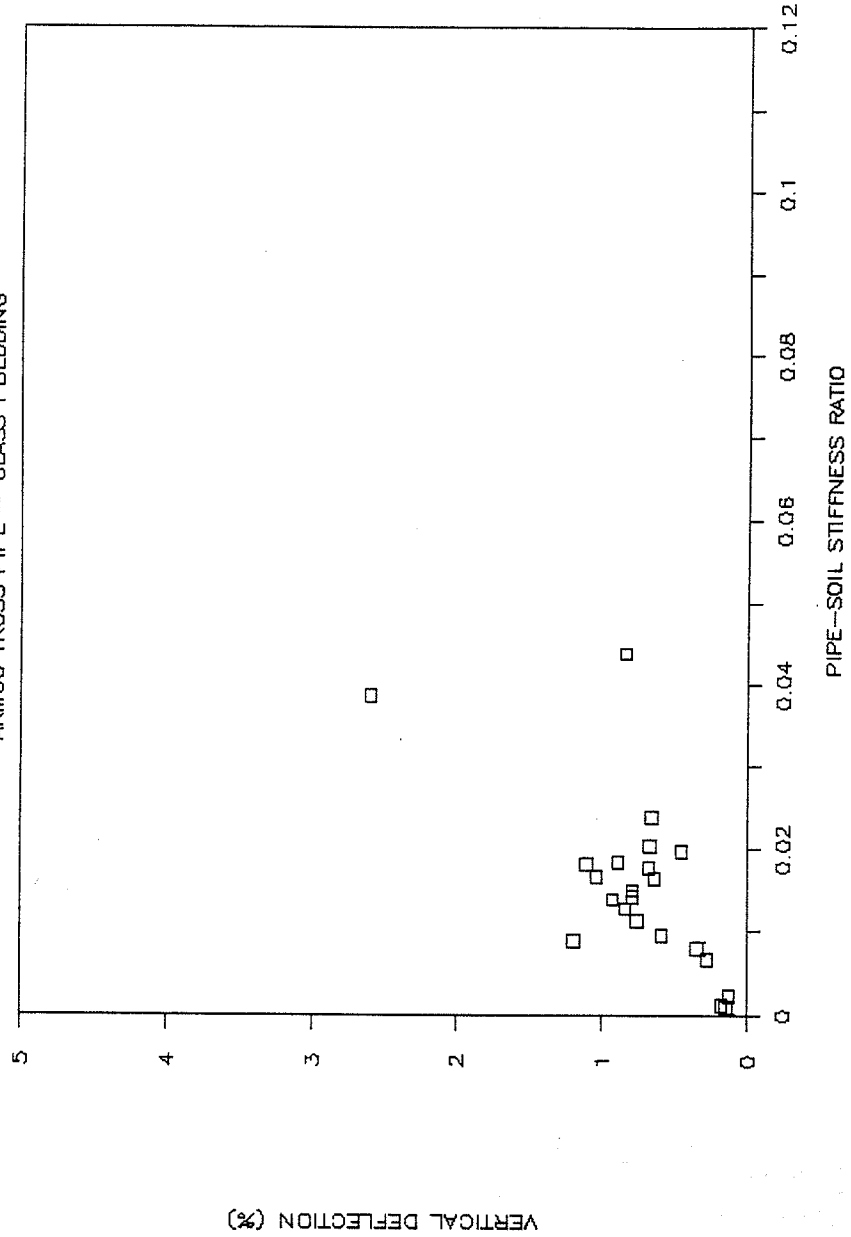


Figure A1.45 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection Truss Pipe - Class I Bedding. (Contech Construction Products Inc.)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS II BEDDING

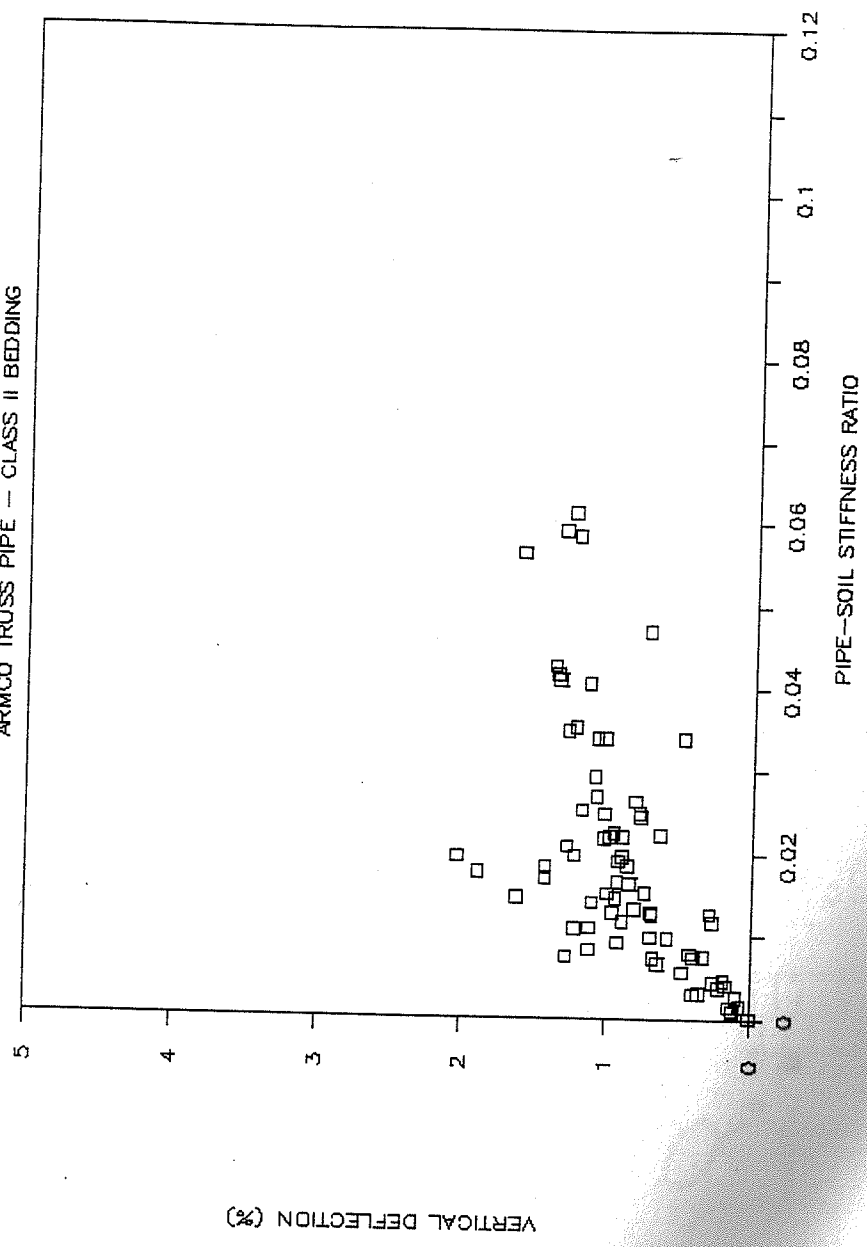


Figure A1.46 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection Truss Pipe - Class II Bedding. (Contech Construction Products Inc.)

VERTICAL DEFLECTION (%)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS III BEDDING

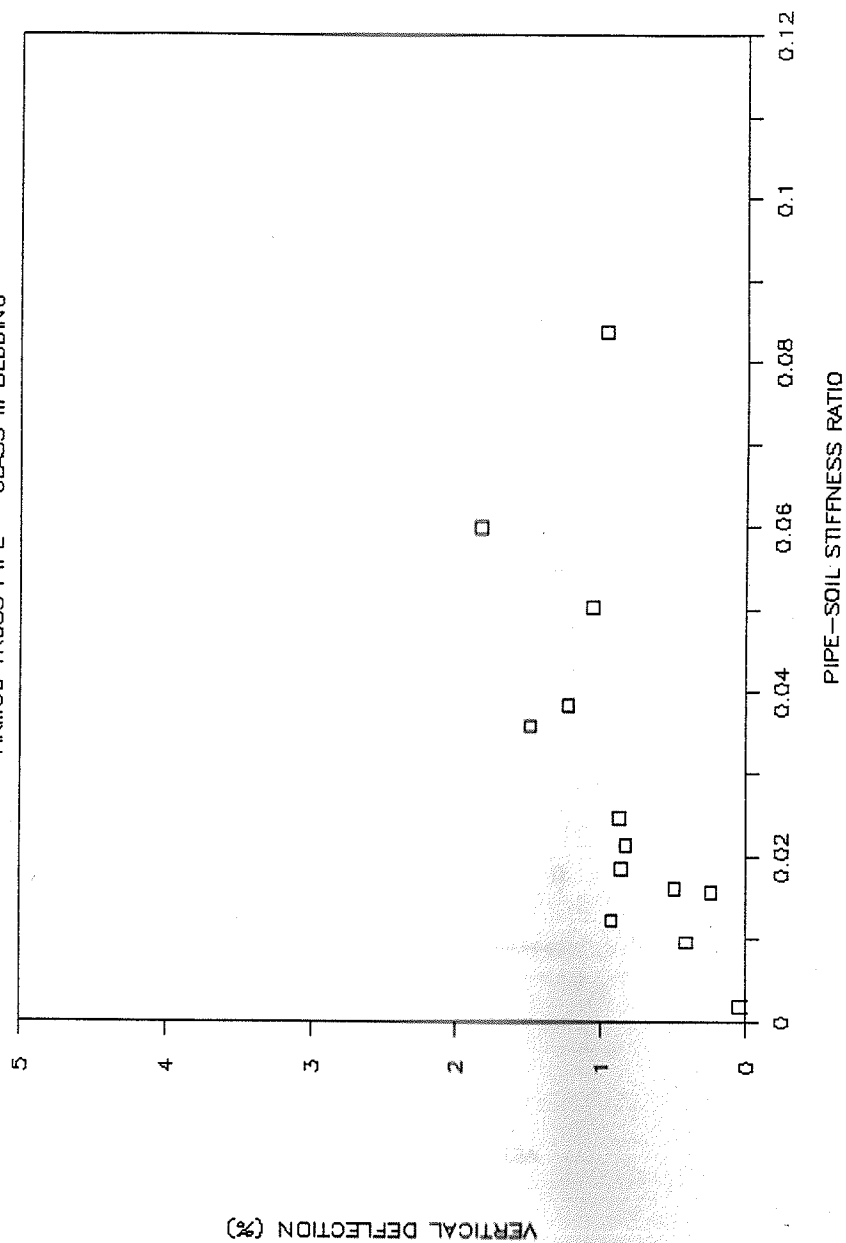


Figure A1.47 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection Truss Pipe - Class III Bedding. (Contech Construction Products Inc.)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS IV BEDDING

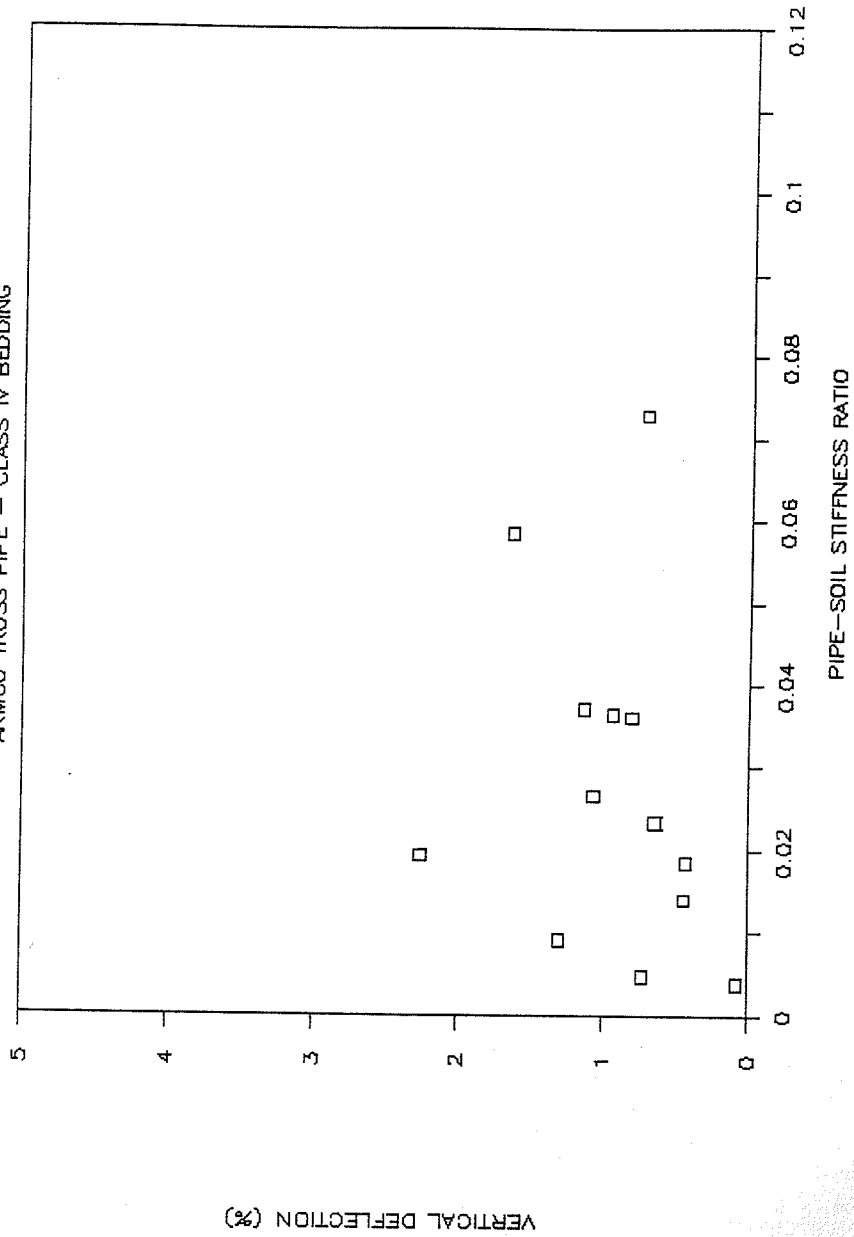


Figure A1.48 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection Truss Pipe - Class IV Bedding. (Contech Construction Products Inc.)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS I BEDDING

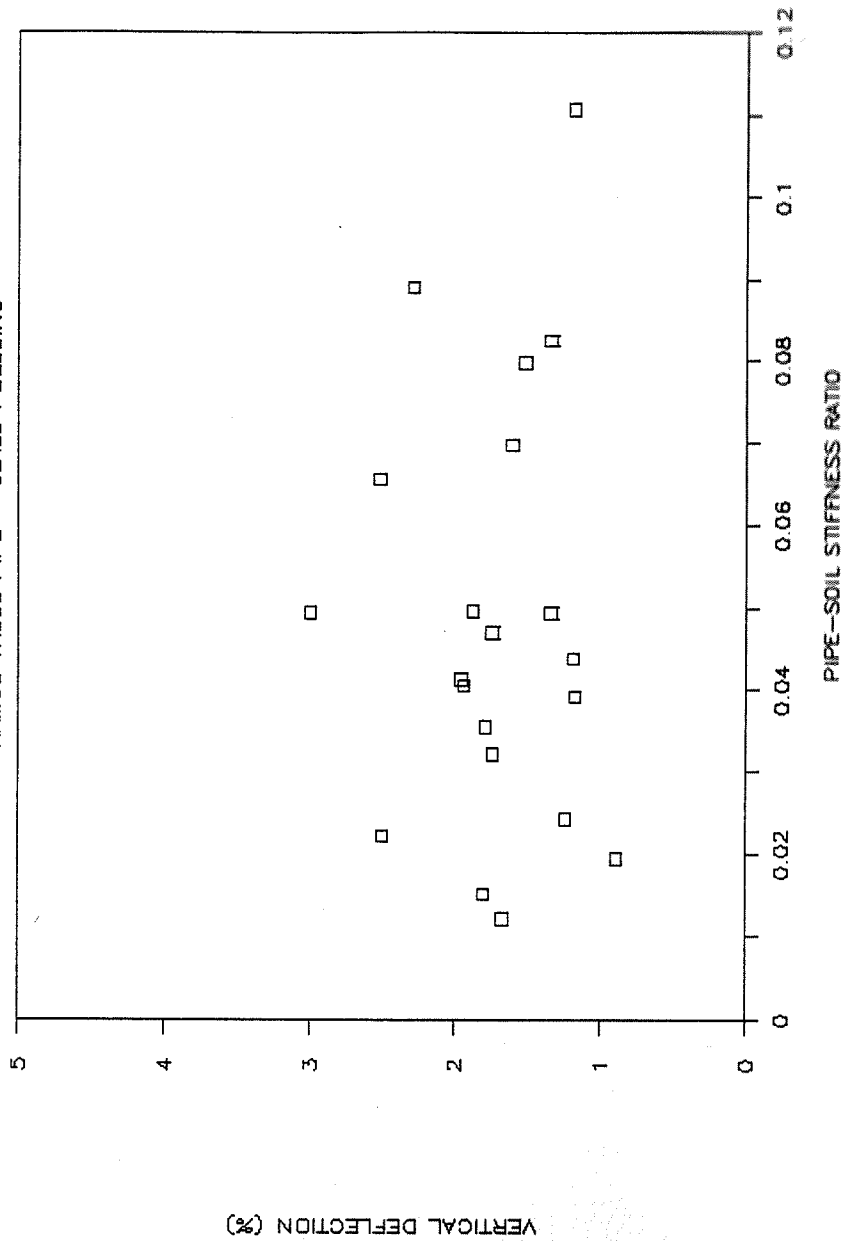


Figure Al.49 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection Truss Pipe - Class I Bedding. (Contech Construction Products Inc.)

VERTICAL DEFLECTION (%)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS II BEDDING

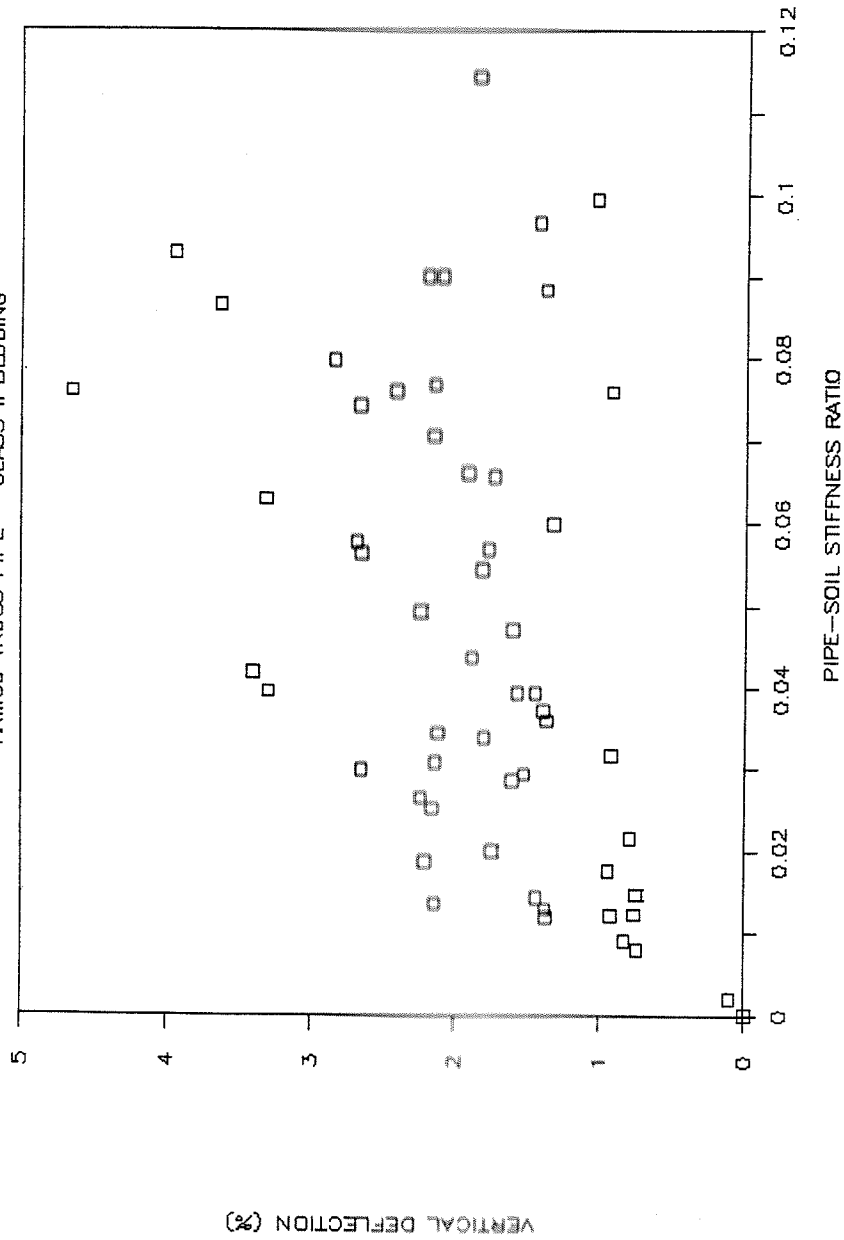


Figure A1.50 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection Truss Pipe - Class II Bedding. (Contech Construction Products Inc.)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS III BEDDING

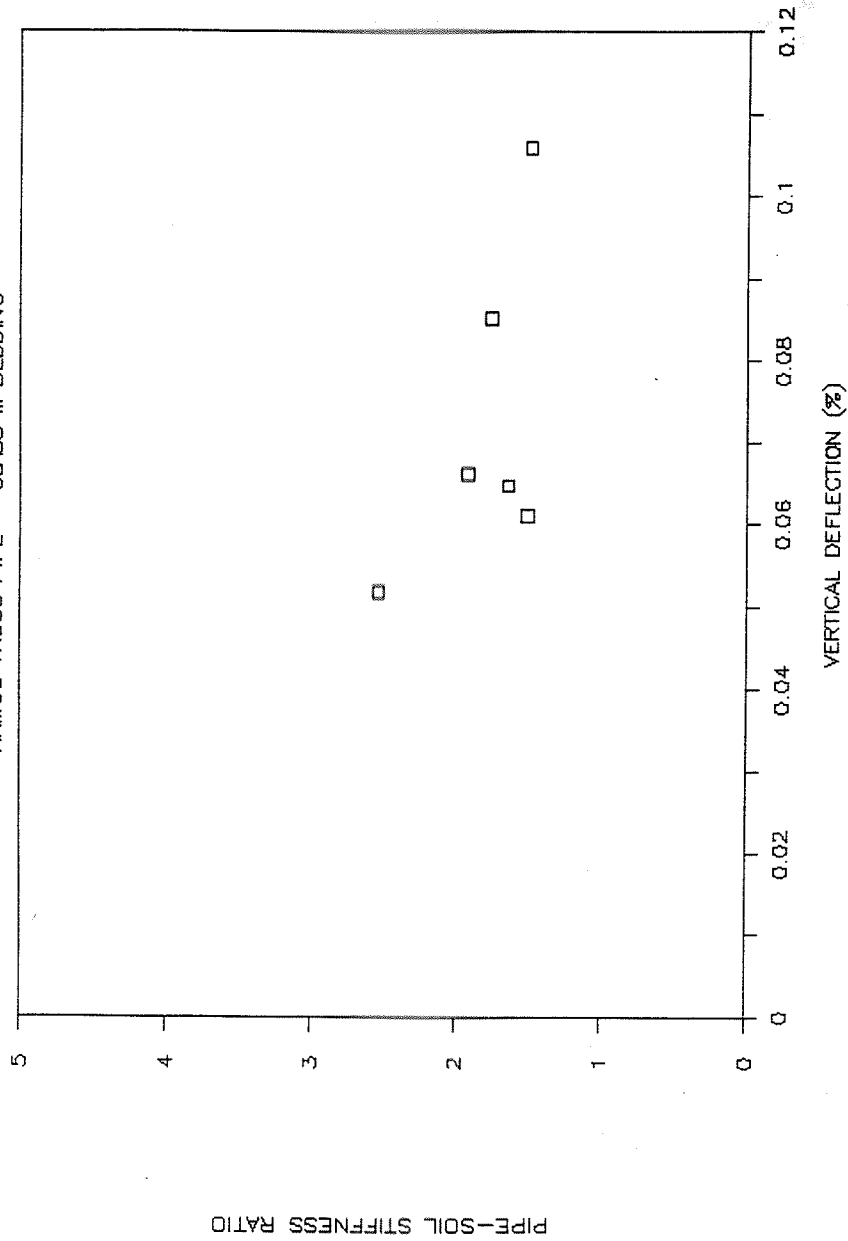


Figure A1.51 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection Truss Pipe - Class III Bedding. (Contech Construction Products Inc.)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS IV BEDDING

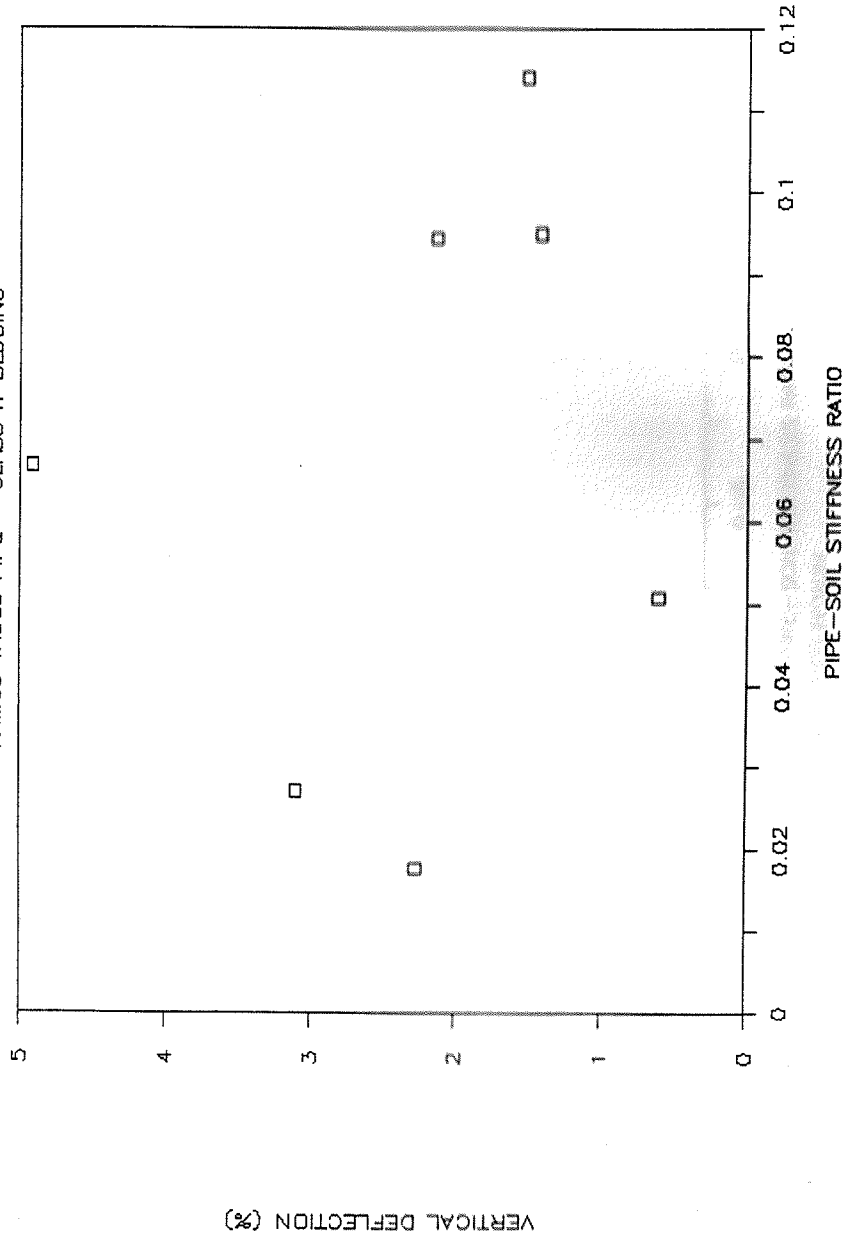


Figure A1.52 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection Truss Pipe - Class IV Bedding. (Contech Construction Products Inc.)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

