NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT 225

# PLASTIC PIPE FOR SUBSURFACE DRAINAGE OF TRANSPORTATION FACILITIES

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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# PLASTIC PIPE FOR SUBSURFACE DRAINAGE OF TRANSPORTATION FACILITIES

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- (AIR TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. OCTOBER 1980

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# FOREWORD

*By Staff*
*Transportation Research Board*

This report focuses on the application of various plastic pipe systems as suitable products for the drainage of highway and other transportation facilities. Guidelines for the selection, design, and installation of plastic pipe systems have been developed which will be of interest to design, construction, and materials engineers. Recommended specifications on two plastic pipe products and the installation of plastic pipe will be of special value to specification writers and specification writing bodies. Researchers, too, will appreciate the contents of the report, especially those portions concerning the challenges associated with determination of the long-term performance of plastic pipes.

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At the time the research problem was conceived, a number of plastic pipe products were available to the transportation industry that appeared to have good potential for economical use as underdrains, storm sewers, culverts, and other drainage structures. However, because of the lack of experience with these products in transportation facilities, their use was limited in these applications. Understandably, there was a reluctance to use them in place of, or as alternates to, more conventional pipe products whose in-service behavior had been established by many years of experience. Accordingly, a need existed for an evaluation of the theoretical considerations and field performance of buried plastic pipe to determine under what conditions they could be used in transportation facilities.

Under NCHRP Project 4-11, Simpson Gumpertz & Heger Inc. was assigned the task of developing and evaluating design, installation, and performance criteria for the use of buried plastic pipe products in transportation facilities. The research resulted in an assessment of this application. Additionally, guidelines for selecting, designing, and installing plastic pipes were developed including sample design problems, recommended specifications for two types of plastic pipe products (corrugated polyethylene tubing and polyvinyl chloride piping), and a recommended standard for field installation practices.

The assessment for transportation-related applications relied primarily on available information and experiences with plastic pipe systems, existing theories on the design of buried pipes, and the evaluation of monitored field installations in New Hampshire, Maine, Illinois, and Georgia. Extending the analysis of data from these various sources to the development of the guidelines and product specifications presented some problems in the area of structural adequacy over the long-term life of a buried plastic pipe. The short history of actual transportation uses, the lack of identified engineering properties of plastic pipe compounds, and the time dependency of important structural parameters over long periods of time were contributing factors to the difficulty of determining long-term structural adequacy. However, on the basis of a comparison of the information available on various generic thermoplastics and theoretical assumptions pertaining to long-term performance with the short-term data from monitored field installations, criteria addressing long-term structural adequacy were conservatively estimated and incorporated into the guidelines and the product specifications mentioned previously. These criteria, although conservative, are recommended by the researchers until further study permits more definitive engineering evaluations.

The report represents a significant contribution on the subject of plastic pipe and its suitability for transportation related drainage uses. Promising plastic pipe products have been identified, and procedures and practices for actual implementation recommended.

# CONTENTS

**ACKNOWLEDGMENTS**

The research reported herein was performed under NCHRP Project 4-11 by Simpson Gumpertz & Heger Inc., Consulting Engineers, Cambridge, Massachusetts. Haley and Aldrich, Inc., Consulting Geotechnical Engineers, were retained under subcontract by Simpson Gumpertz & Heger Inc., and were responsible for geotechnical aspects of the projects. Mr. Richard E. Chambers, Senior Associate, and Dr. Frank J. Heger, Senior Principal, were principal investigators. Mr. Timothy J. McGrath, Senior Engineer, was project engineer for the program. Mr. J. J. Rixner, Associate, Haley and Aldrich, Inc., was responsible for geotechnical portions of the project, with general supervision provided by Dr. Harl P. Aldrich, Senior Principal.

Numerous individuals from government agencies and private industry were consulted throughout the project. Grateful acknowledgment is extended to these individuals who contributed their time and background of experience to further this research effort. Special thanks are given to the New Hampshire Department of Public Works