PVC PIPE - SAND BEDDING

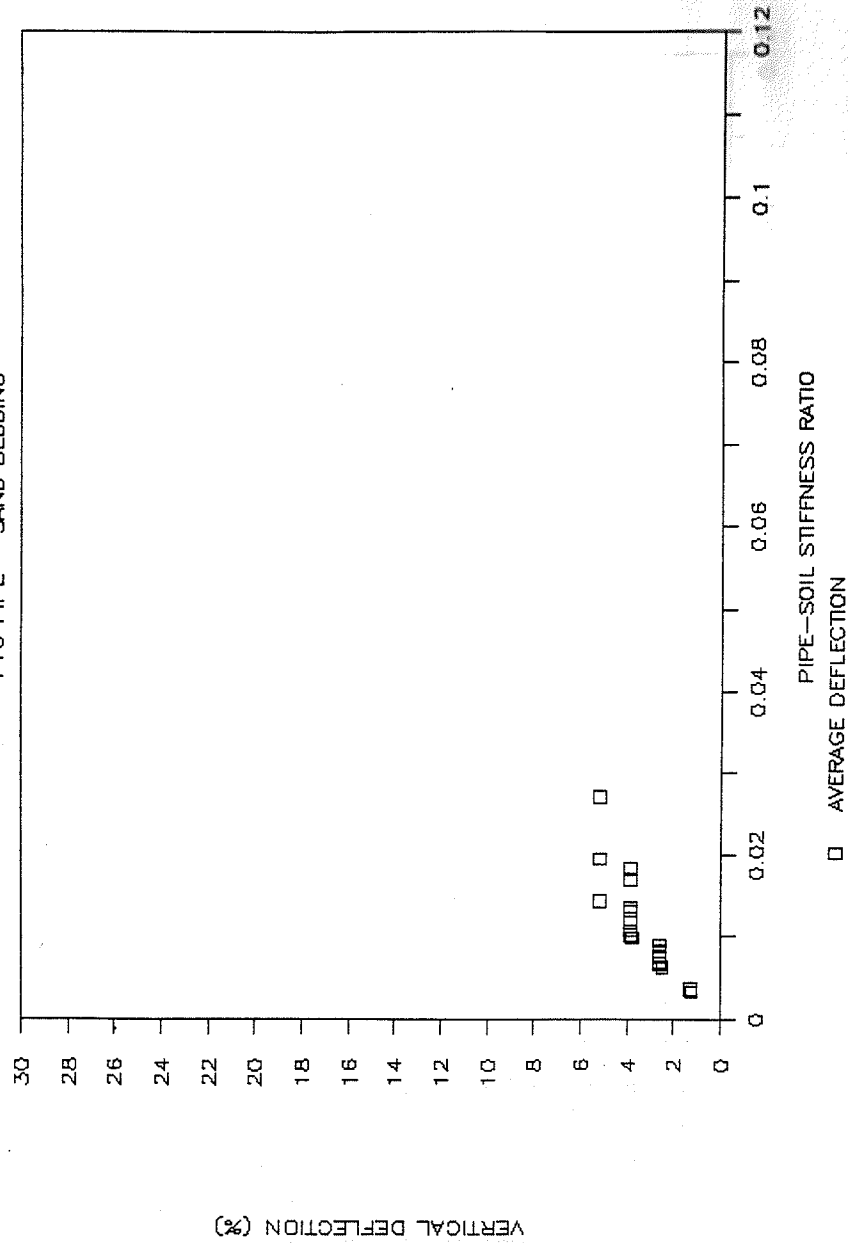


Figure A1.53 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection PVC Pipe - Sand Bedding. (Donahue & Associates Inc.)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

PVC PIPE - CRUSHED STONE ENVELOPE

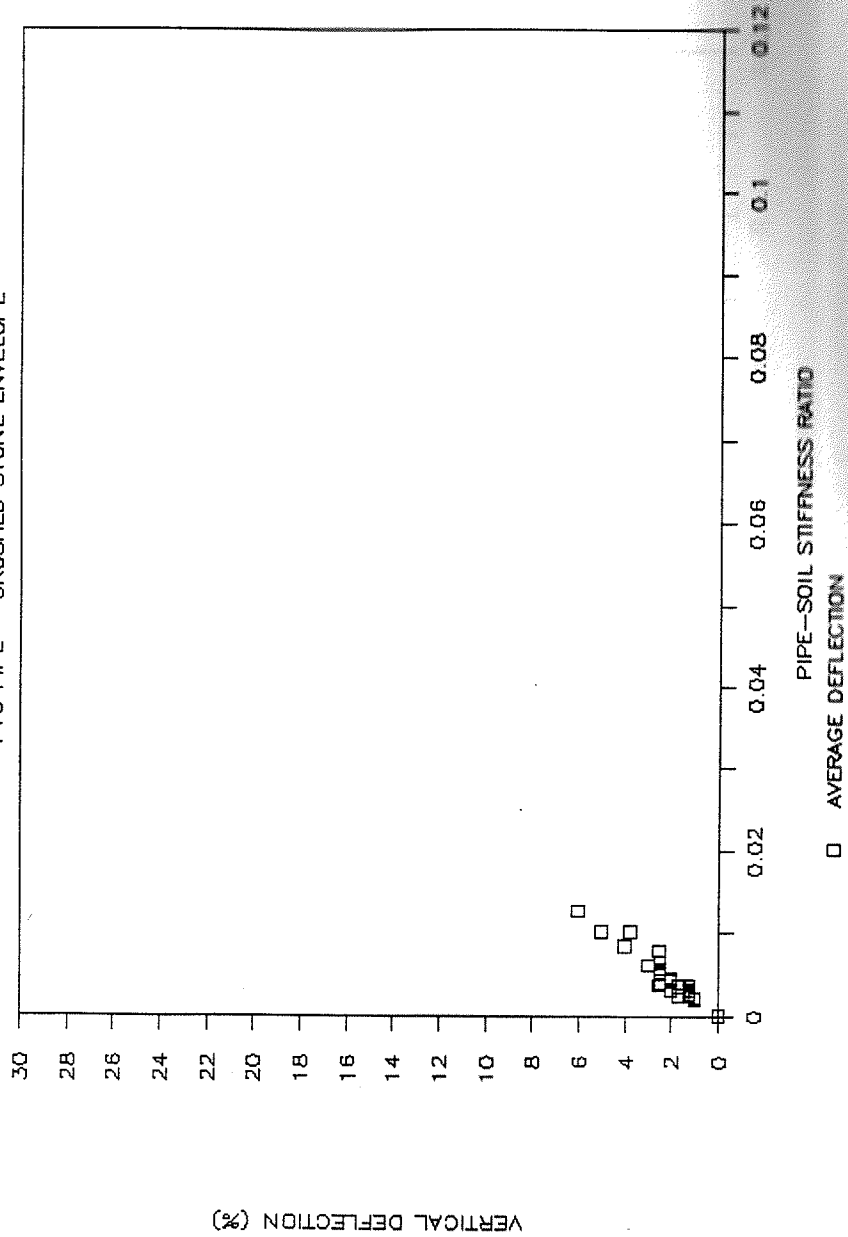


Figure A1.54 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Average Deflection PVC Pipe - Crushed Stone Envelope. (Donahue & Associates Inc.)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO

PVC PIPE - SAND BEDDING

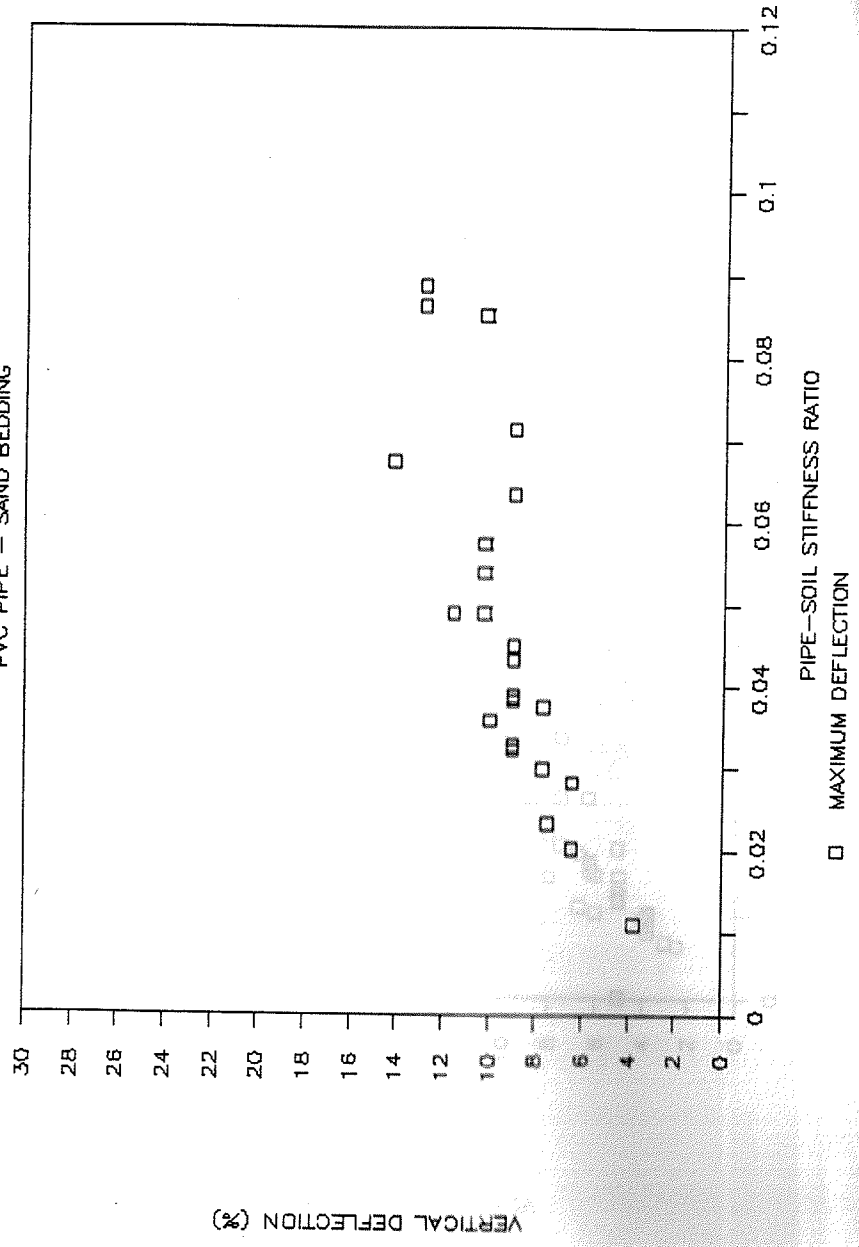


Figure A1.55 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection PVC Pipe - Sand Bedding. (Donahue & Associates Inc.)

DEFLECTION VS PIPE-SOIL STIFFNESS RATIO
PVC PIPE - CRUSHED STONE ENVELOPE

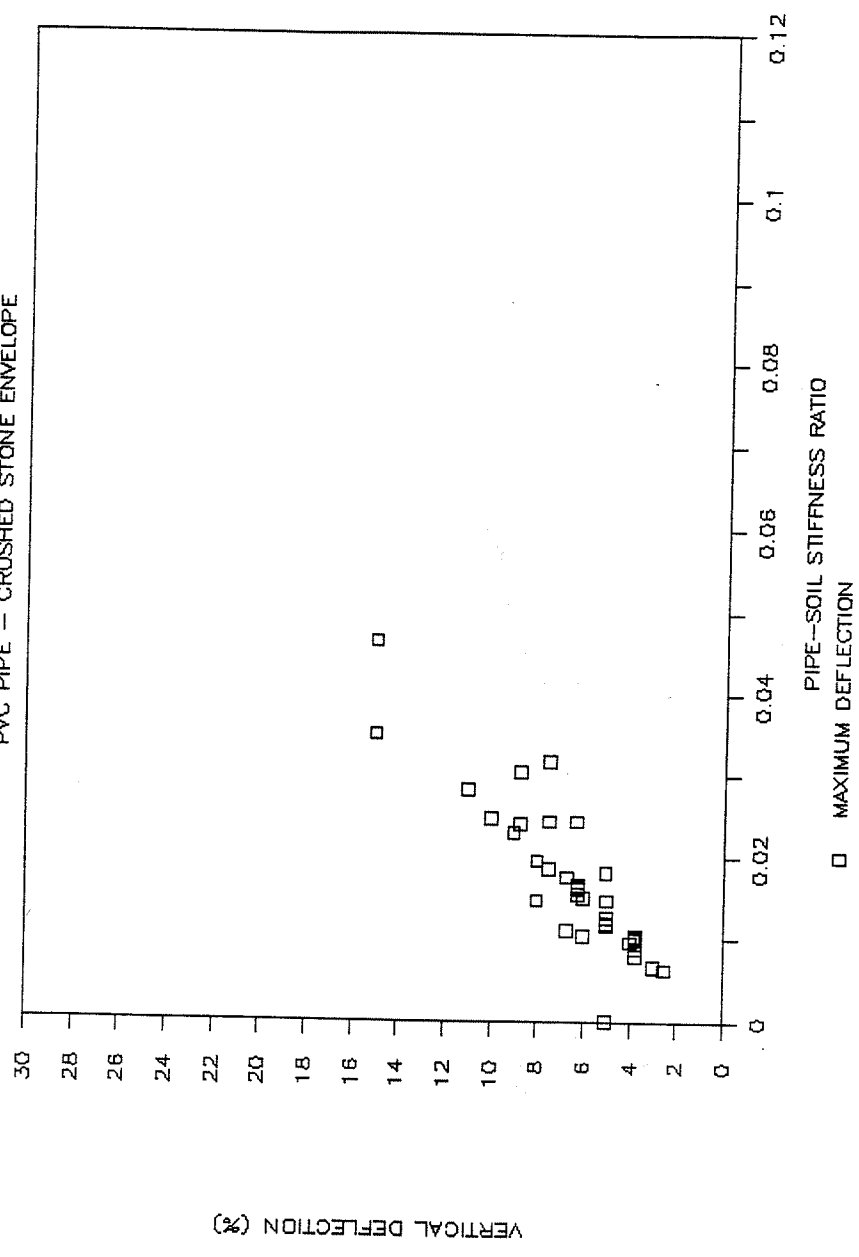


Figure A1.56 Vertical Deflection vs Pipe-Soil Stiffness Ratio - Maximum Deflection PVC Pipe - Crushed Stone Envelope. (Donahue & Associates Inc.)

VERTICAL DEFLECTION (%)

E' VS DEPTH OF COVER 8 INCH SDR35 PVC PIPE - UNKNOWN BEDDING

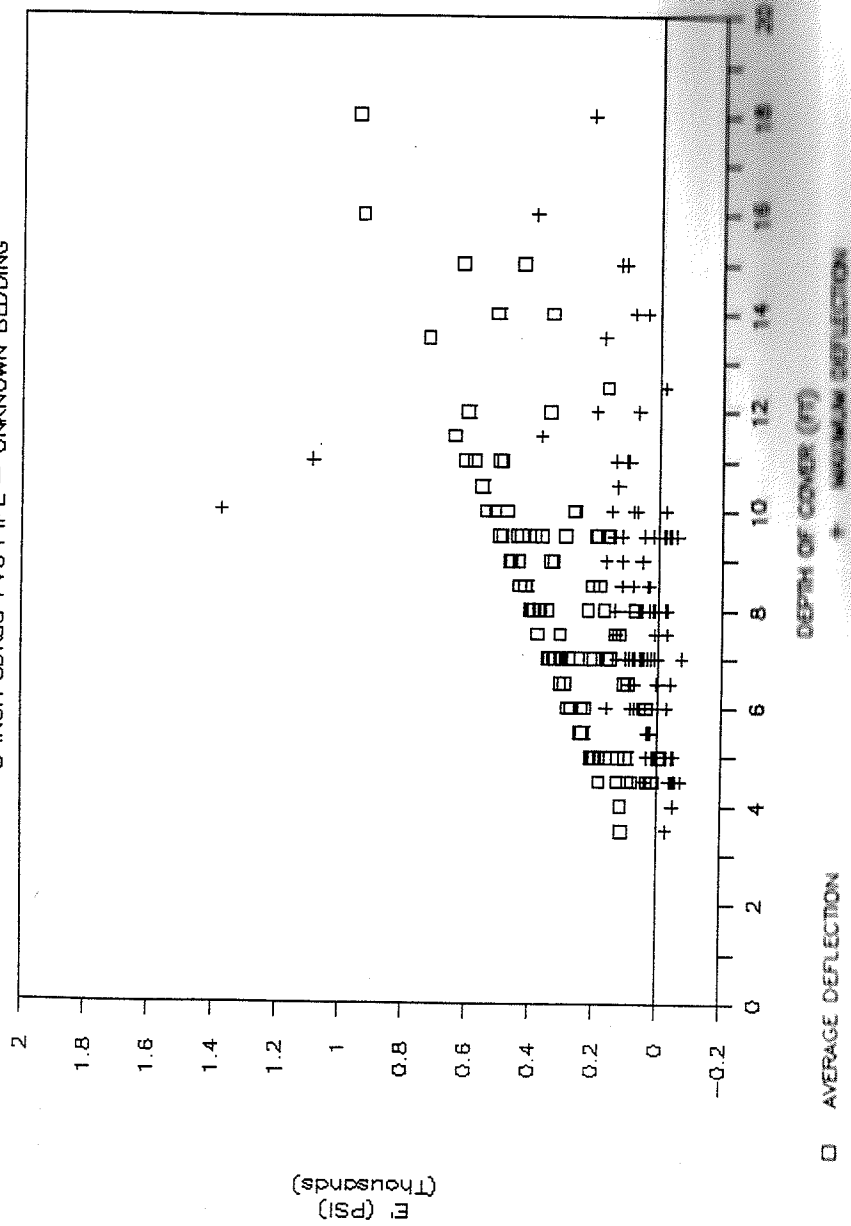


Figure A1.57 E' vs Depth of Cover
8 inch SDR35 PVC Pipe
Unknown Bedding.
(National Clay Pipe Institute)

E' VS DEPTH OF COVER

8 INCH SDR35 PVC PIPE—CLASS II BEDDING

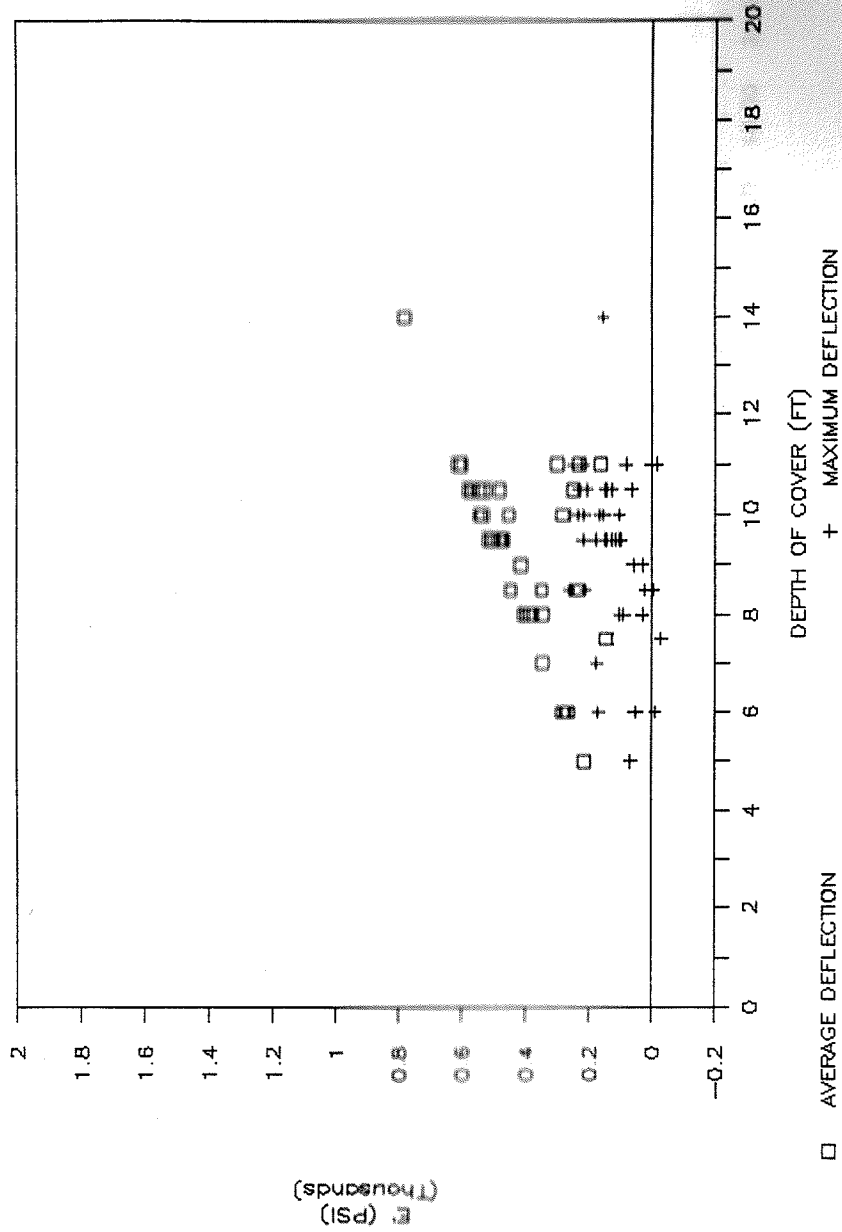
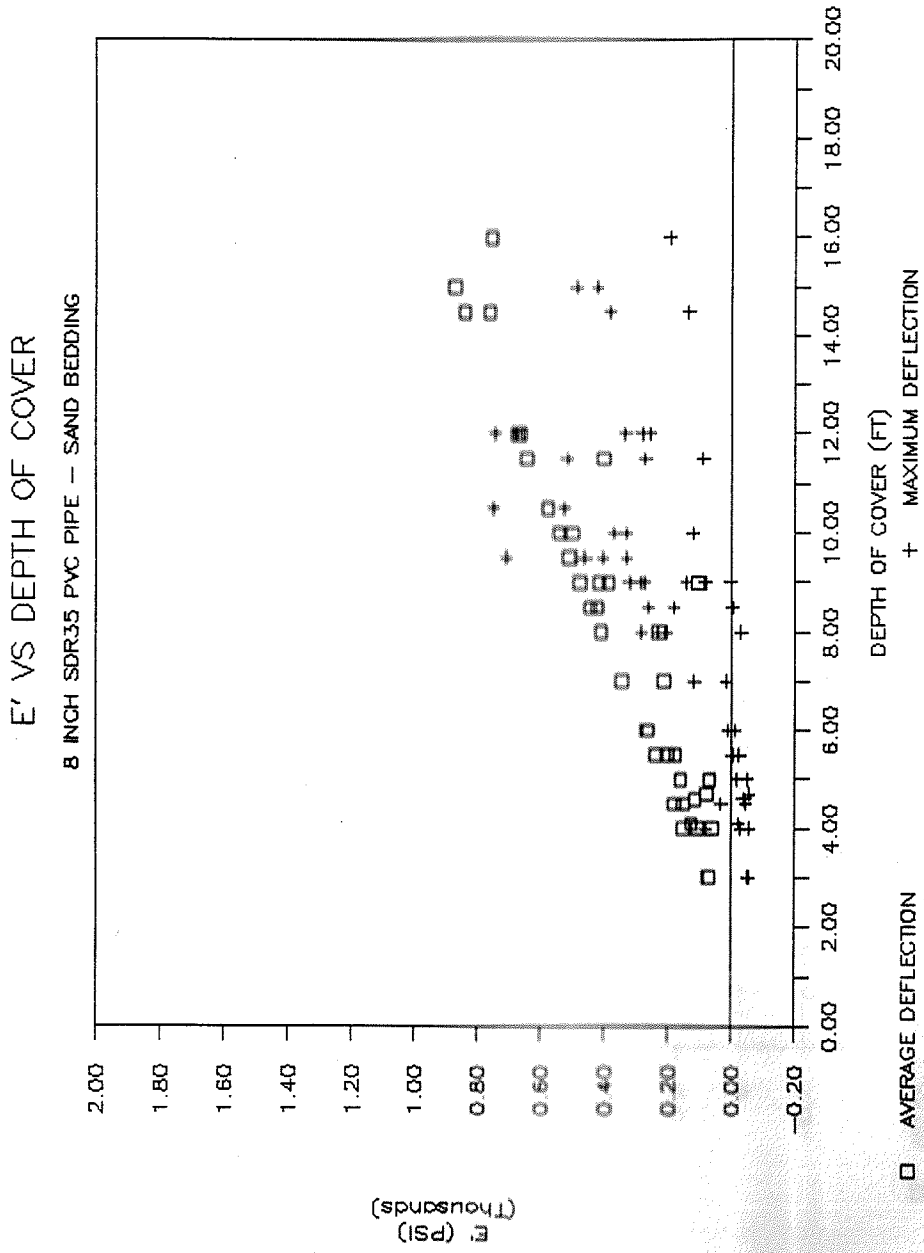


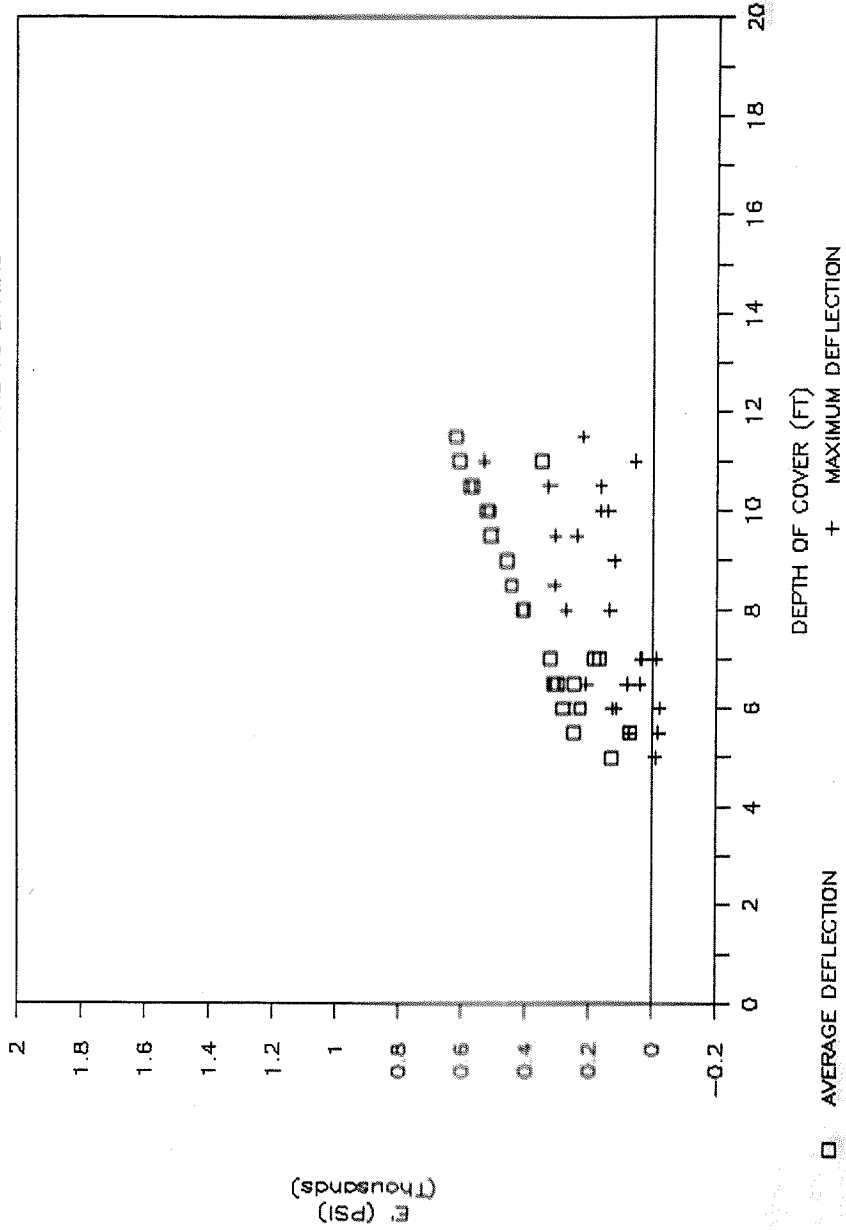
Figure A1.58 E' vs Depth of Cover
8 inch SDR35 PVC Pipe
Class II Bedding.
(National Clay Pipe Institute)



**Figure A1.59 E' vs Depth of Cover
8 inch SDR35 PVC Pipe
Sand Bedding.
(National Clay Pipe Institute)**

E' VS DEPTH OF COVER

8 INCH SDR35 PVC PIPE - STONE TO SPRING



**Figure A1.60 E' vs Depth of Cover
8 inch SDR35 PVC Pipe
Crushed Stone to the Springline.
(National Clay Pipe Institute)**

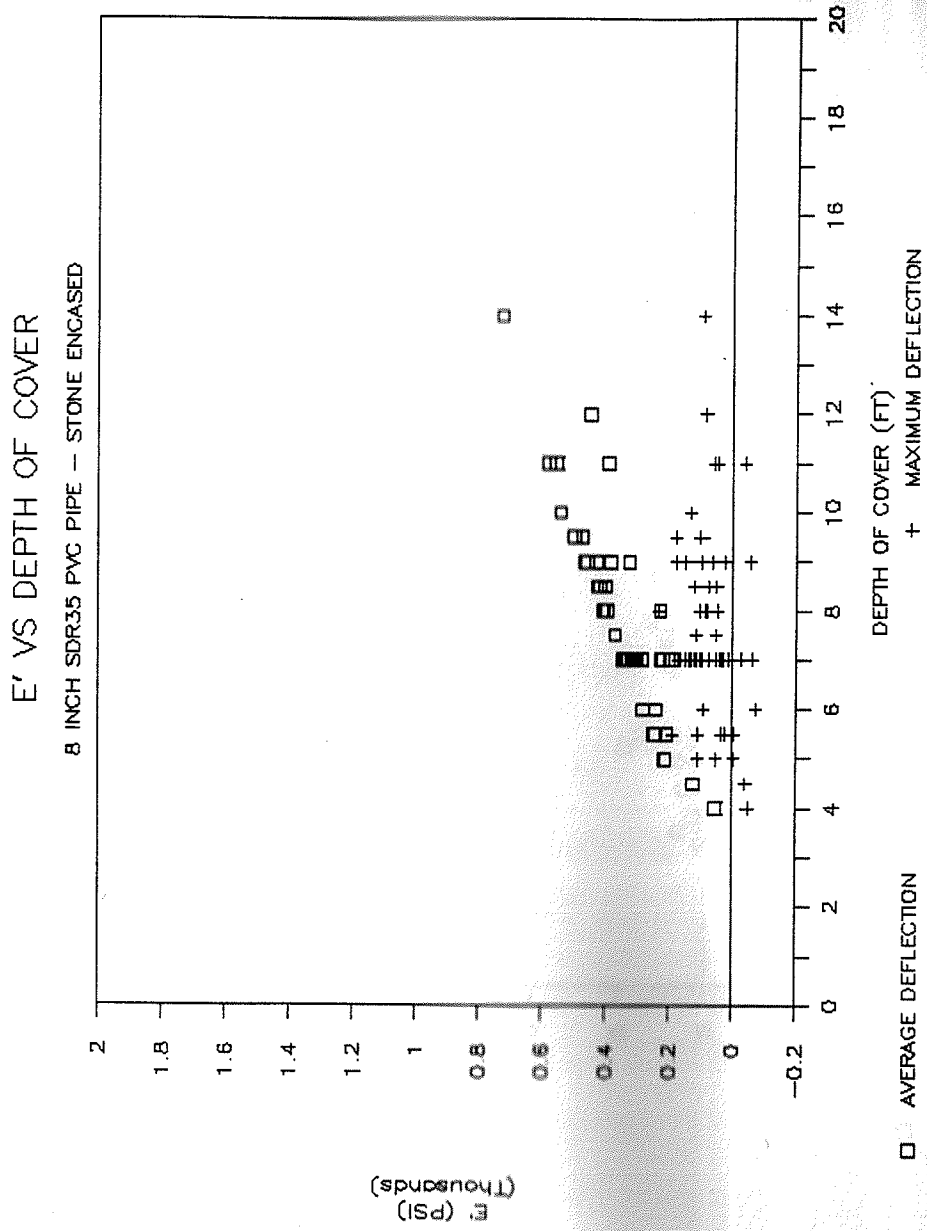
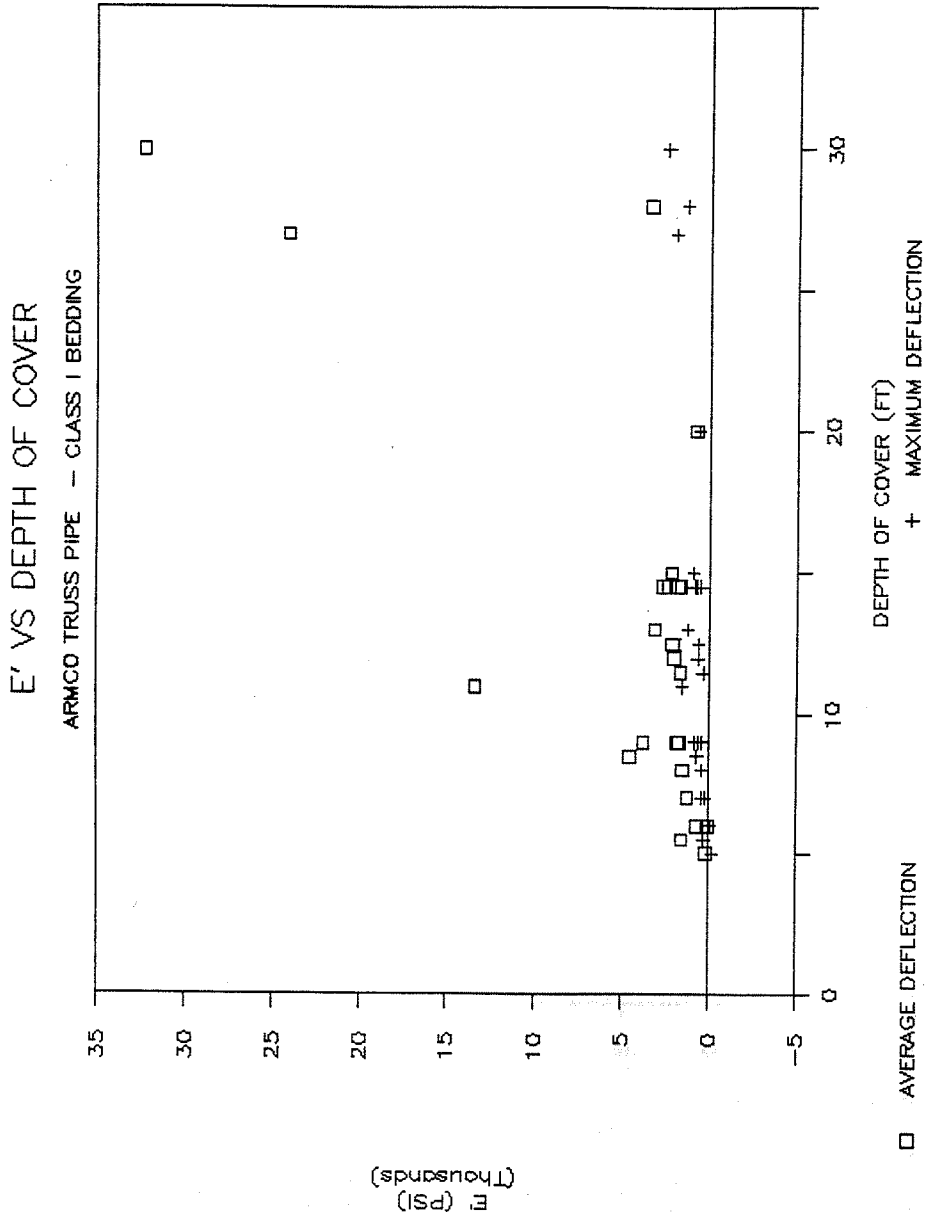
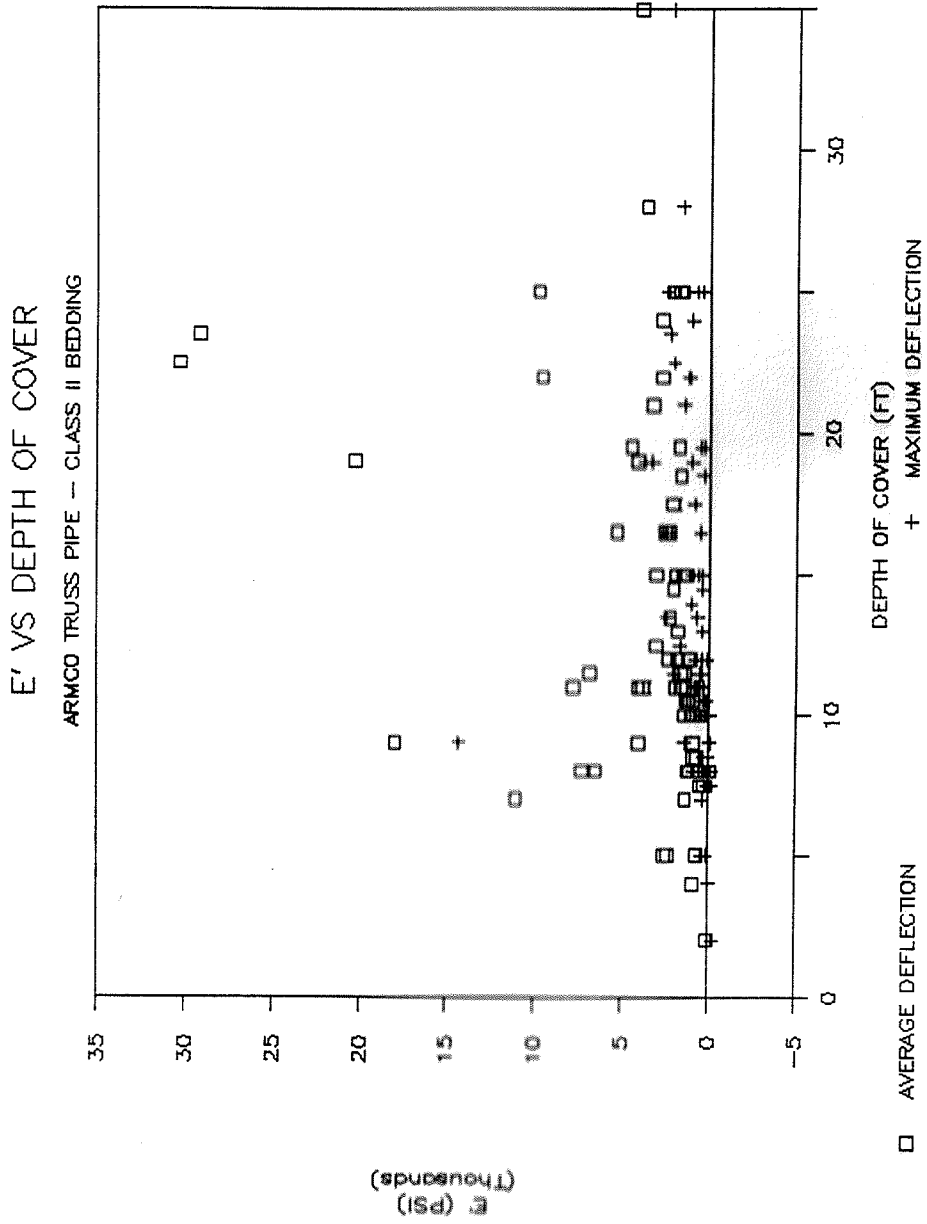


Figure A1.61 E' vs Depth of Cover
8 inch SDR35 PVC Pipe
Crushed Stone Envelope.
(National Clay Pipe Institute)



**Figure A1.62 E' vs Depth of Cover
Truss Pipe - Class I Bedding.
(Contech Construction Products Inc.)**



**Figure A1.63 E' vs Depth of Cover
Truss Pipe - Class II Bedding.
(Contech Construction Products Inc.)**

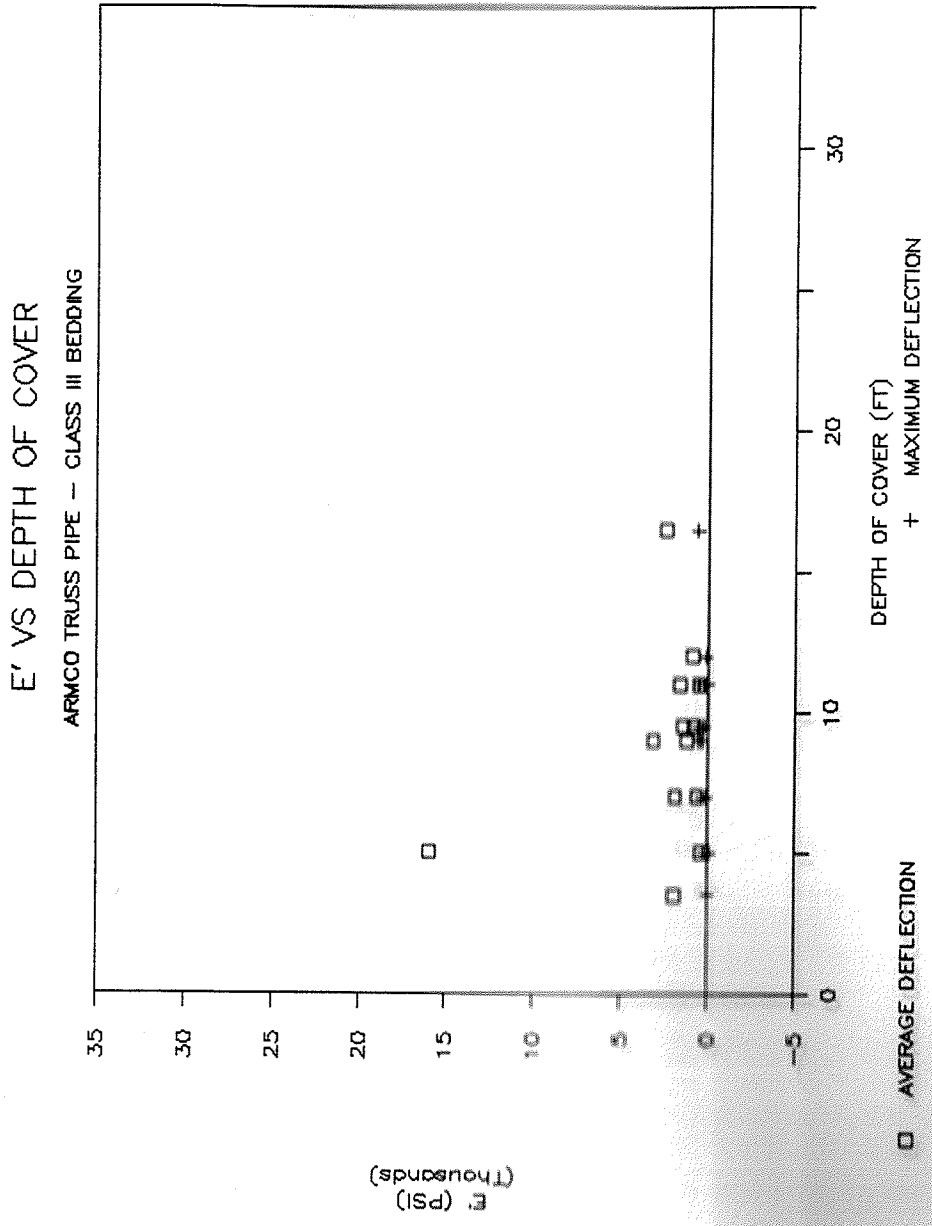


Figure A1.64 E' vs Depth of Cover
Truss Pipe - Class III Bedding.
(Contech Construction Products Inc.)

E' VS DEPTH OF COVER

ARMCO TRUSS PIPE - CLASS IV BEDDING

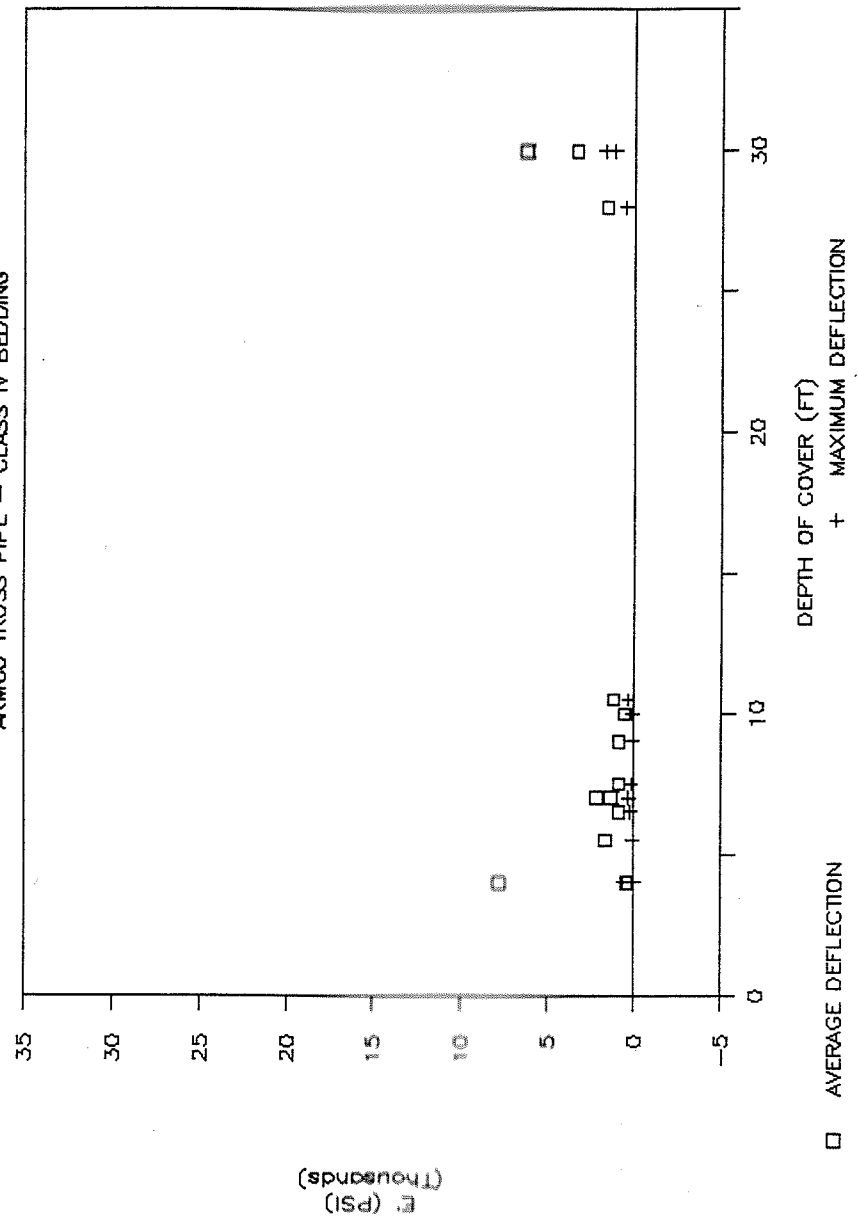
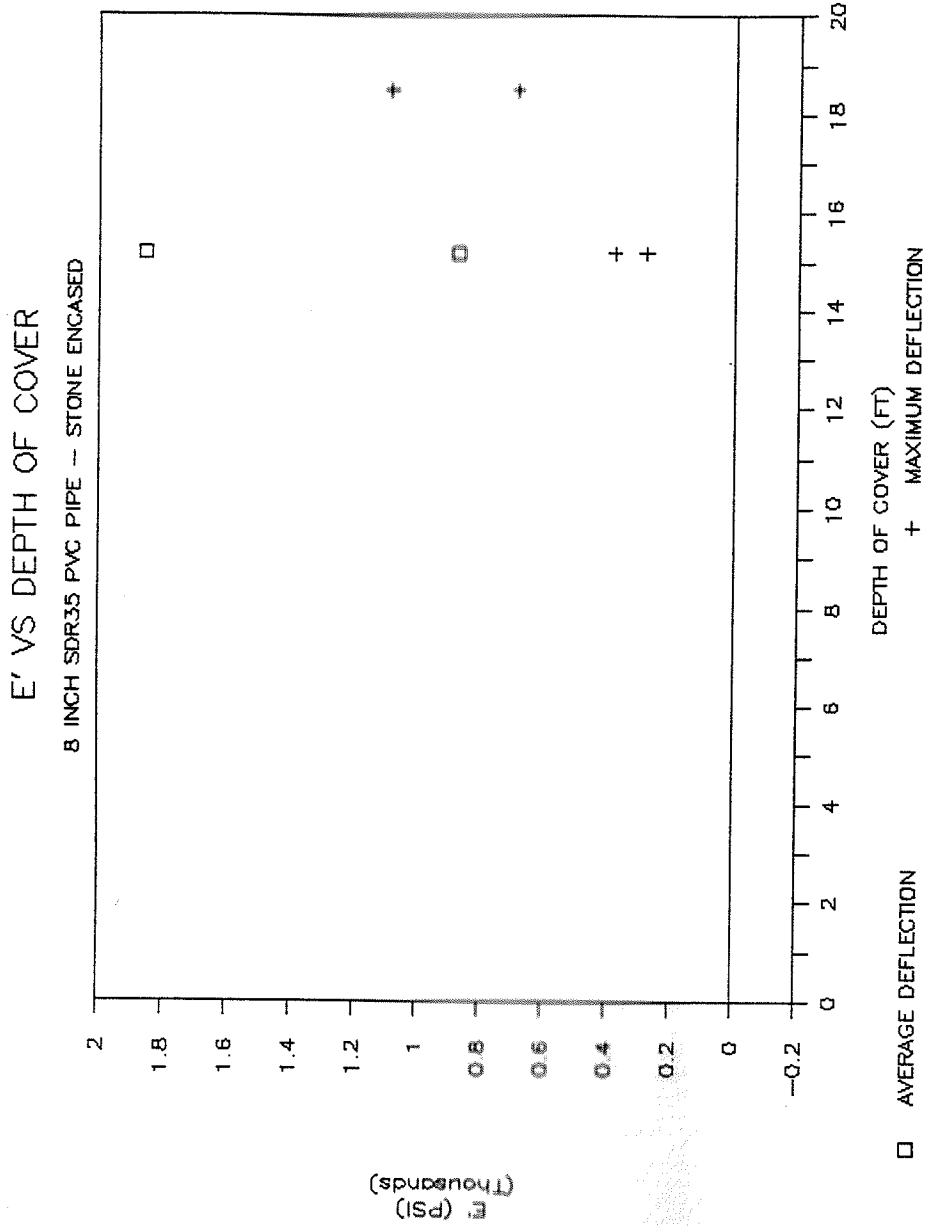
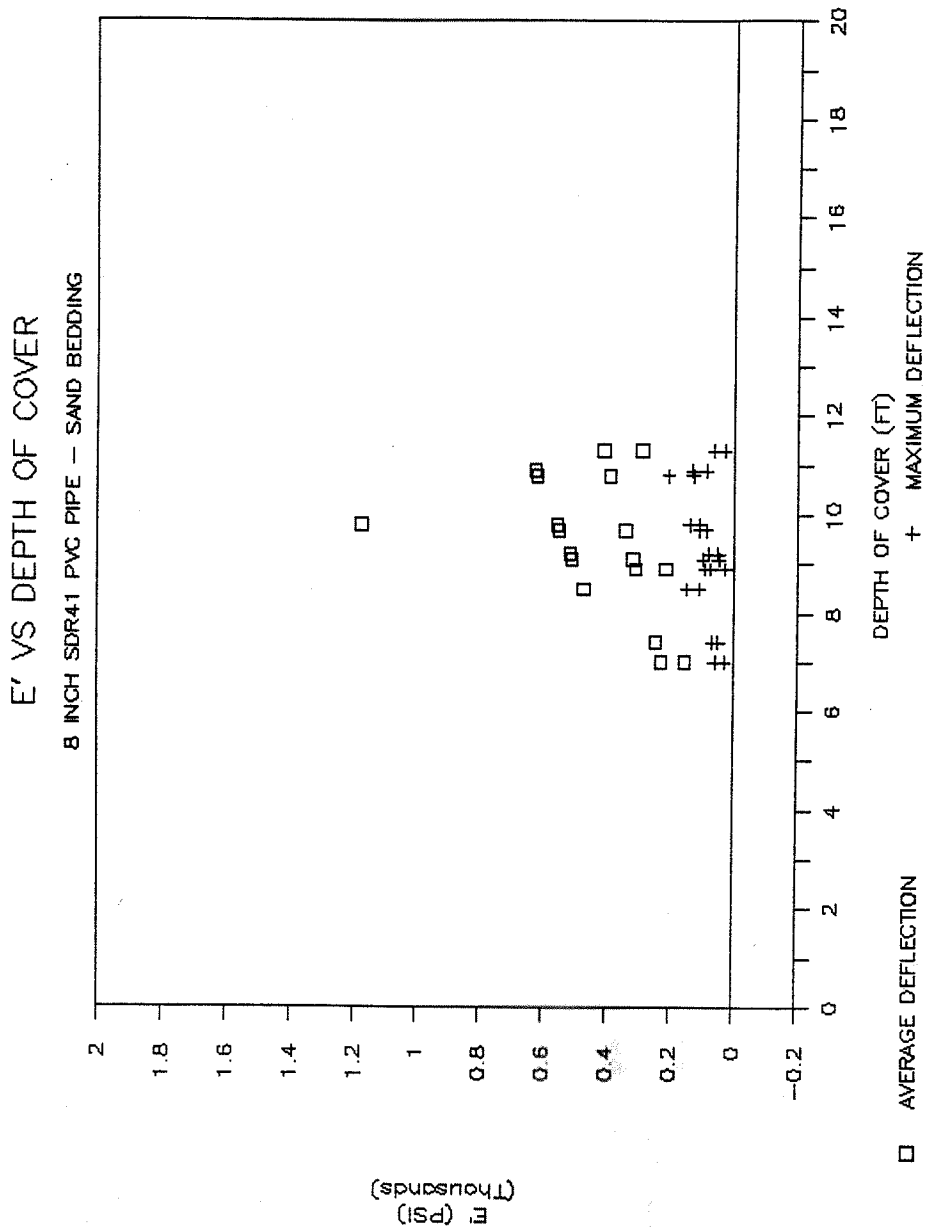


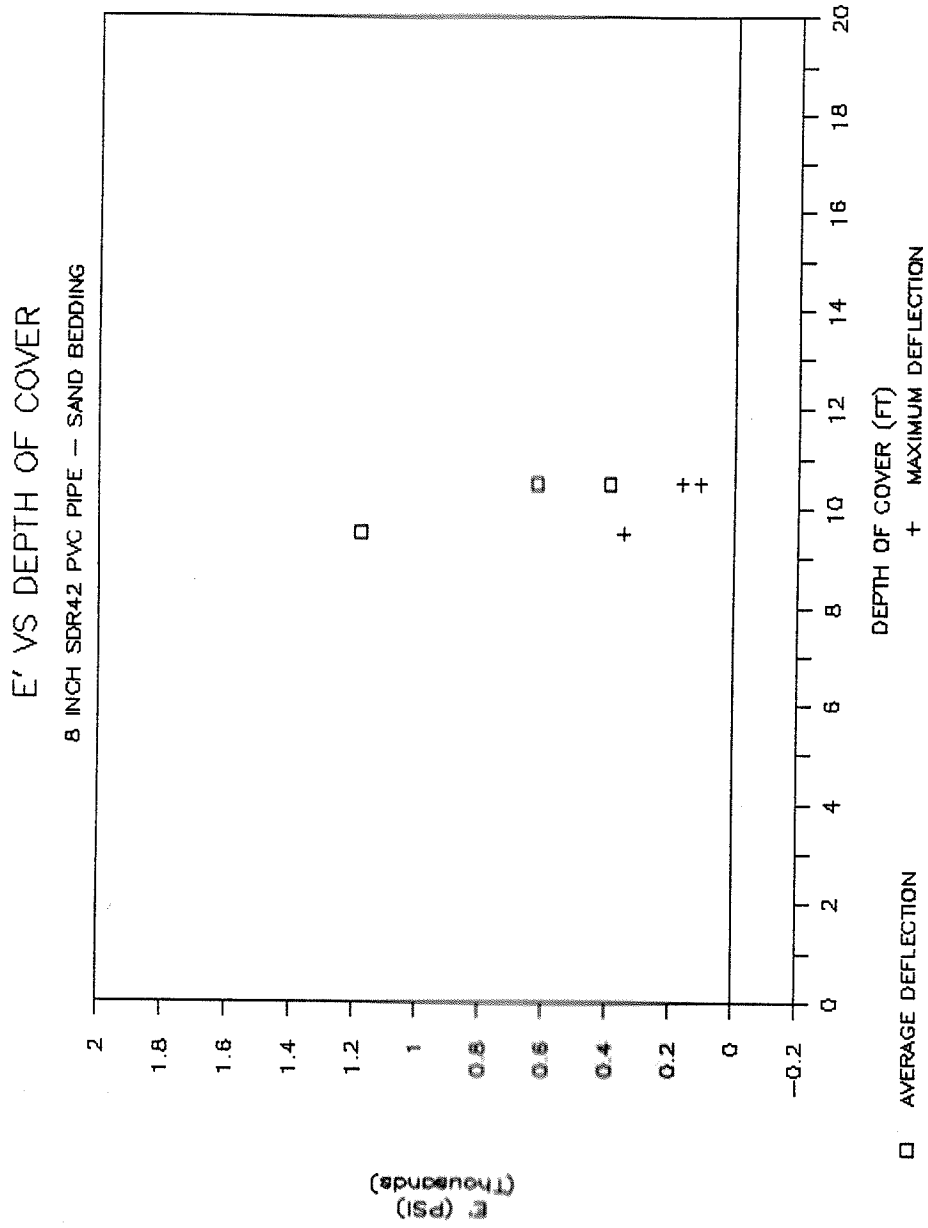
Figure A1.65 E' vs Depth of Cover
Truss Pipe - Class IV Bedding.
(Contech Construction Products Inc.)



**Figure A1.66 E' vs Depth of Cover
8 inch SDR35 PVC Pipe
Crushed Stone Envelope.
(Donahue & Associates Inc.)**



**Figure A1.67 E' vs Depth of Cover
8 inch SDR41 PVC Pipe
Sand Bedding.
(Donahue & Associates Inc.)**



**Figure A1.68 E' vs Depth of Cover
8 inch SDR42 PVC Pipe
Sand Bedding.
(Donahue & Associates Inc.)**

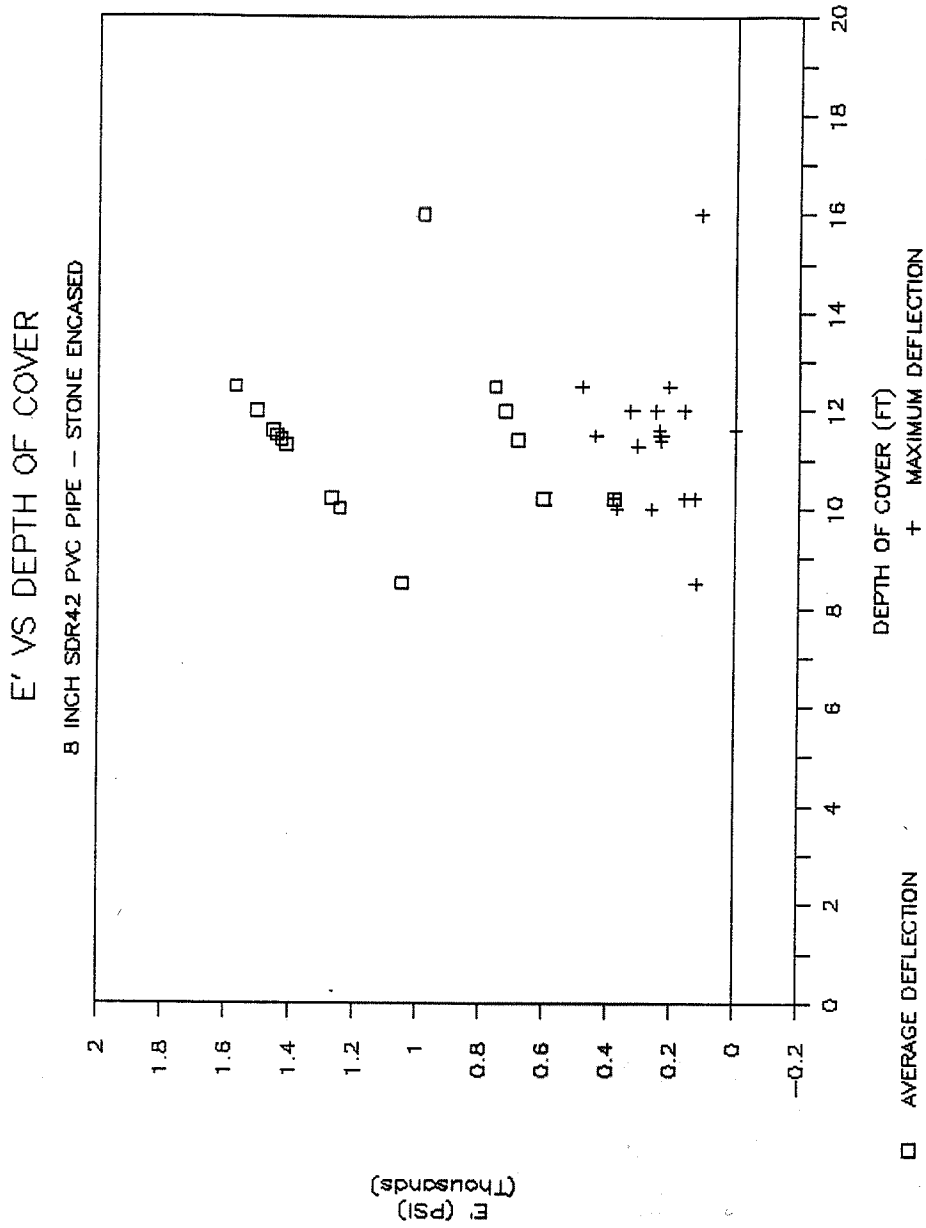


Figure A1.69 E' vs Depth of Cover
8 inch SDR42 PVC Pipe
Crushed Stone Envelope.
(Donahue & Associates Inc.)

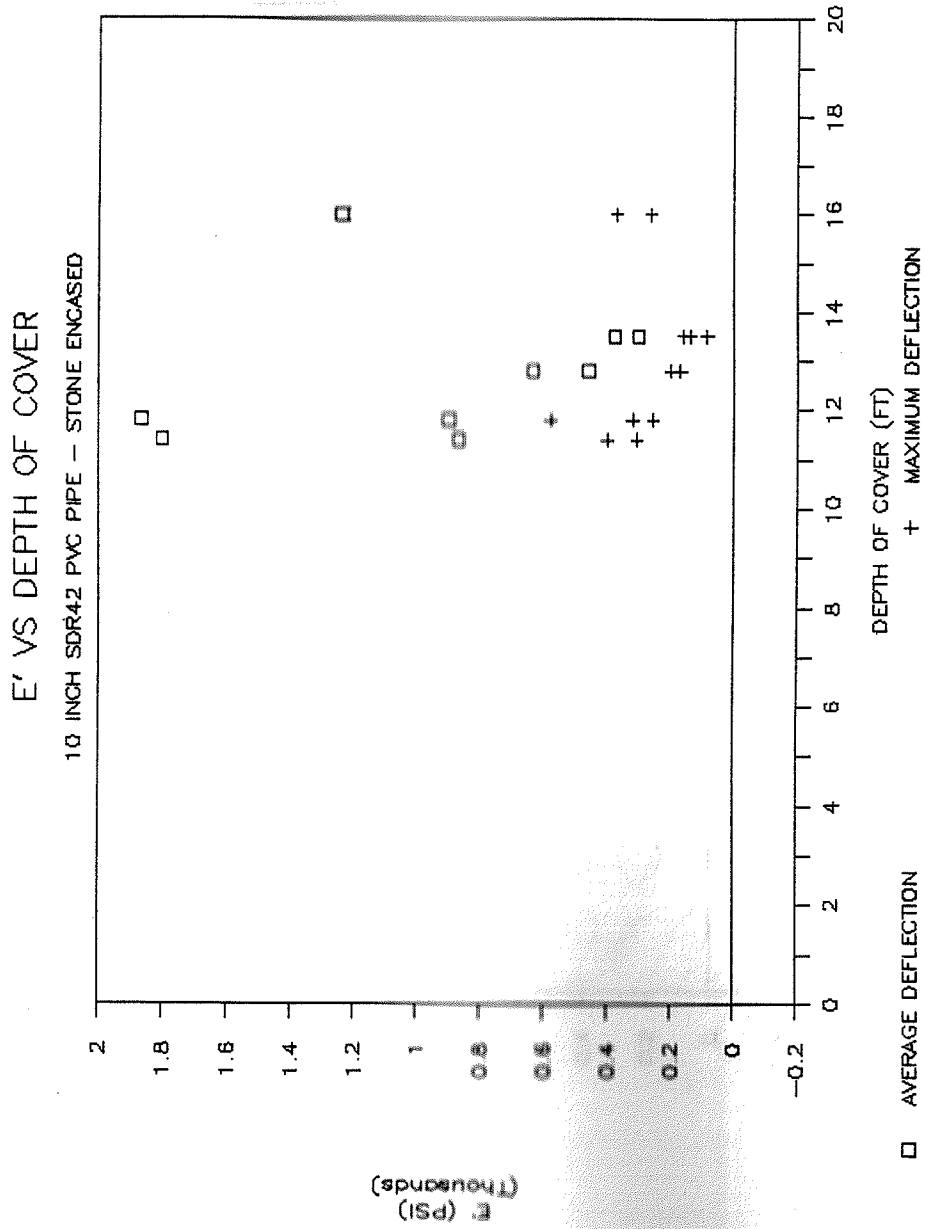


Figure A1.70 E' vs Depth of Cover
10 inch SDR42 PVC Pipe
Crushed Stone Envelope.
(Donahue & Associates Inc.)

E' VS DEPTH OF COVER

12 INCH SDR42 PVC PIPE - STONE ENCASED

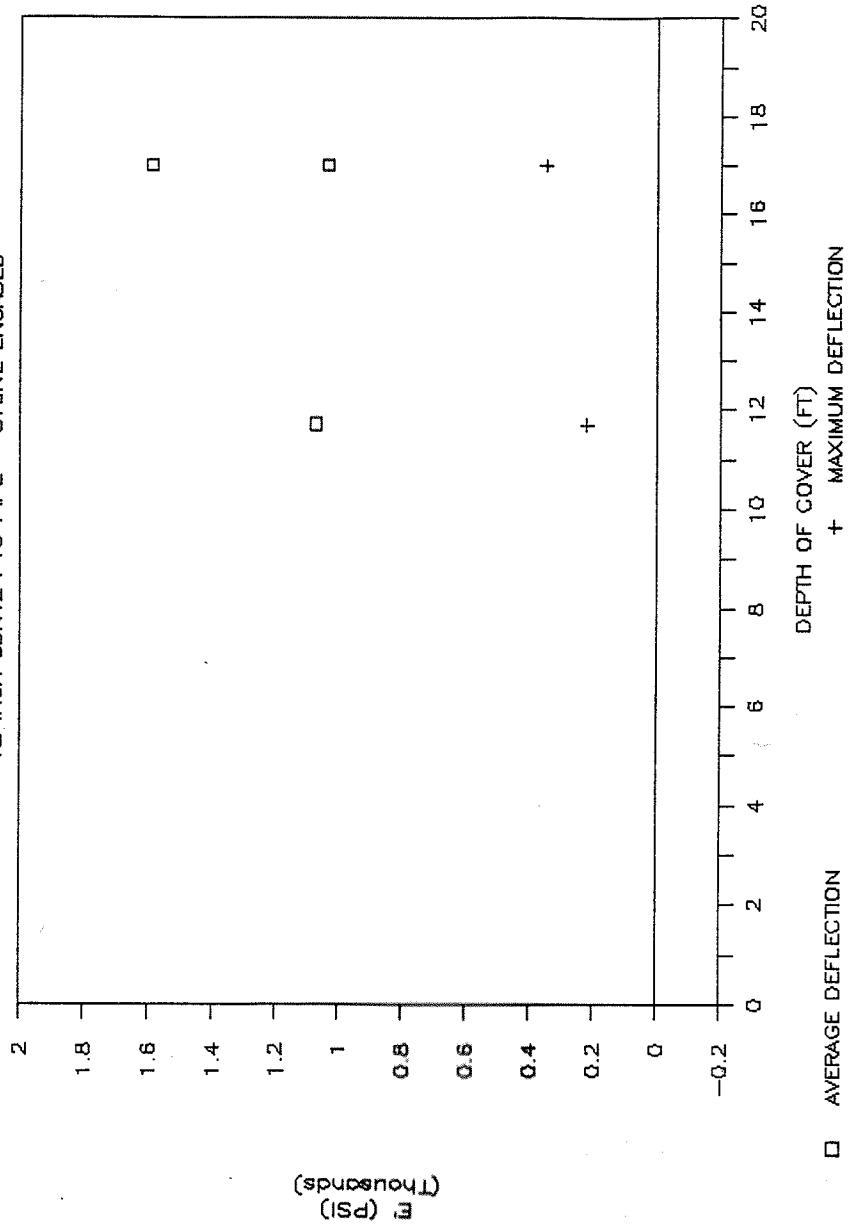


Figure A1.71 E' vs Depth of Cover
12 inch SDR42 PVC Pipe
Crushed Stone Envelope.
(Donahue & Associates Inc.)

E' VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - UNKNOWN BEDDING

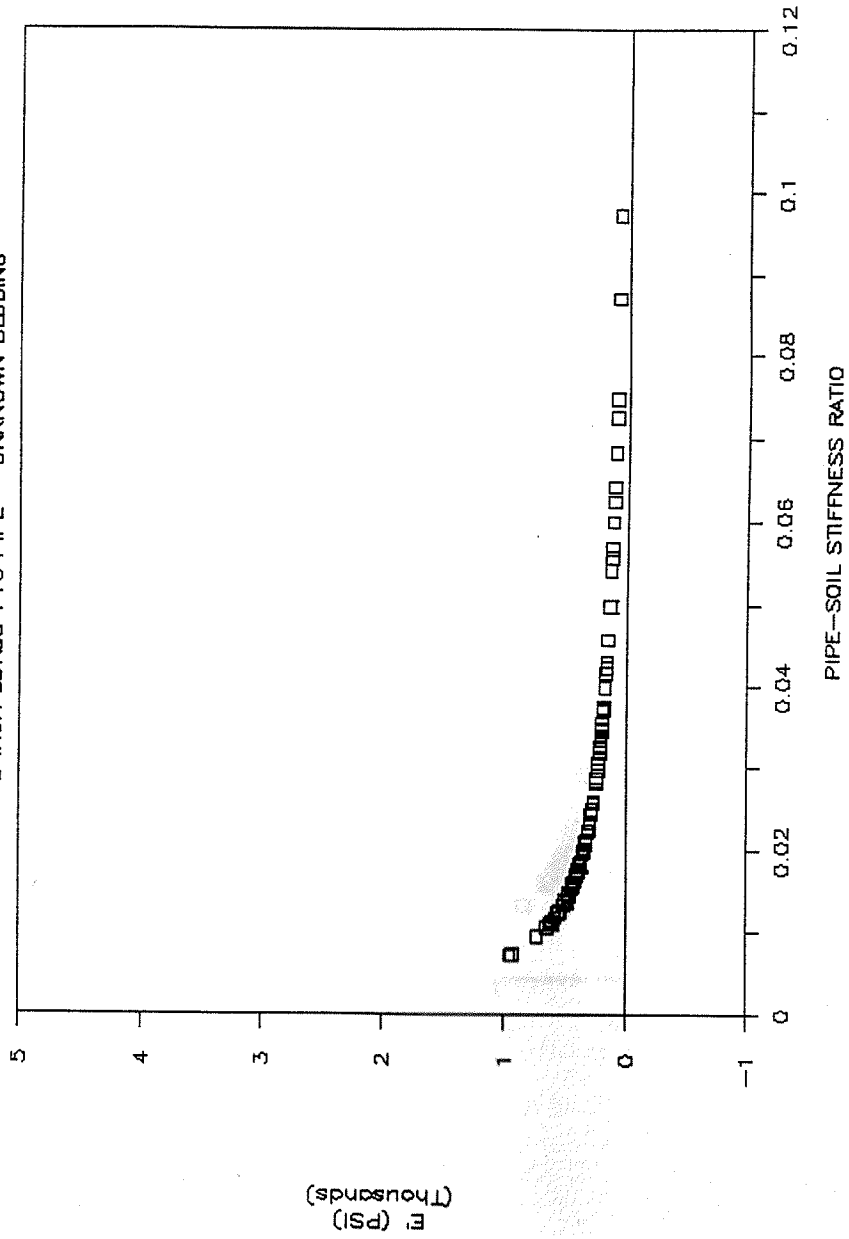


Figure A1.72 E' vs Pipe-Soil Stiffness Ratio
8 inch SDR35 PVC Pipe
Unknown Bedding.
(National Clay Pipe Institute)

E' VS PIPE-SOIL STIFFNESS RATIO
8 INCH SDR35 PVC PIPE-CLASS II BEDDING

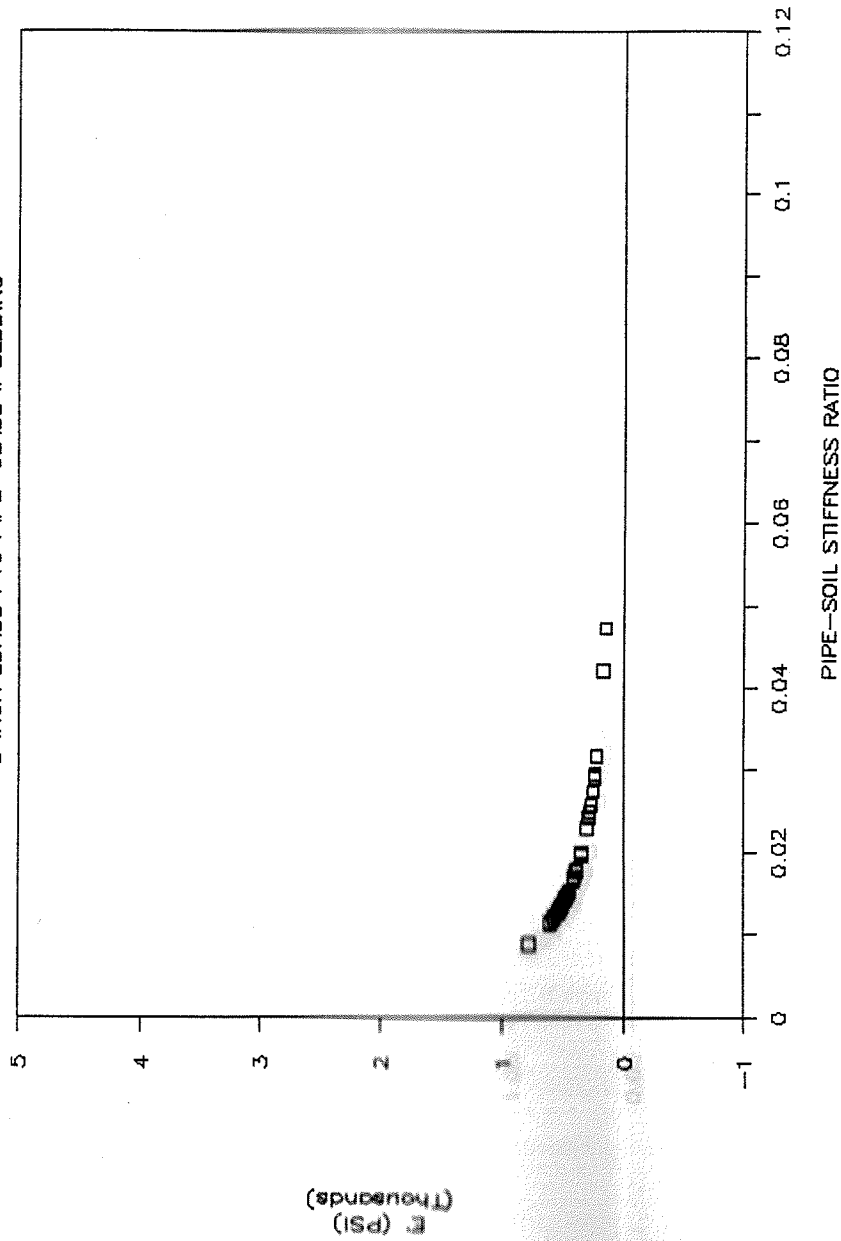


Figure A1.73 E' vs Pipe-Soil Stiffness Ratio
8 inch SDR35 PVC Pipe
Class II Bedding.
(National Clay Pipe Institute)

E' VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - SAND BEDDING

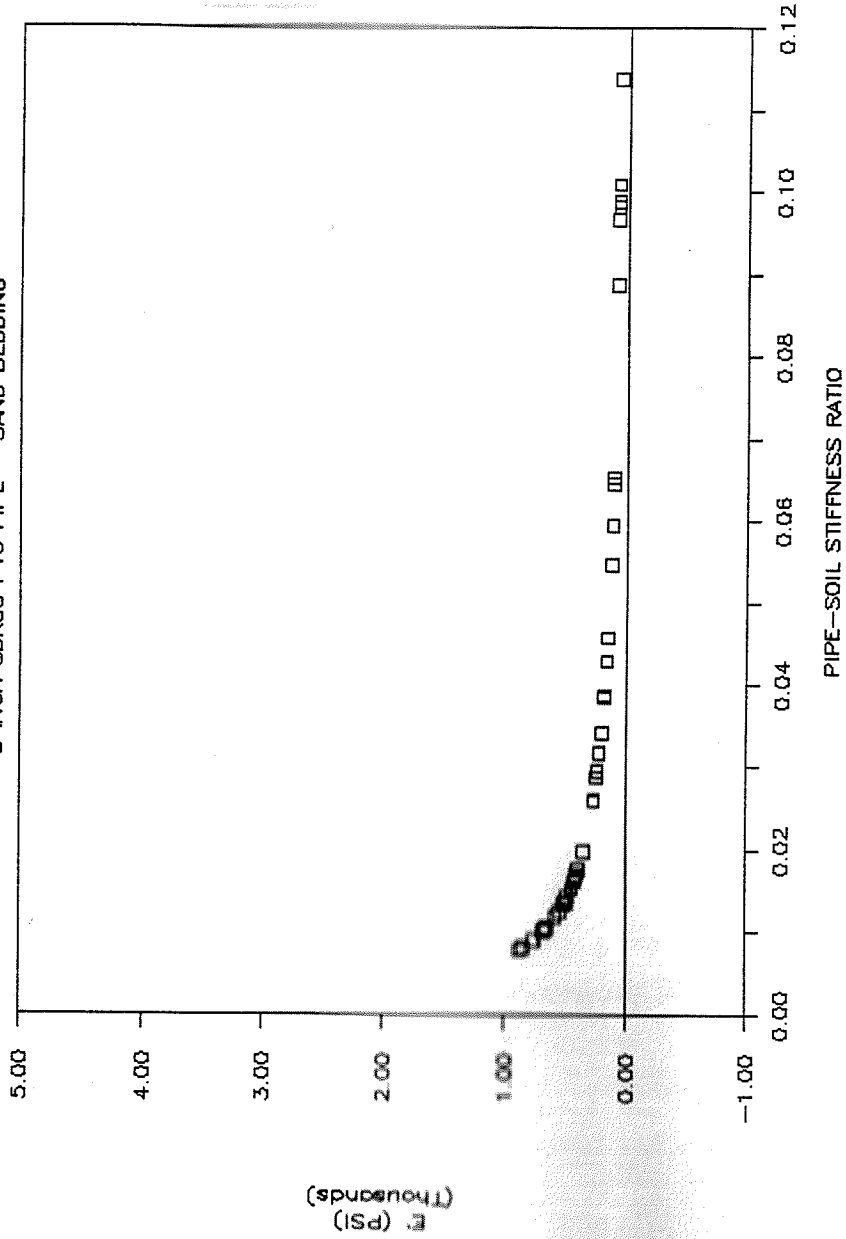


Figure A1.74 E' vs Pipe-Soil Stiffness Ratio
8 inch SDR35 PVC Pipe
Sand Bedding.
(National Clay Pipe Institute)

E' VS PIPE-SOIL STIFFNESS RATIO

8 INCH SDR35 PVC PIPE - STONE TO SPRING

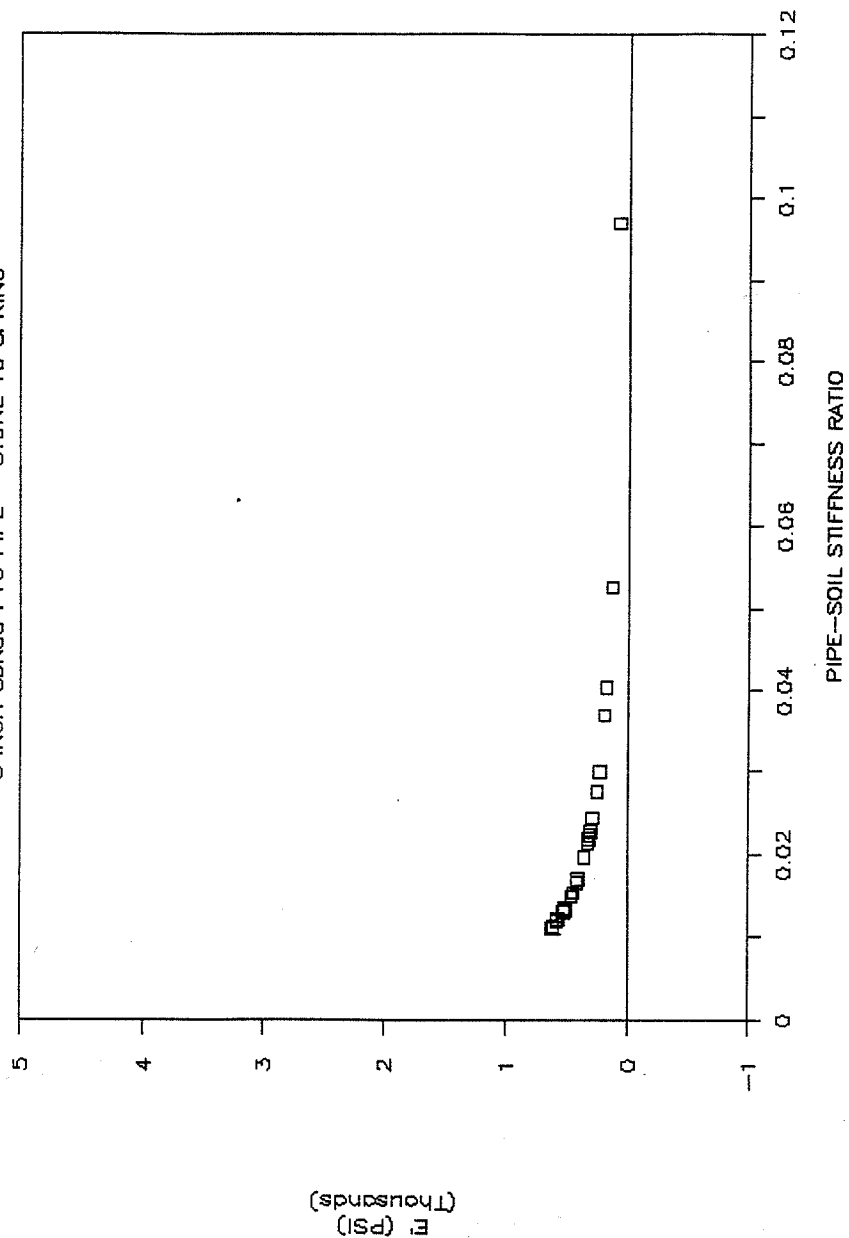


Figure A1.75 E' vs Pipe-Soil Stiffness Ratio
8 inch SDR35 PVC Pipe
Crushed Stone to the Springline.
(National Clay Pipe Institute)

E' VS PIPE-SOIL STIFFNESS RATIO
8 INCH SDR35 PVC PIPE - STONE ENCASED

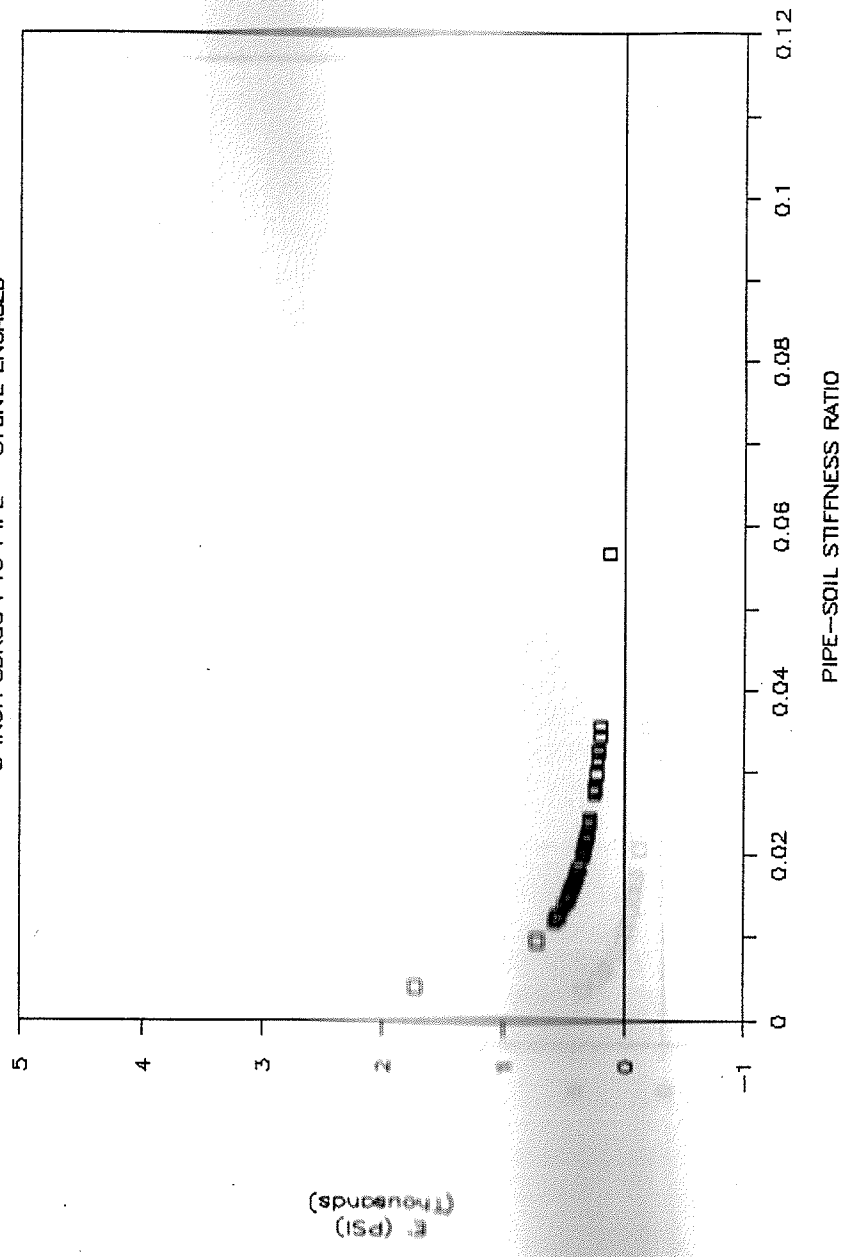


Figure A1.76 E' vs Pipe-Soil Stiffness Ratio
8 inch SDR35 PVC Pipe
Crushed Stone Envelope.
(National Clay Pipe Institute)

E' VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS I BEDDING

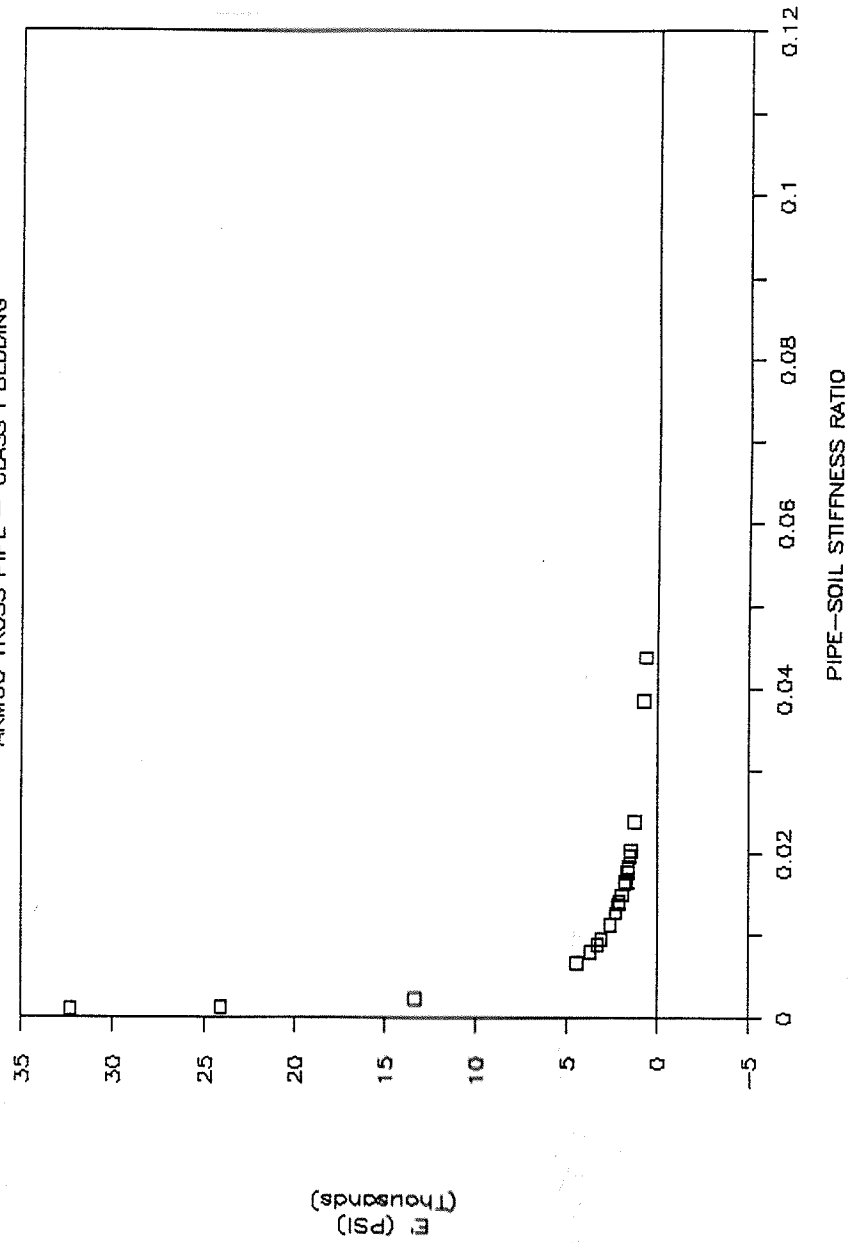


Figure A1.77 E' vs Pipe-Soil Stiffness Ratio
Truss Pipe - Class I Bedding.
(Contech Construction Products Inc.)

E' VS PIPE-SOIL STIFFNESS RATIO ARMCO TRUSS PIPE - CLASS II BEDDING

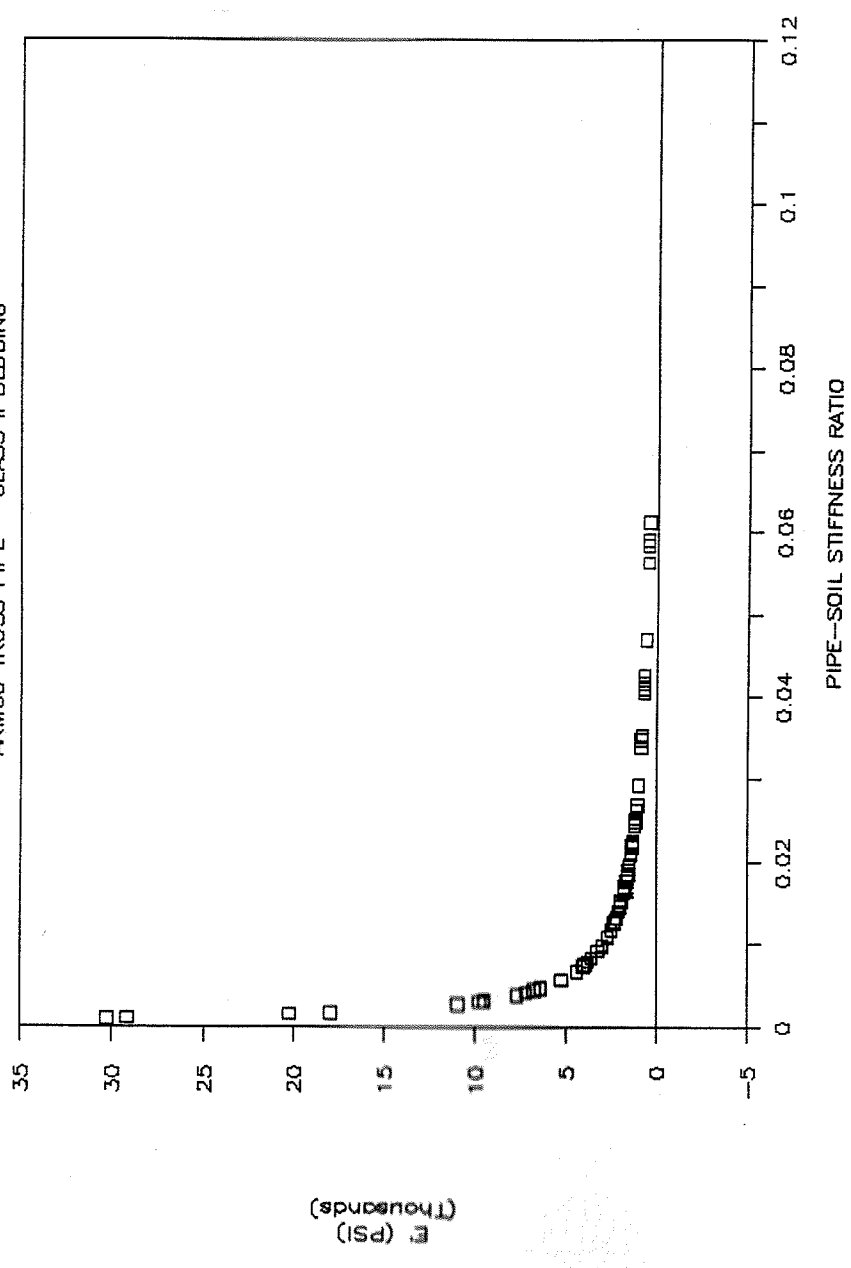


Figure A1.78 E' vs Pipe-Soil Stiffness Ratio
Truss Pipe - Class II Bedding.
(Contech Construction Products Inc.)

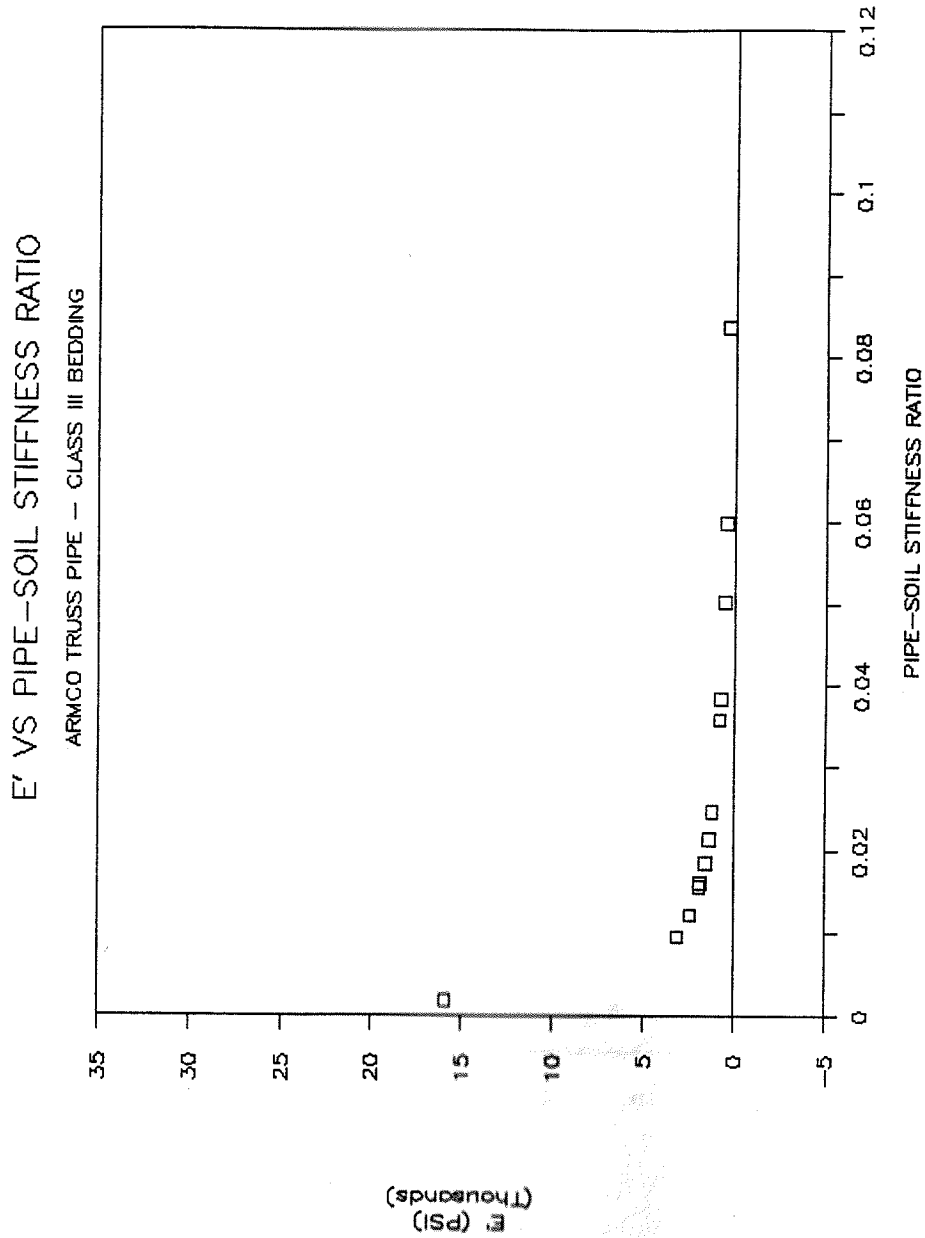


Figure A1.79 E' vs Pipe-Soil Stiffness Ratio
Truss Pipe - Class III Bedding.
(Contech Construction Products Inc.)

E' VS PIPE-SOIL STIFFNESS RATIO

ARMCO TRUSS PIPE - CLASS IV BEDDING

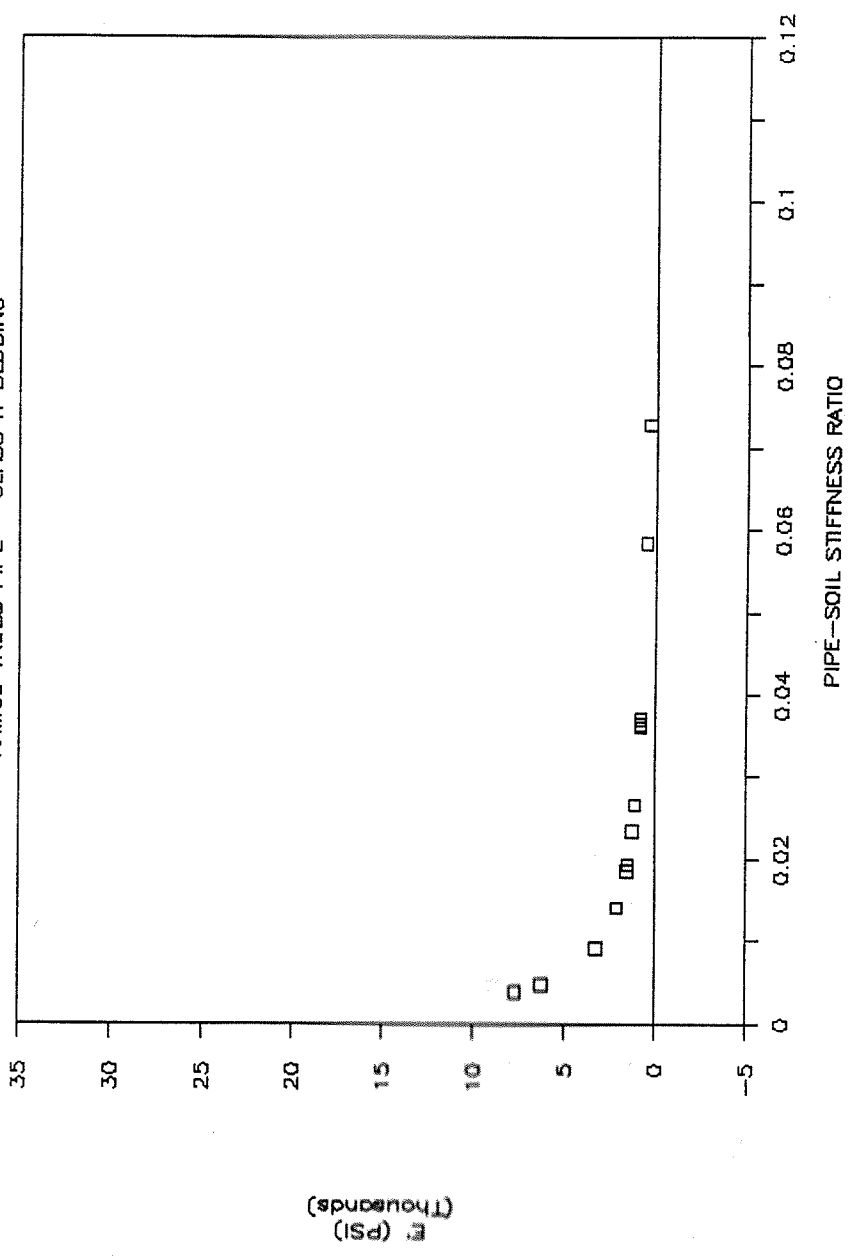
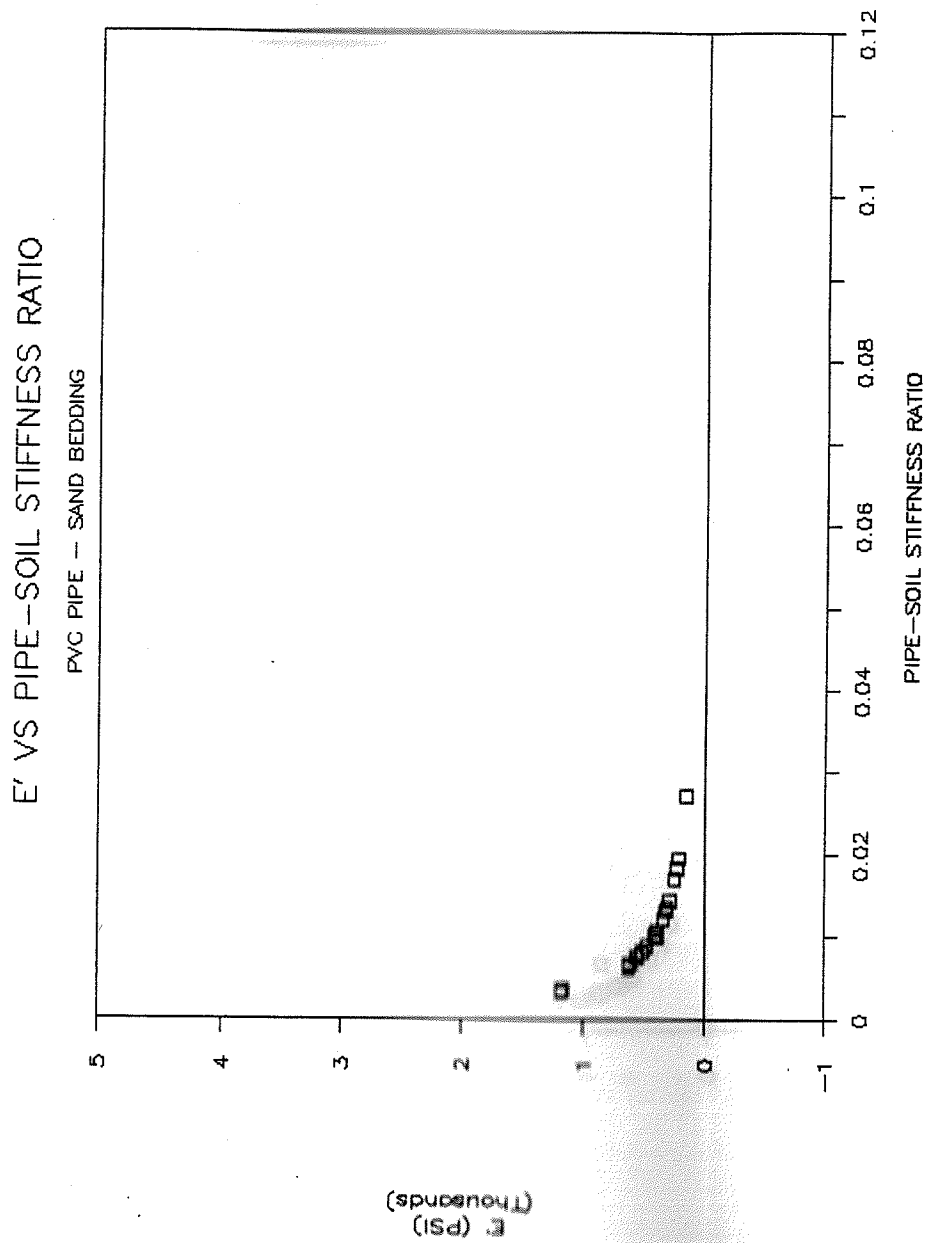


Figure A1.80 E' vs Pipe-Soil Stiffness Ratio
Truss Pipe - Class IV Bedding.
(Contech Construction Products Inc.)



**Figure A1.81 E' vs Pipe-Soil Stiffness Ratio
PVC Pipe - Sand Bedding.
(Donahue & Associates Inc.)**

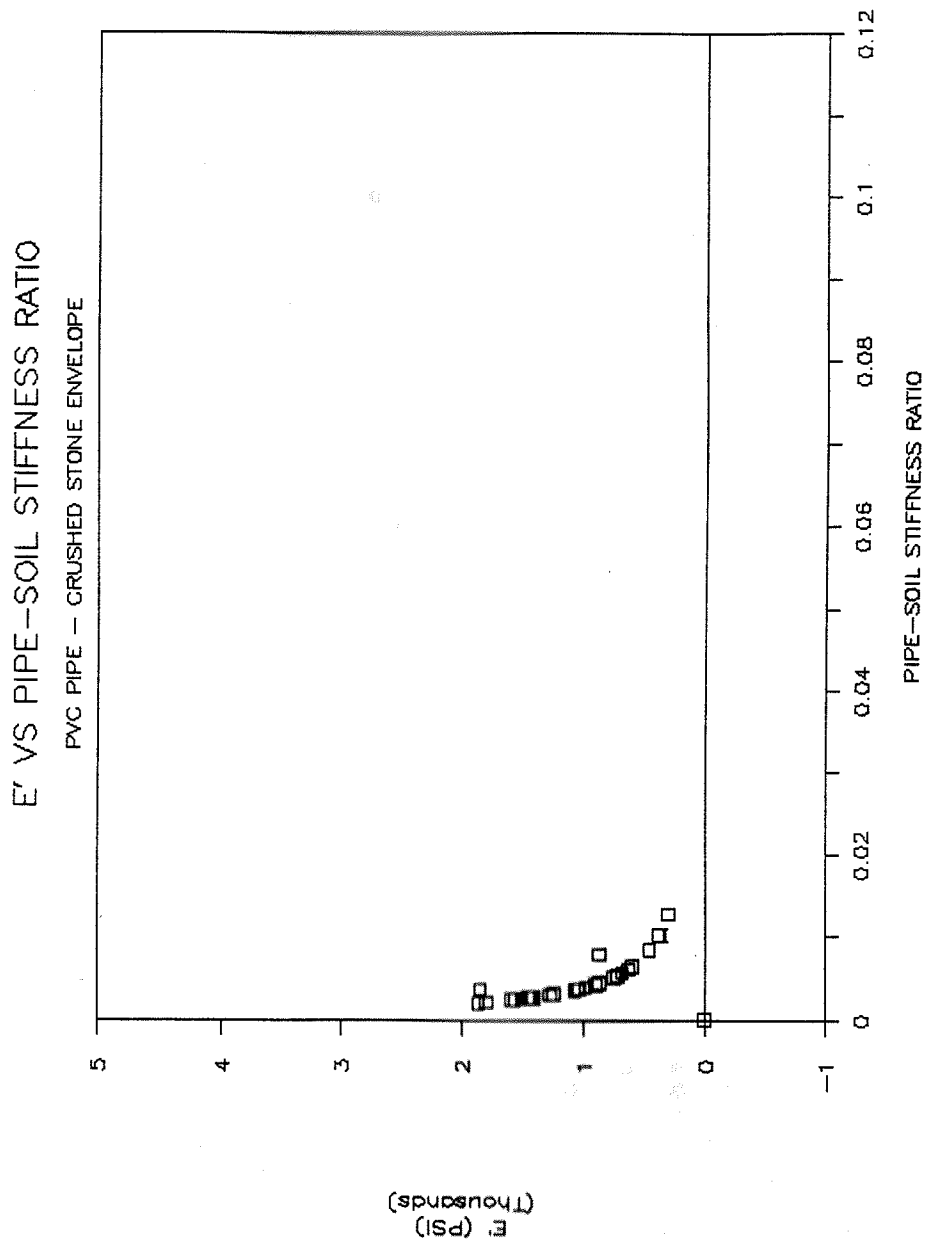


Figure A1.82 E' vs Pipe-Soil Stiffness Ratio
PVC Pipe - Crushed Stone Envelope.
(Donahue & Associates Inc.)

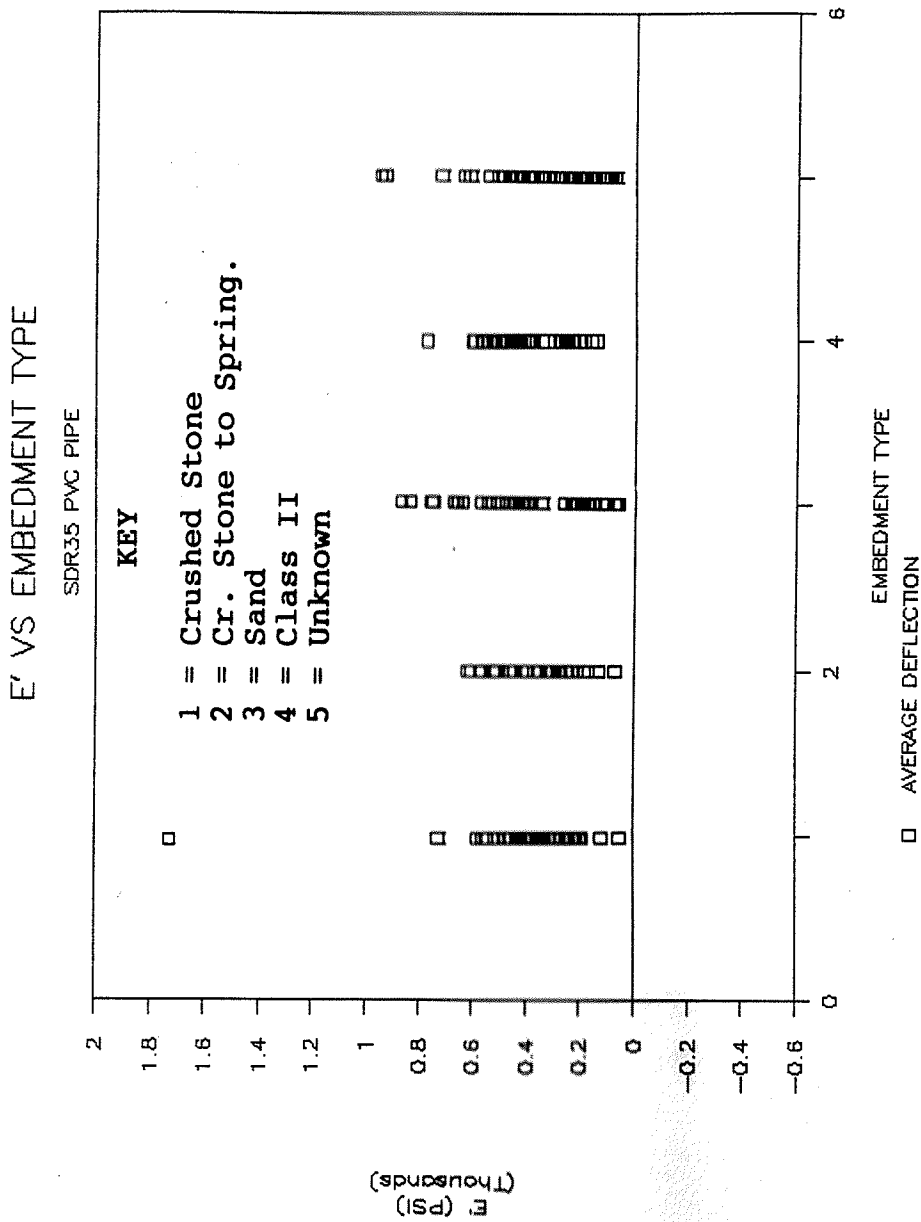


Figure A1.83 E' vs Embedment Type
SDR35 PVC Pipe - Average Deflection.
 (National Clay Pipe Institute)

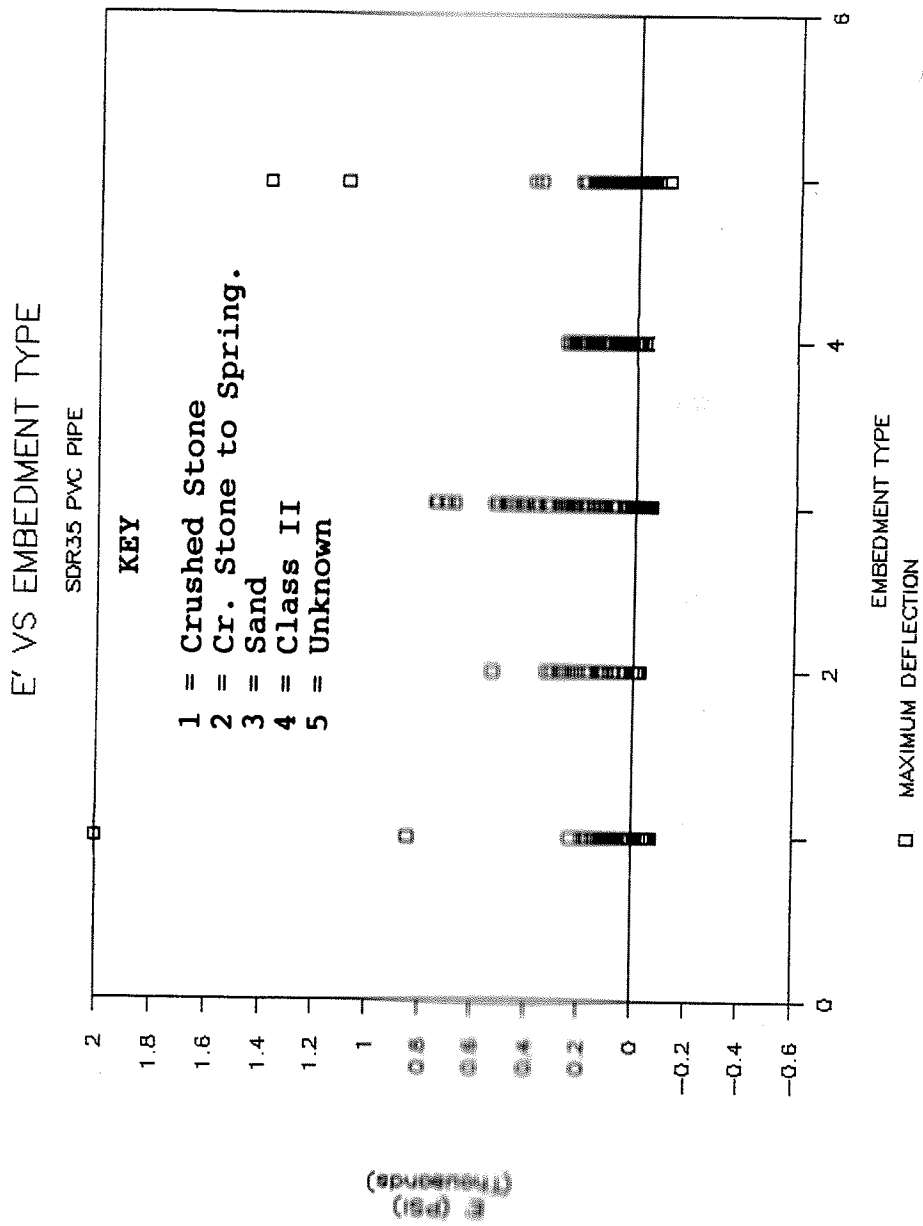


Figure A1.84 E' vs Embedment Type
SDR35 PVC Pipe - Maximum Deflection.
(National Clay Pipe Institute)

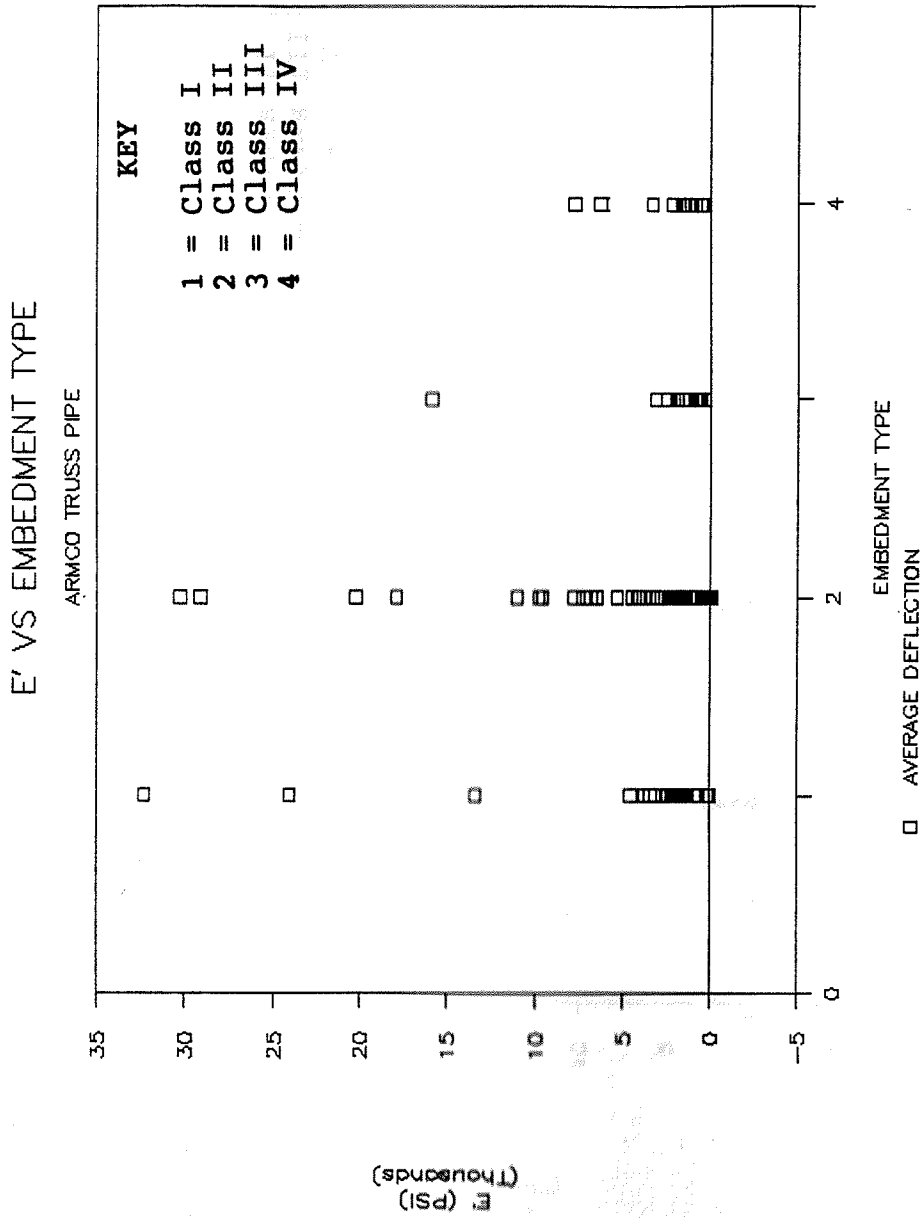


Figure A1.85 E' vs Embedment Type
Truss Pipe - Average Deflection.
(National Clay Pipe Institute)

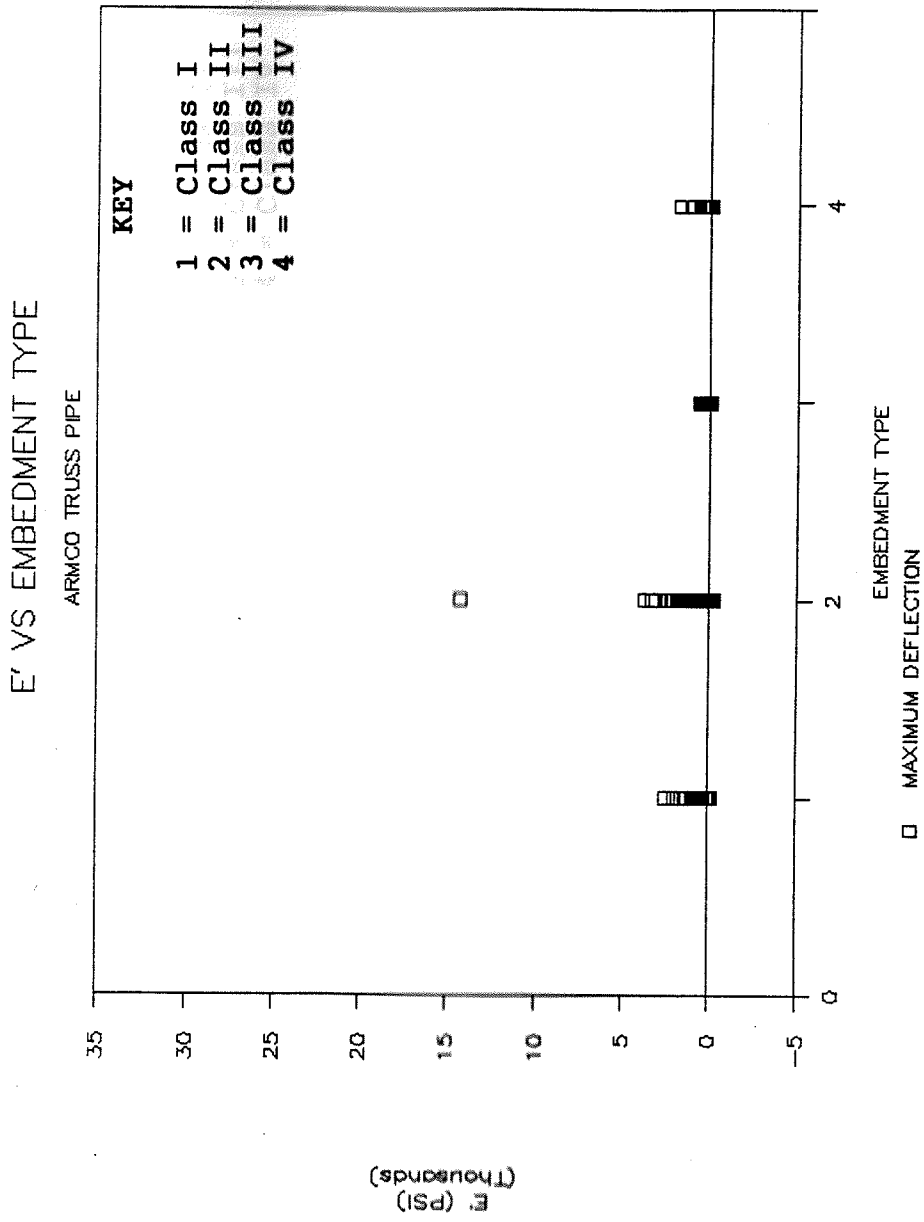


Figure A1.86 E' vs Embedment Type Truss Pipe - Maximum Deflection. (National Clay Pipe Institute)

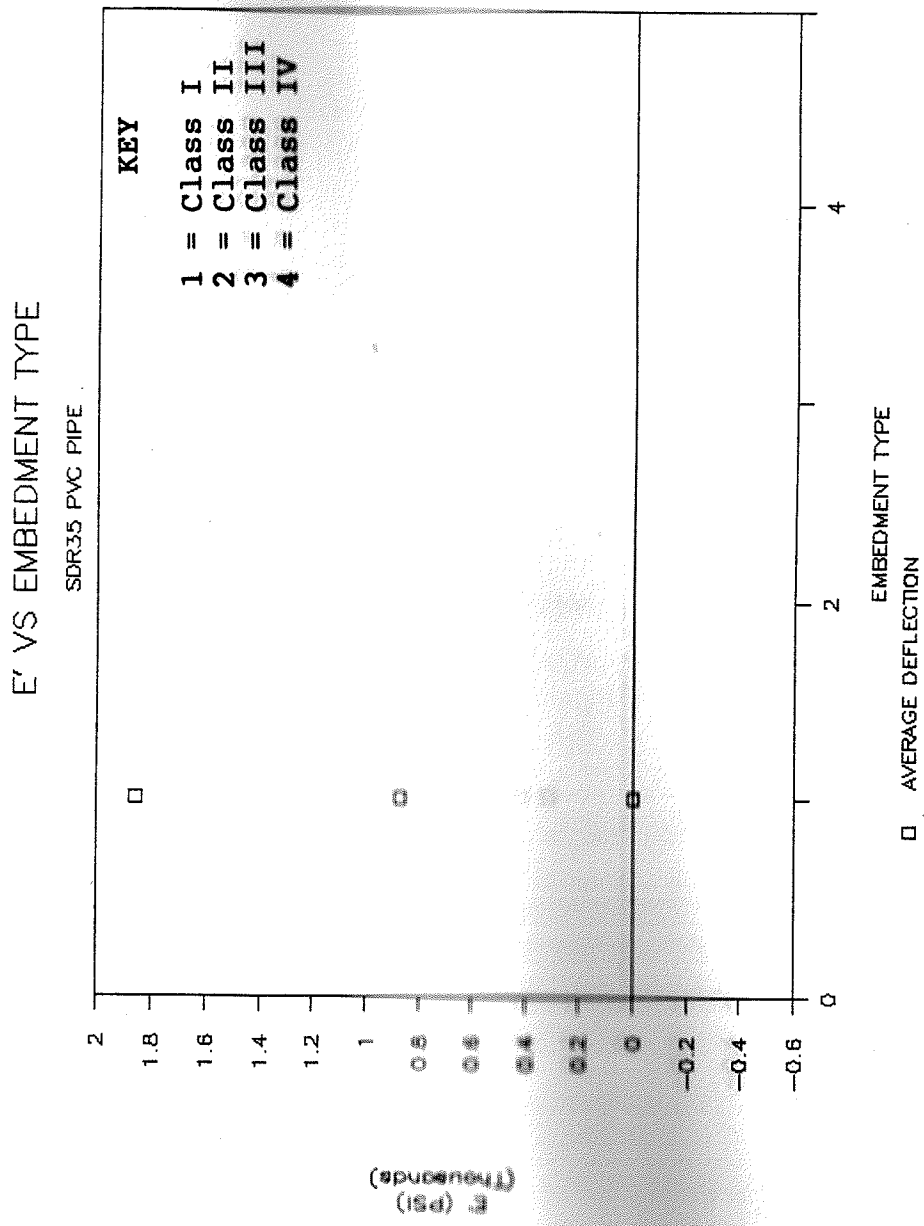


Figure A1.87 E' vs Embedment Type
SDR35 PVC Pipe - Average Deflection.
(Donahue & Associates Inc.)

E' VS EMBEDMENT TYPE

SDR35 PVC PIPE

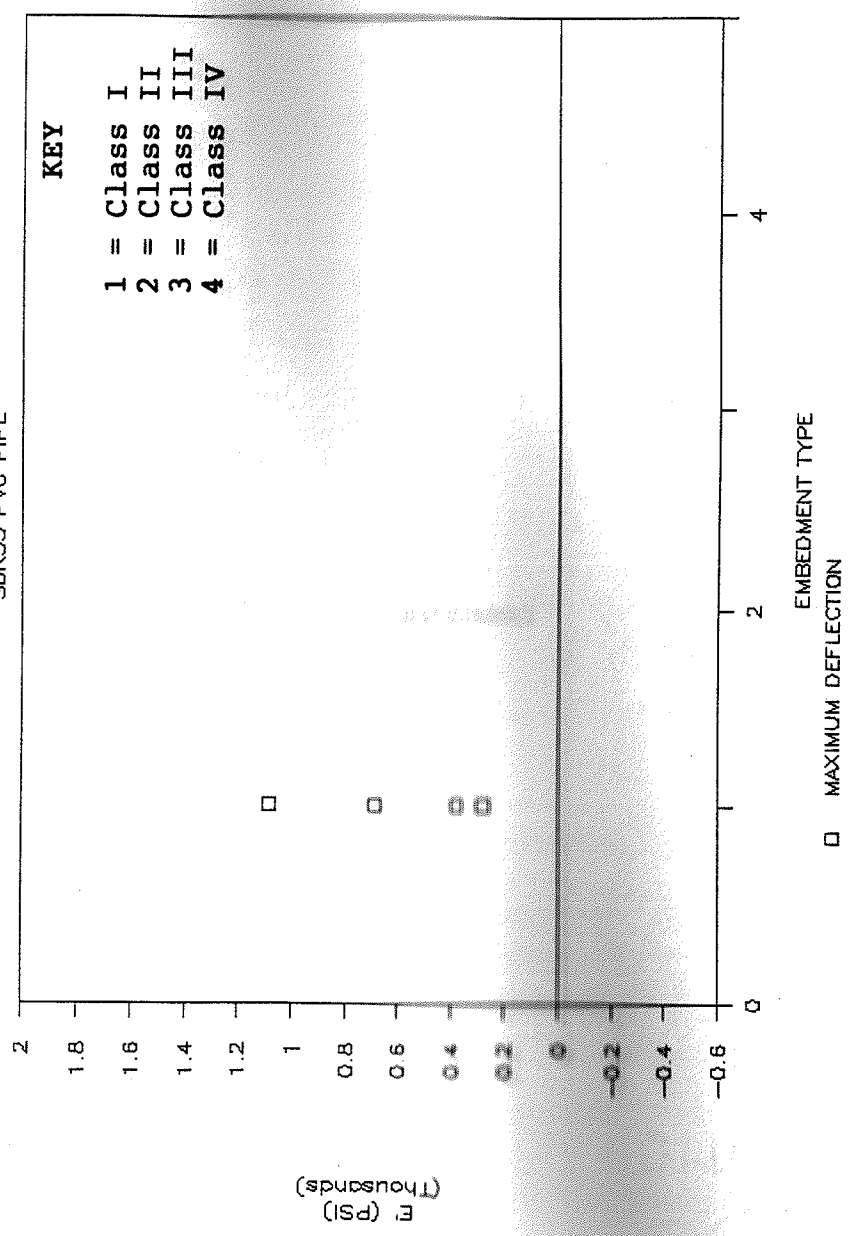


Figure A1.88 E' vs Embedment Type
SDR35 PVC Pipe - Maximum Deflection.
(Donahue & Associates Inc.)

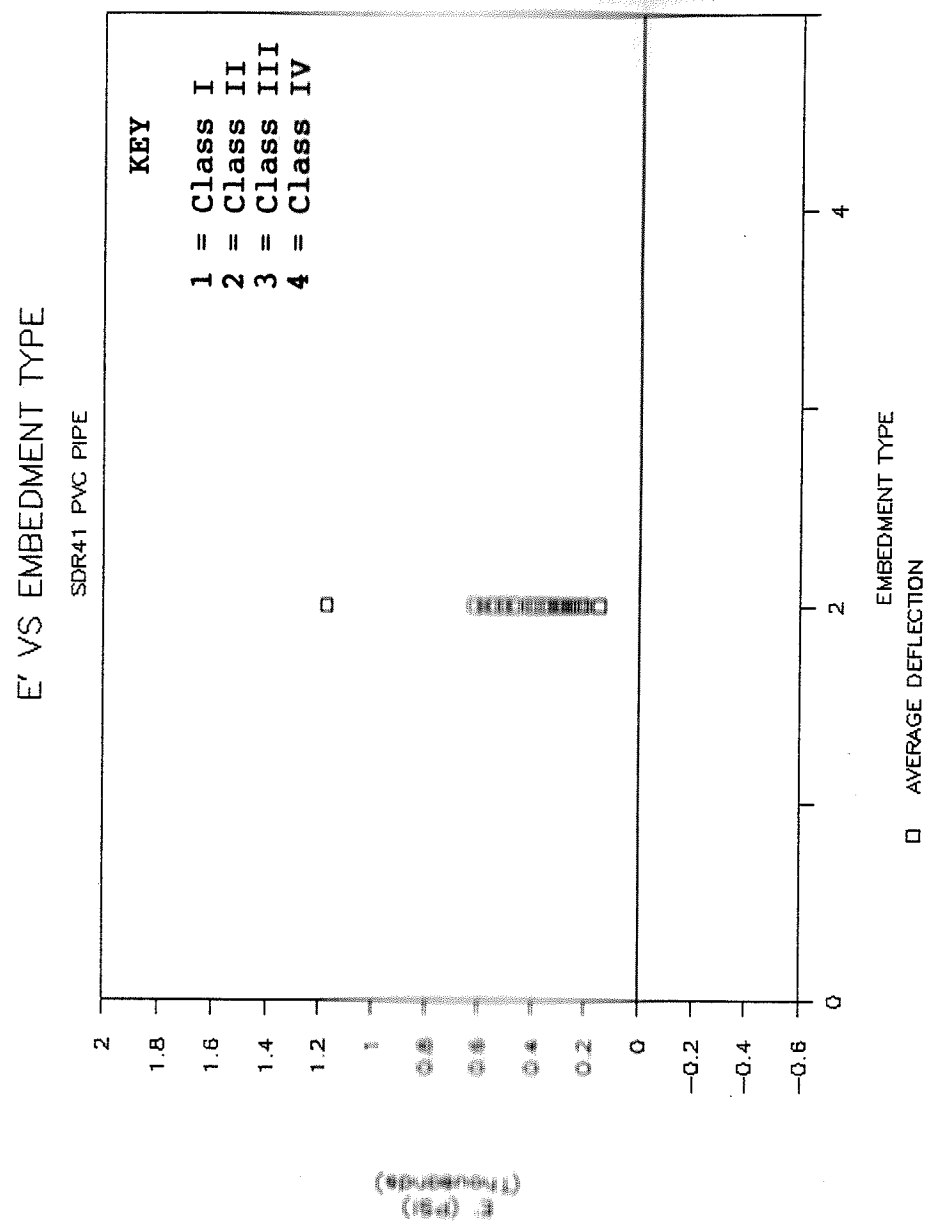


Figure A1.89 E' vs Embedment Type
SDR41 PVC Pipe - Average Deflection.
(Donahue & Associates Inc.)

E' VS EMBEDMENT TYPE

SDR41 PVC PIPE

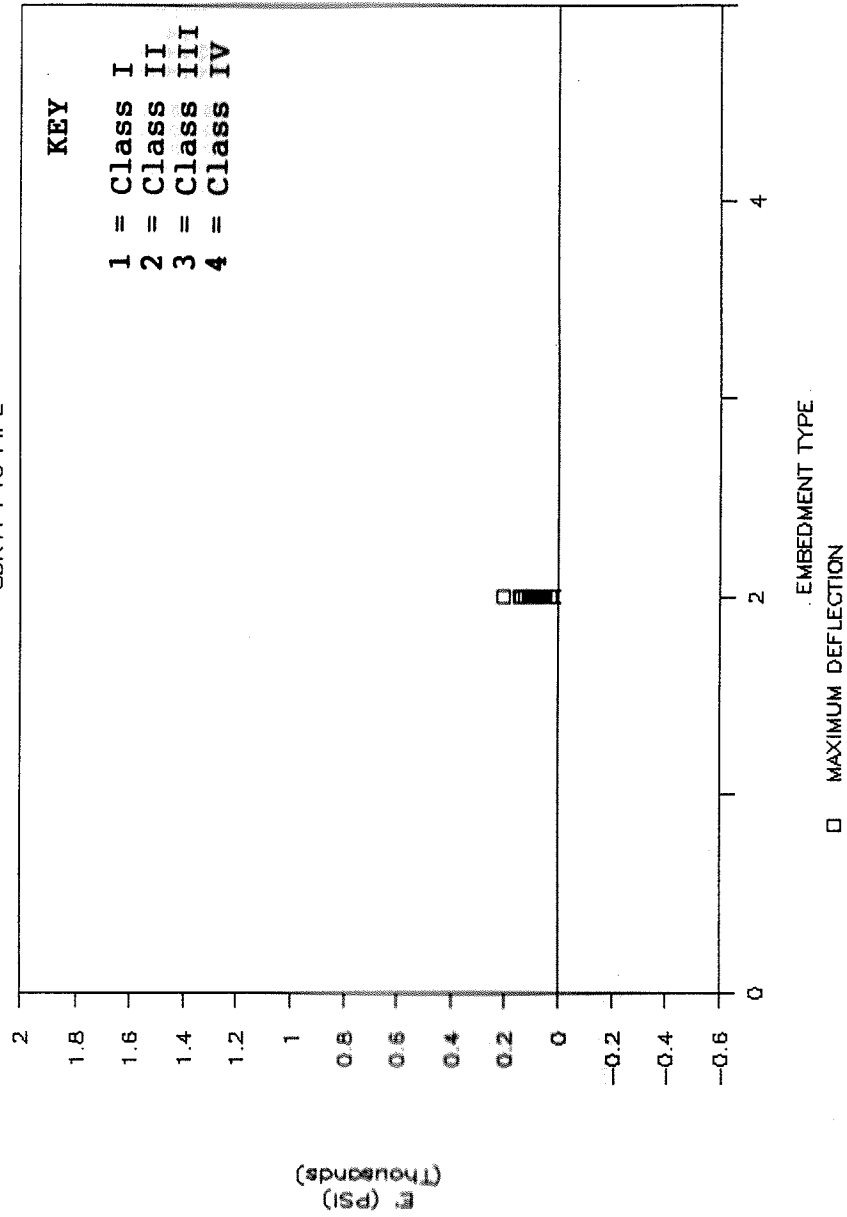


Figure A1.90 E' vs Embedment Type
SDR41 PVC Pipe - Maximum Deflection.
(Donahue & Associates Inc.)

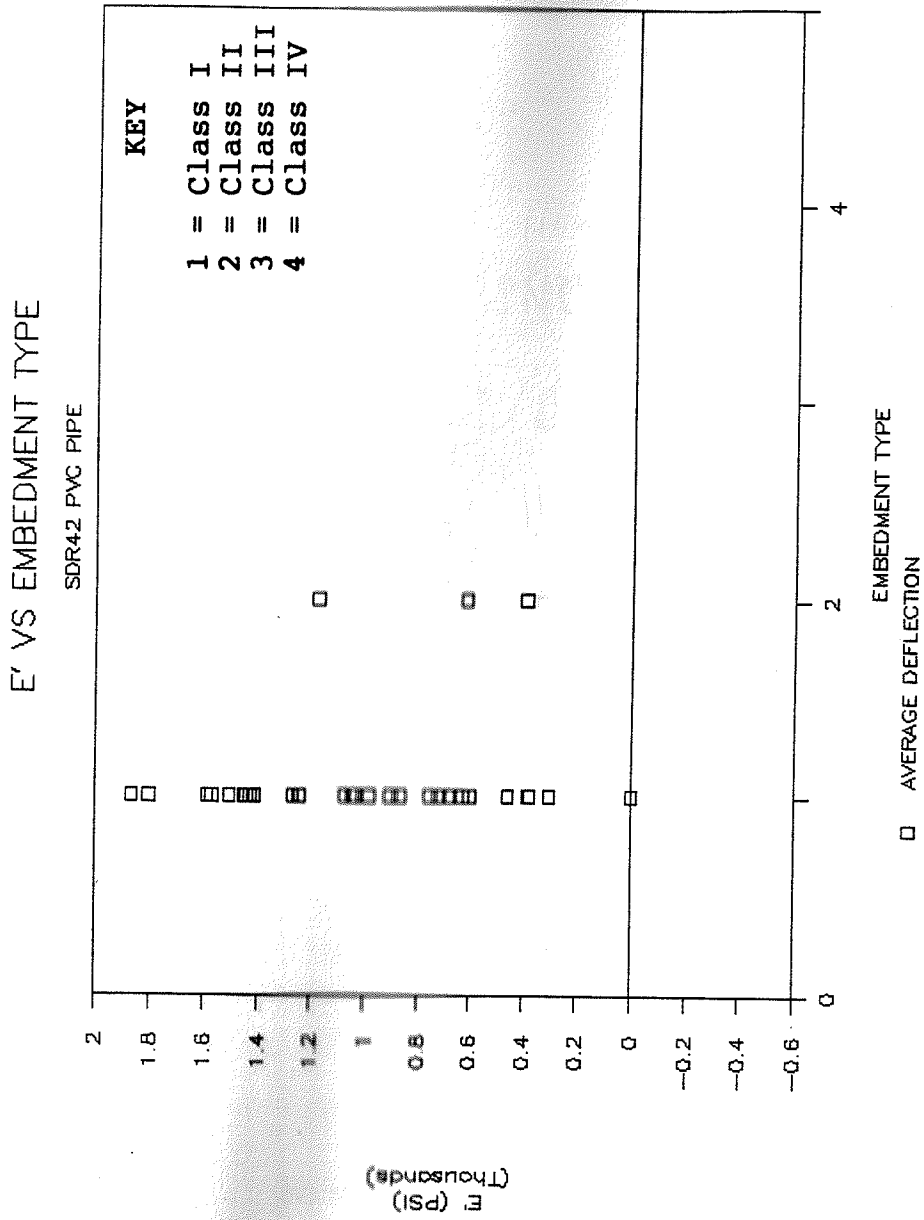


Figure A1.91 E' vs Embedment Type
SDR42 PVC Pipe - Average Deflection.
(Donahue & Associates Inc.)

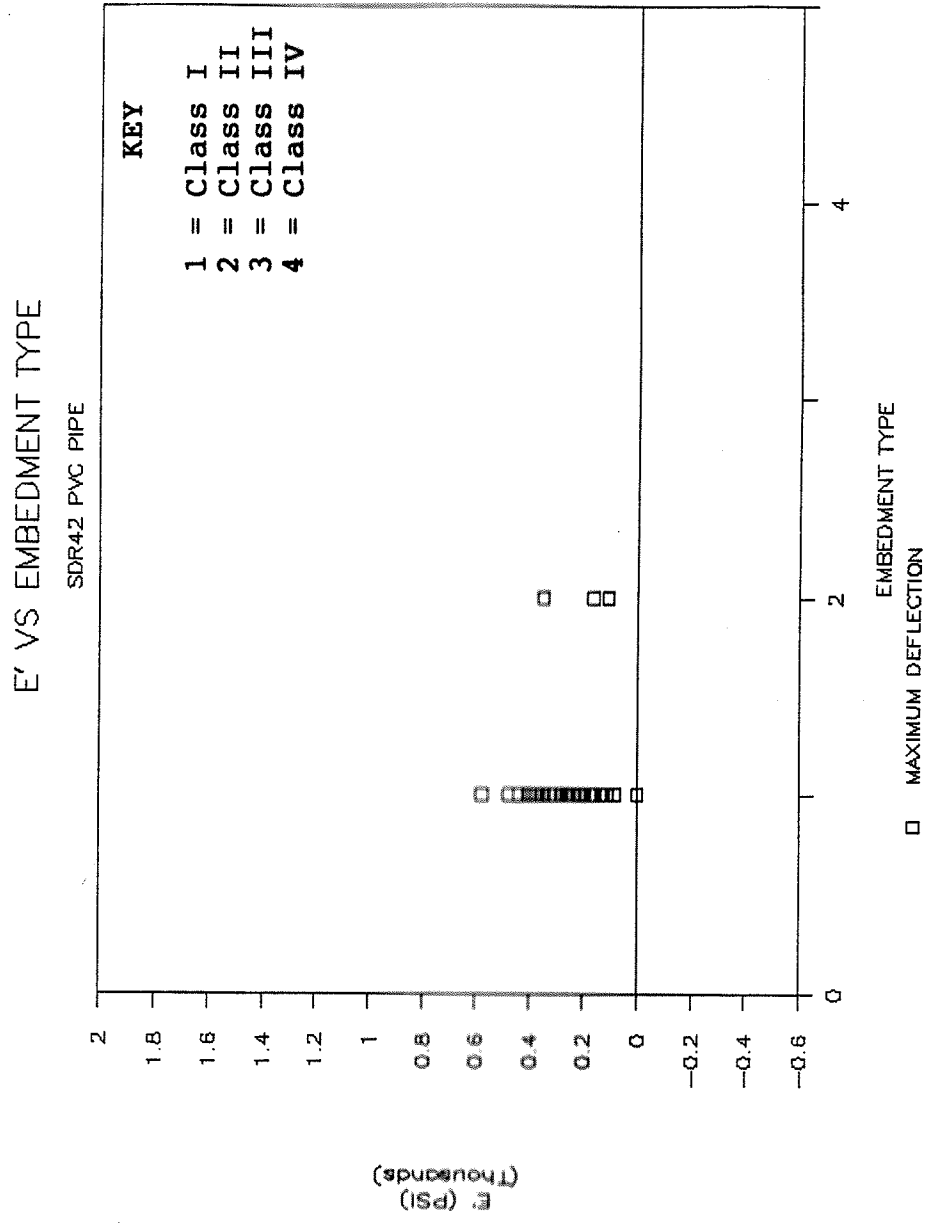


Figure A1.92 E' vs Embedment Type
SDR42 PVC Pipe - Maximum Deflection.
(Donahue & Associates Inc.)

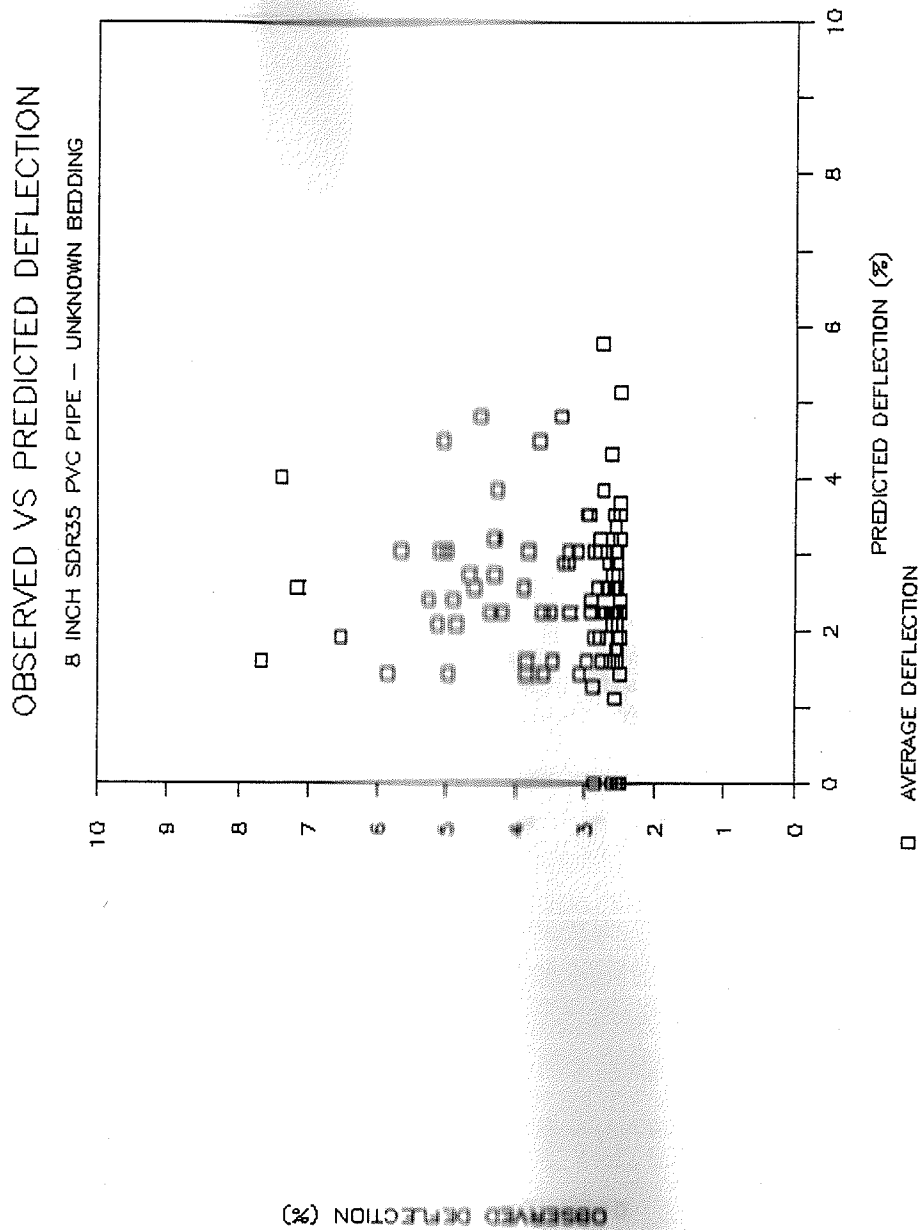
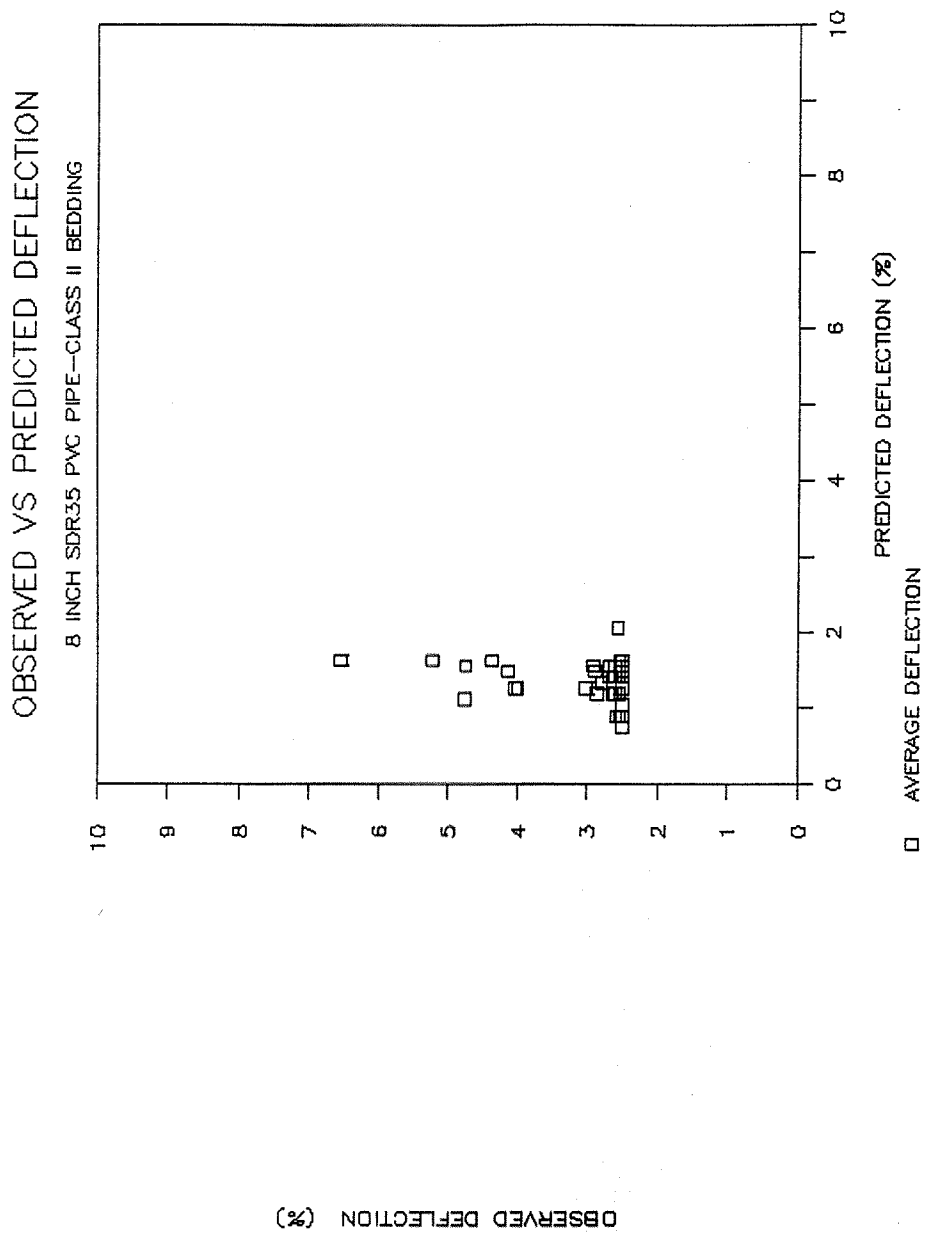


Figure A1.93 Observed vs Predicted Deflection
8 inch SDR35 PVC Pipe
Unknown Bedding.
(National Clay Pipe Institute)



**Figure A1.94 Observed vs Predicted Deflection
8 inch SDR35 PVC Pipe
Class II Bedding.
(National Clay Pipe Institute)**

OBSERVED VS PREDICTED DEFLECTION

8 INCH SDR35 PVC PIPE — SAND BEDDING

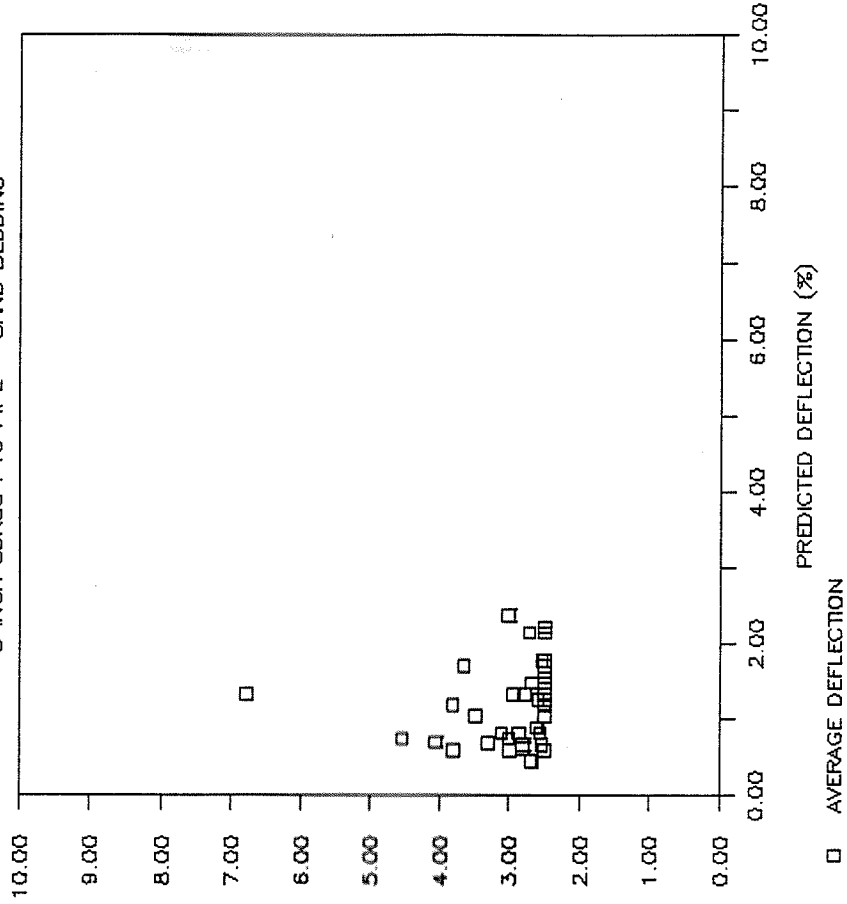


Figure A1.95 Observed vs Predicted Deflection
8 inch SDR35 PVC Pipe
Sand Bedding.
(National Clay Pipe Institute)

OBSERVED DEFLECTION (%)

OBSERVED VS PREDICTED DEFLECTION

8 INCH SDR35 PVC PIPE - STONE ENCASED

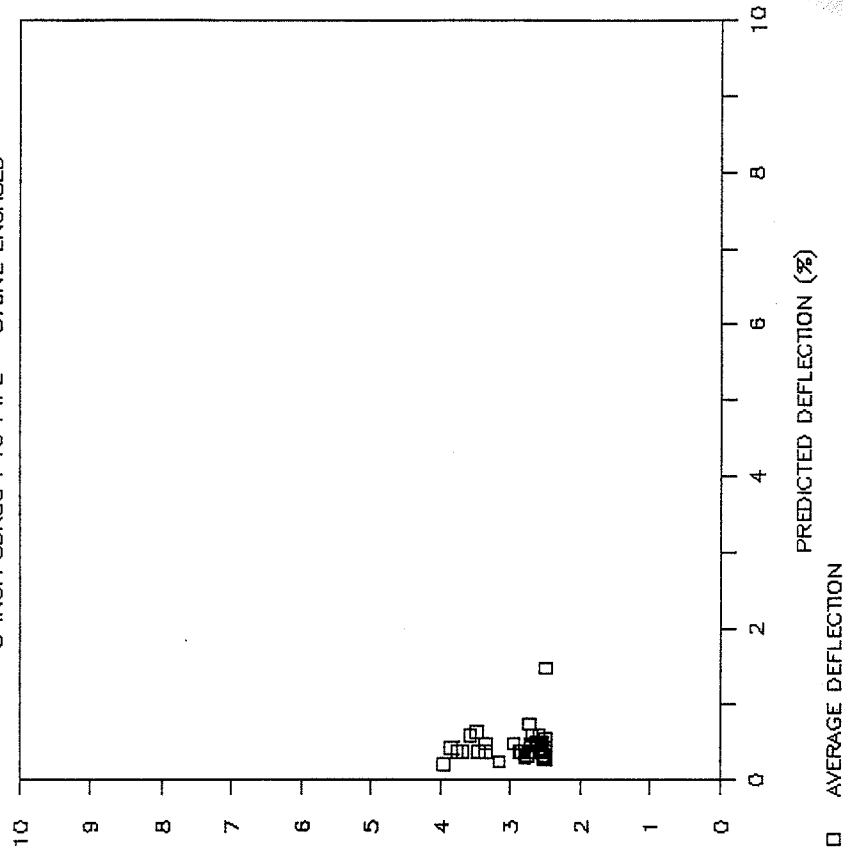
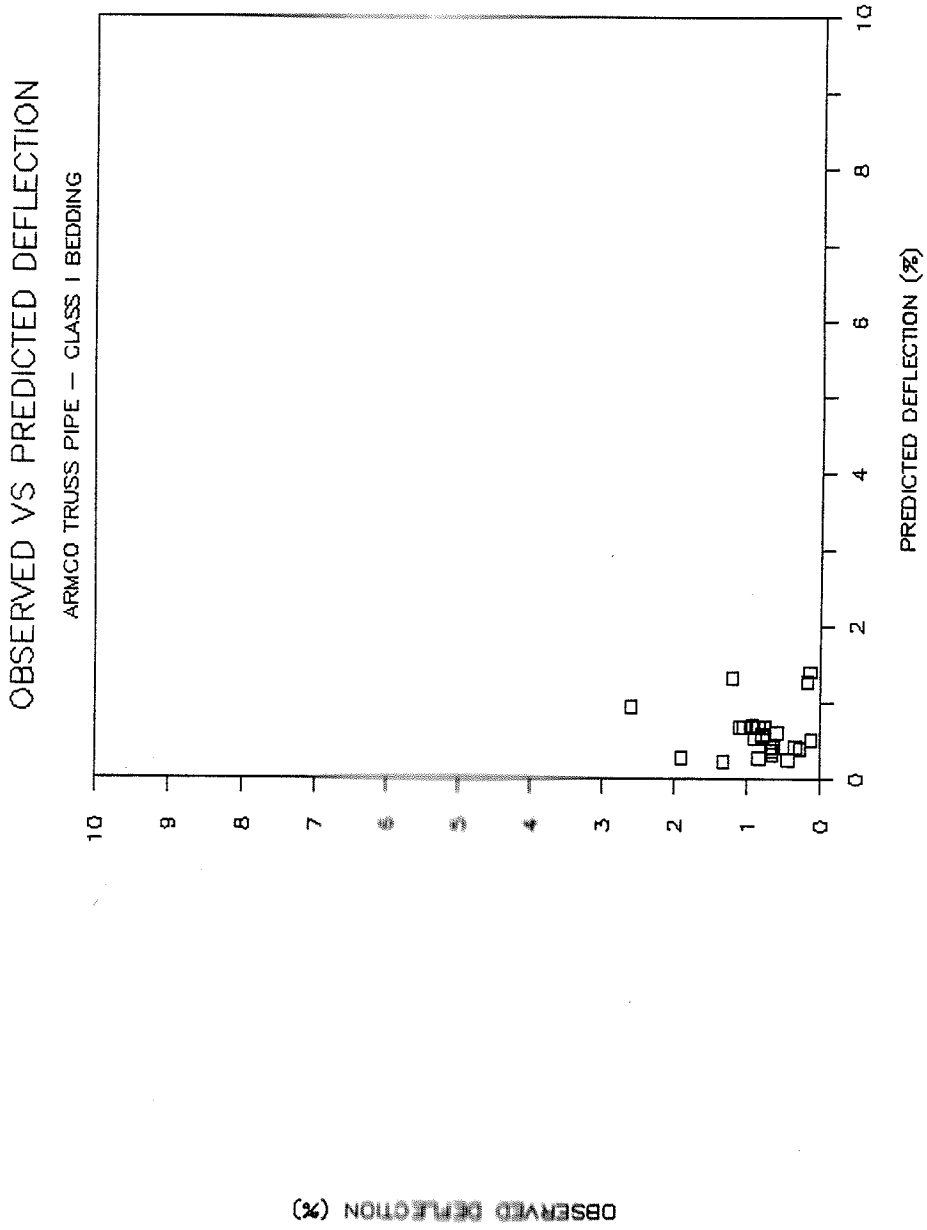


Figure A1.97 Observed vs Predicted Deflection
8 inch SDR35 PVC Pipe
Crushed Stone Envelope.
(National Clay Pipe Institute)

OBSERVED DEFLECTION (%)



**Figure A1.98 Observed vs Predicted Deflection
Truss Pipe - Class I Bedding.
(Contech Construction Products Inc.)**

OBSERVED VS PREDICTED DEFLECTION

ARMCO TRUSS PIPE - CLASS II BEDDING

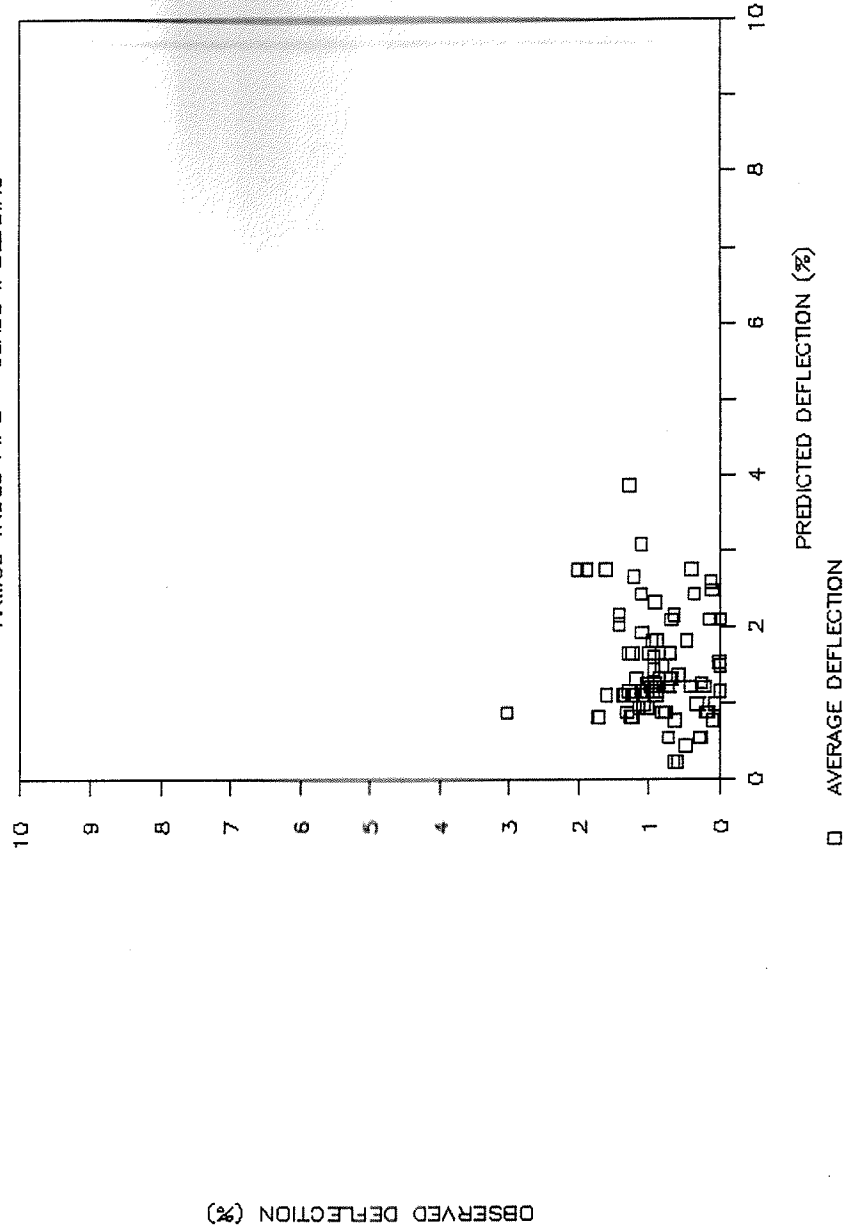


Figure A1.99 Observed vs Predicted Deflection
Truss Pipe - Class II Bedding.
(Contech Construction Products Inc.)

OBSERVED VS PREDICTED DEFLECTION

ARMCO TRUSS PIPE - CLASS III BEDDING

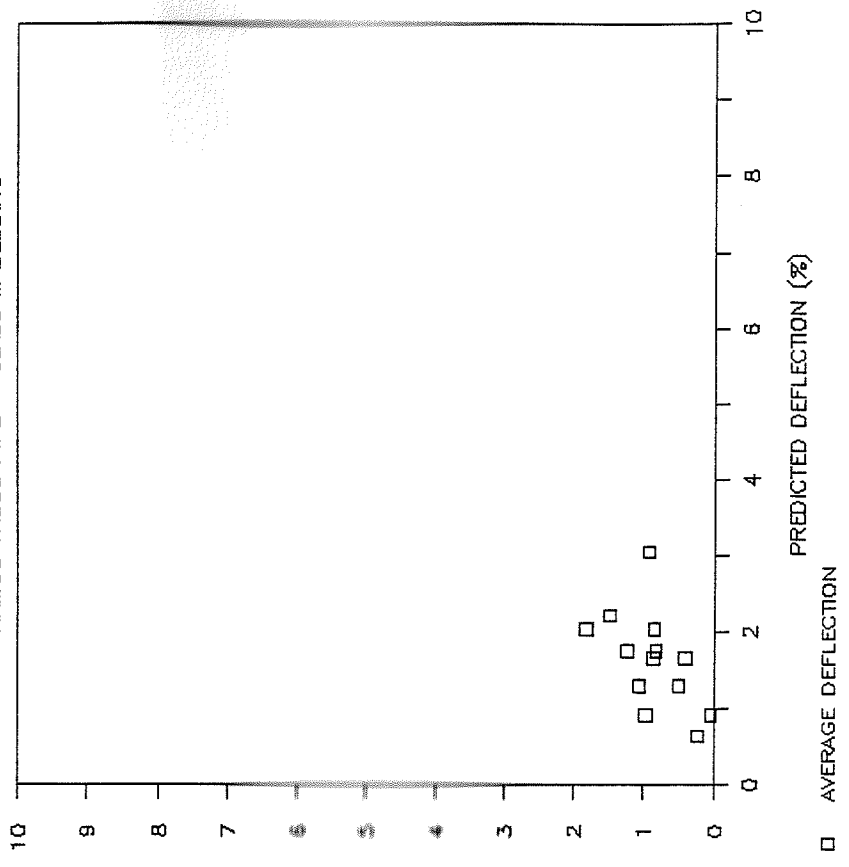


Figure A1.100 Observed vs Predicted Deflection Truss Pipe - Class III Bedding. (Contech Construction Products Inc.)

OBSERVED DEFLECTION (%)

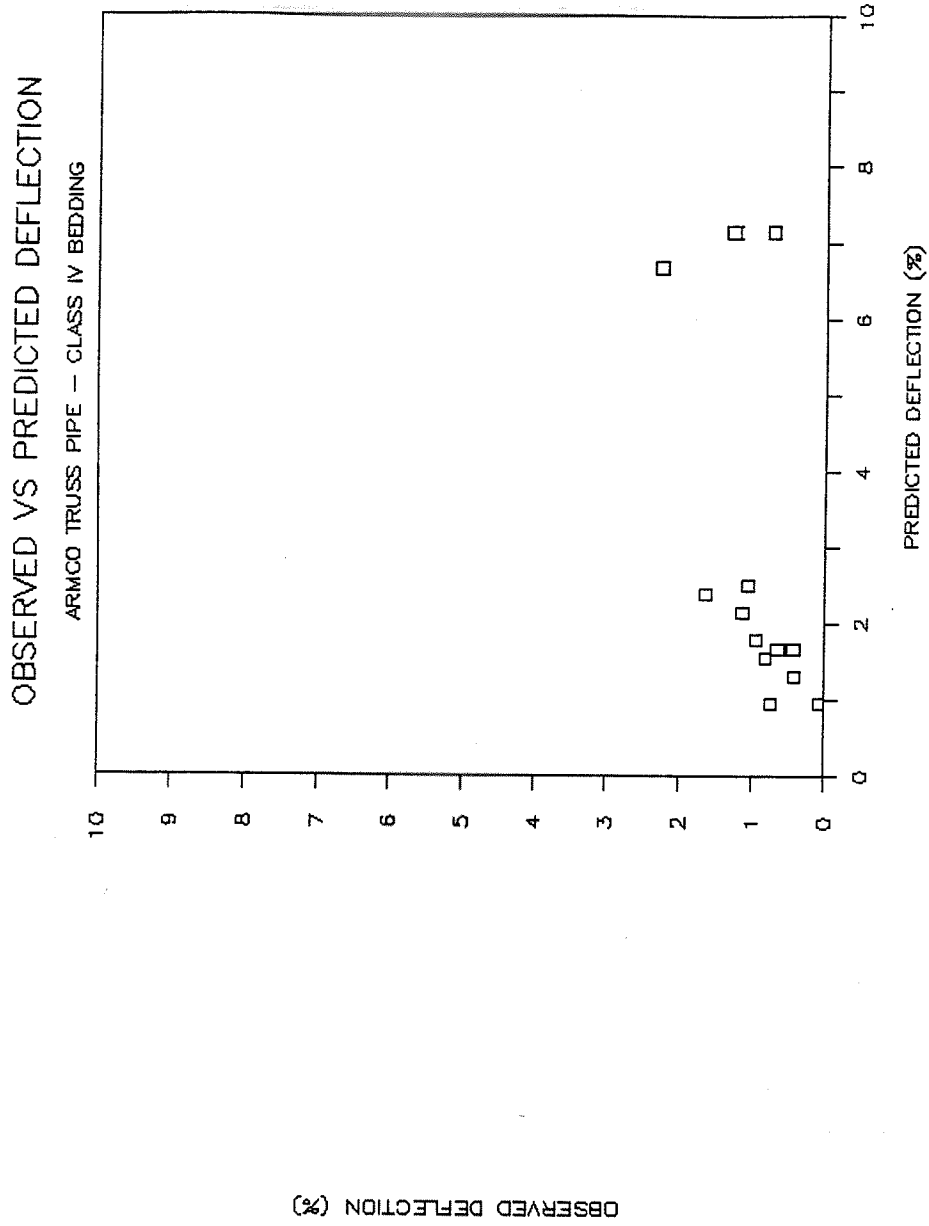
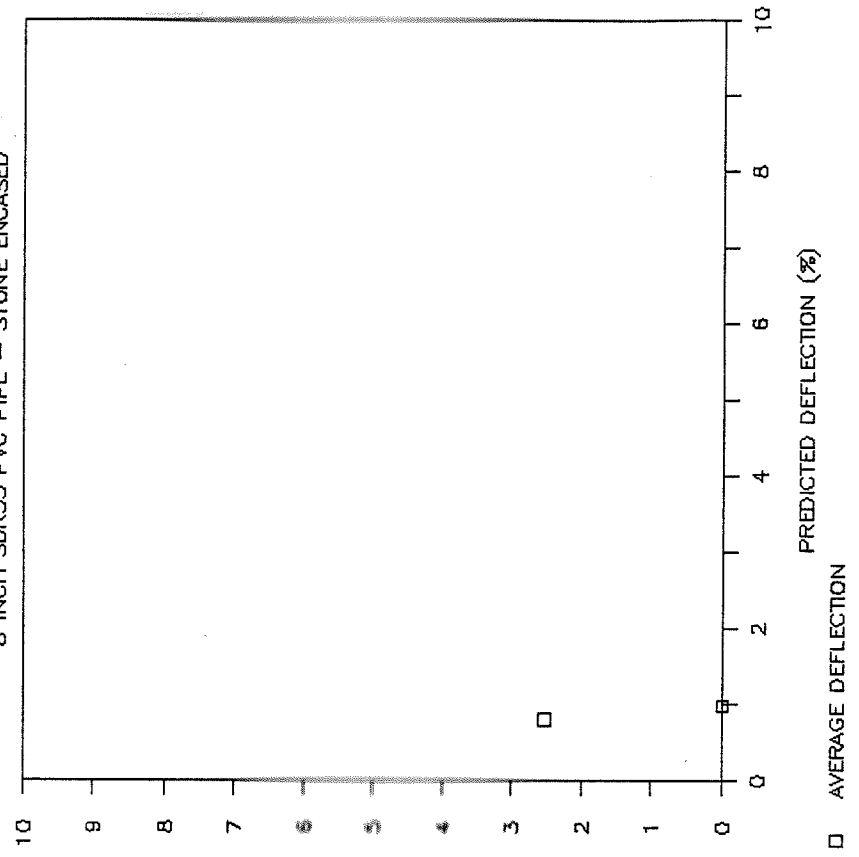


Figure A1.101 Observed vs Predicted Deflection
Truss Pipe - Class IV Bedding.
(Contech Construction Products Inc.)

OBSERVED DEFLECTION (%)

OBSERVED VS PREDICTED DEFLECTION

8 INCH SDR35 PVC PIPE — STONE ENCASED



OBSERVED DEFLECTION (%)

Figure A1.102 Observed vs Predicted Deflection
8 inch SDR35 PVC Pipe
Crushed Stone Envelope.
(Donahue & Associates Inc.)

□ AVERAGE DEFLECTION

OBSERVED VS PREDICTED DEFLECTION

8 INCH SDR41 PVC PIPE - SAND BEDDING

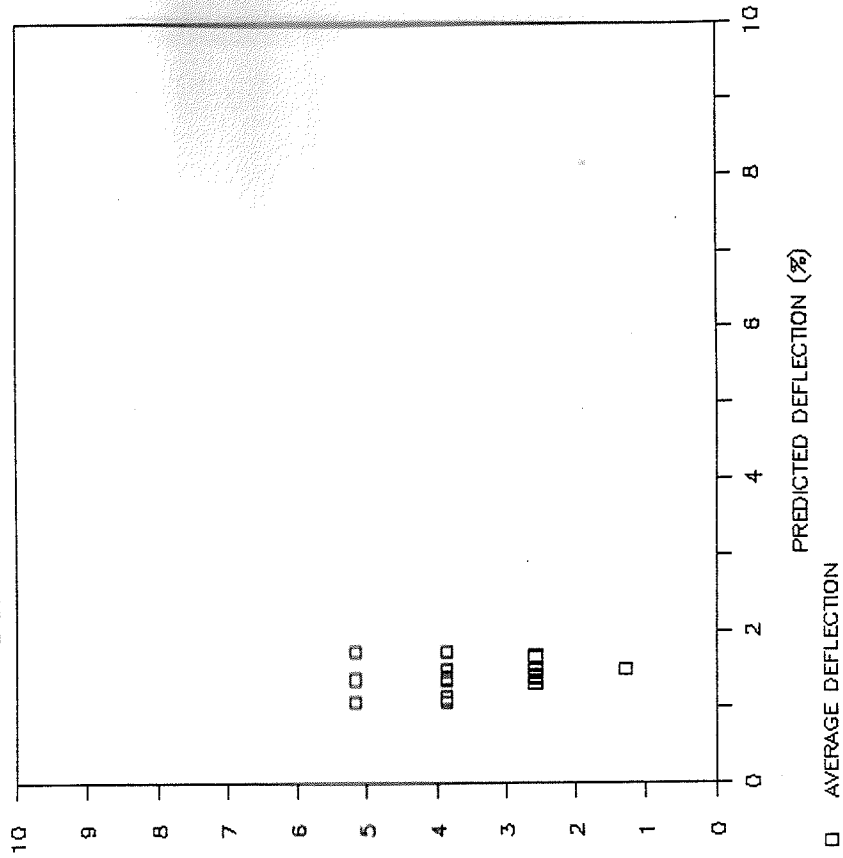
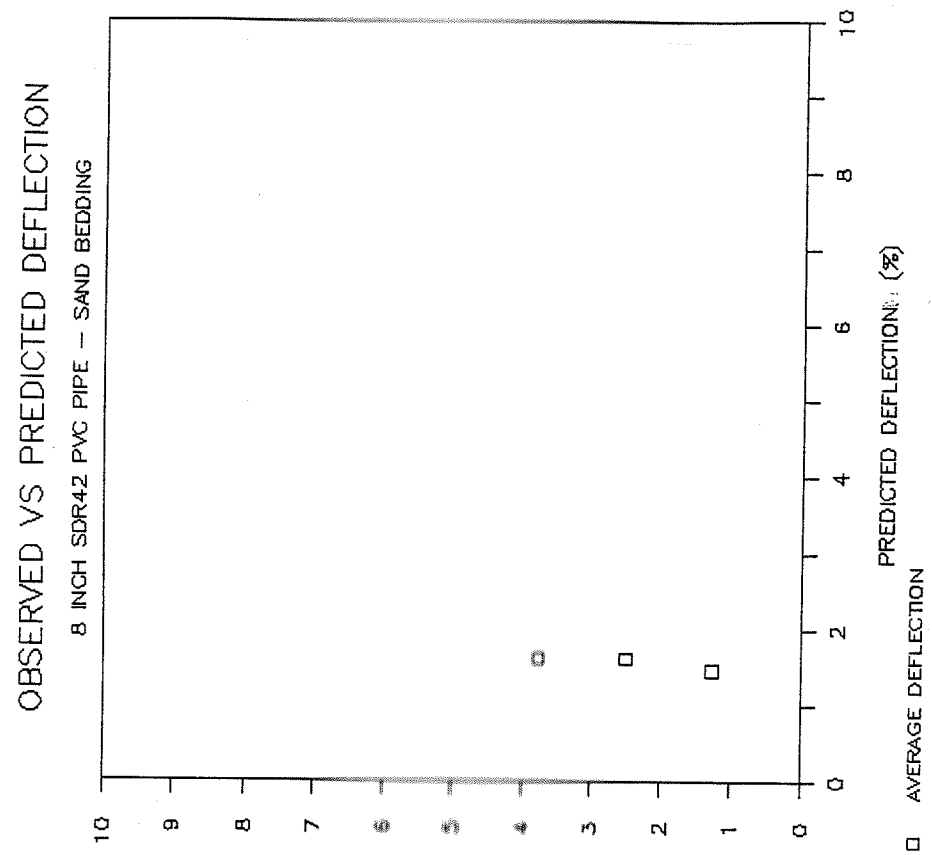


Figure A1.103 Observed vs Predicted Deflection
8 inch SDR41 PVC Pipe
Sand Bedding.
(Donahue & Associates Inc.)

OBSERVED DEFLECTION (%)



OBSERVED DEFLECTION (%)

**Figure A1.104 Observed vs Predicted Deflection
8 inch SDR42 PVC Pipe
Sand Bedding.
(Donahue & Associates Inc.)**

OBSERVED VS PREDICTED DEFLECTION
8 INCH SDR42 PVC PIPE - STONE ENCASED

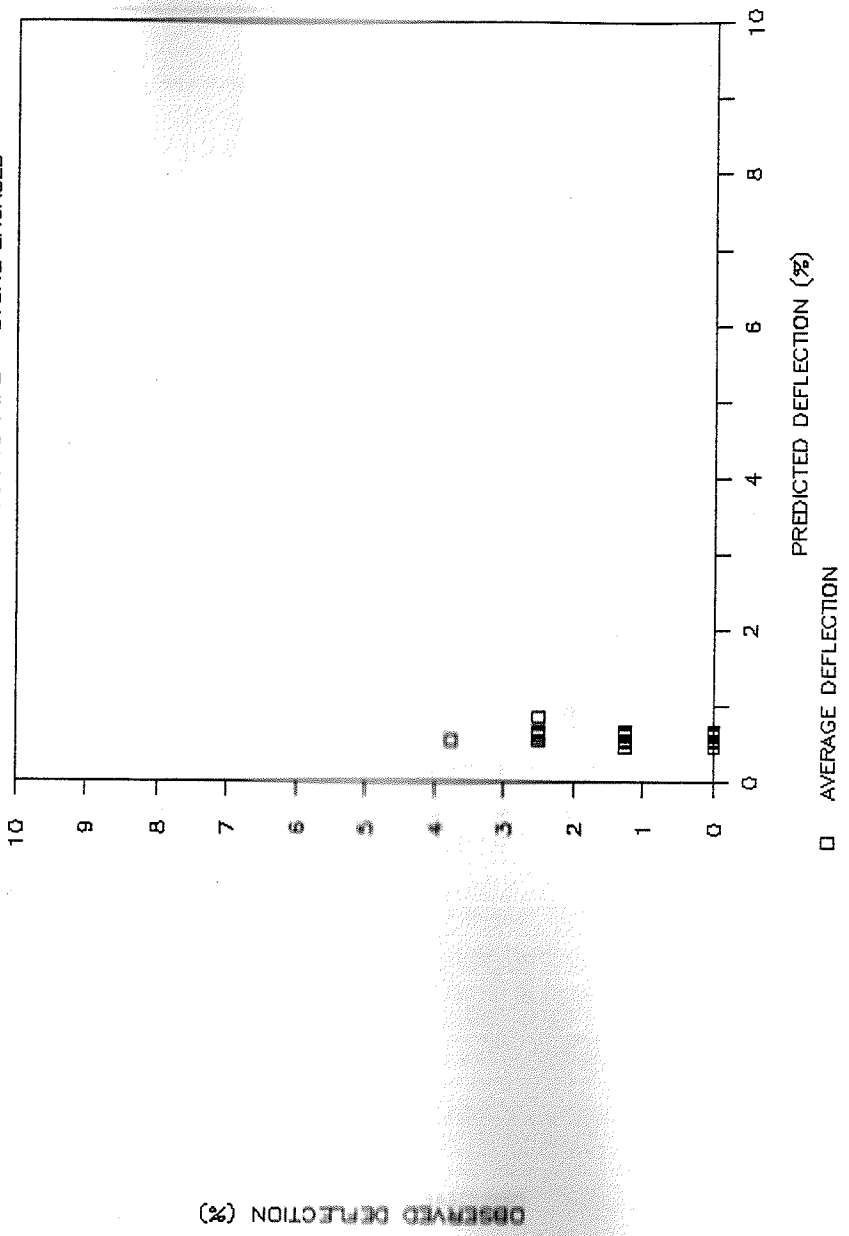


Figure A1.105 Observed vs Predicted Deflection
8 inch SDR42 PVC Pipe
Crushed Stone Envelope.
(Donahue & Associates Inc.)

OBSERVED VS PREDICTED DEFLECTION

10 INCH SDR42 PVC PIPE - STONE ENCASED

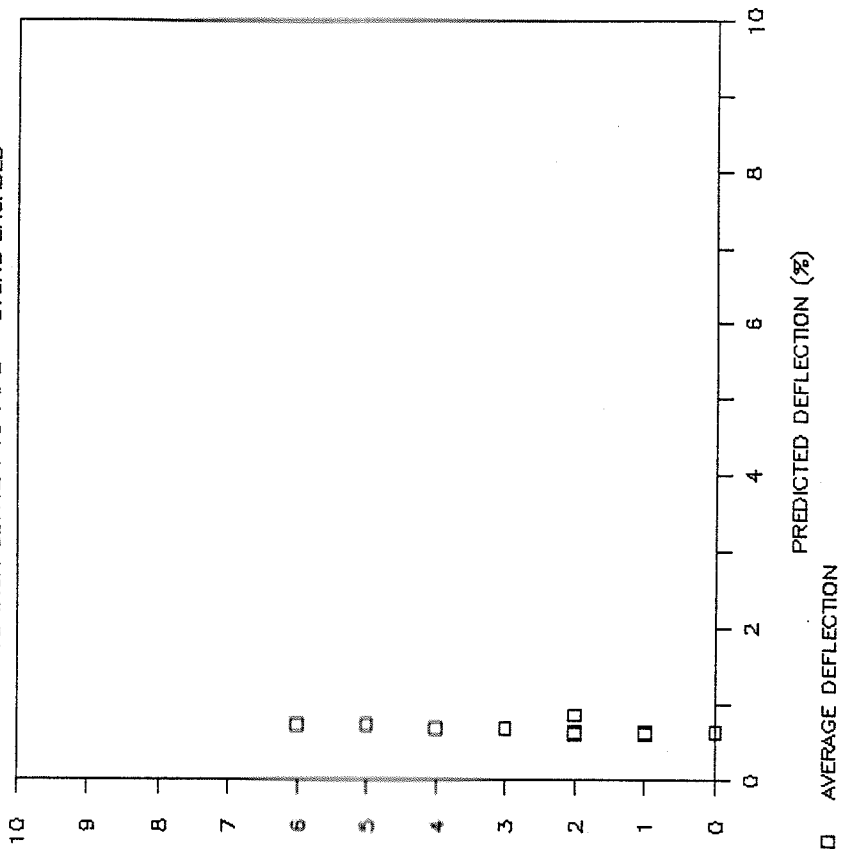


Figure A1.106 Observed vs Predicted Deflection
10 inch SDR42 PVC Pipe
Crushed Stone Envelope.
(Donahue & Associates Inc.)

OBSERVED DEFLECTION (%)

OBSERVED VS PREDICTED DEFLECTION

12 INCH SDR42 PVC PIPE — STONE ENCASED

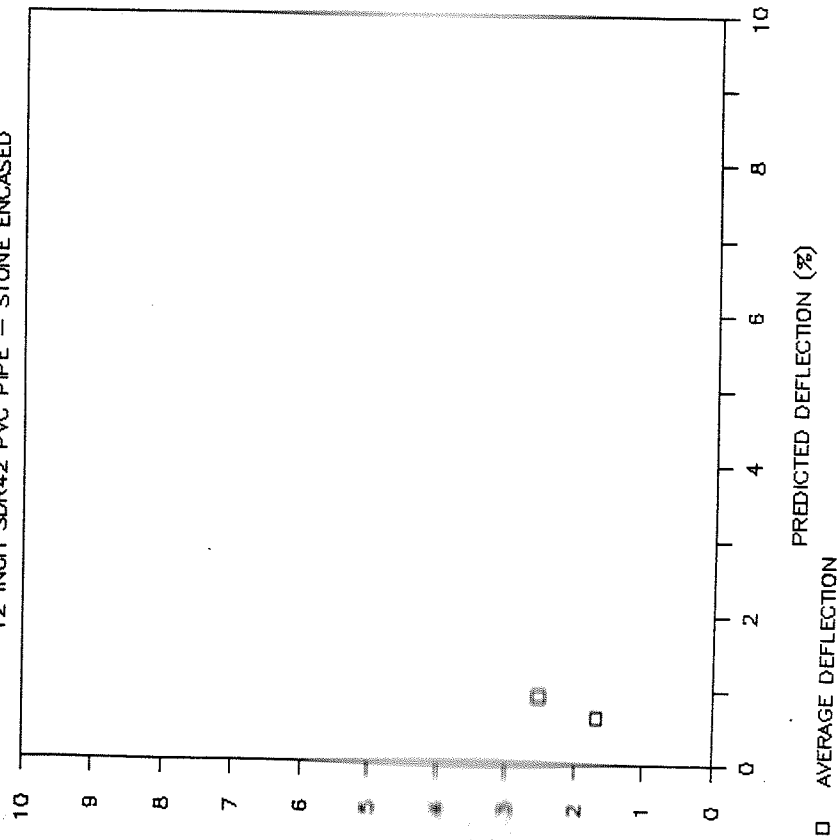


Figure A1.107 Observed vs Predicted Deflection
12 inch SDR42 PVC Pipe
Crushed Stone Envelope.
(Donahue & Associates Inc.)

OBSERVED DEFLECTION (%)

APPROVED



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Professor - Materials Science & Engineering Department

February 28, 1989

date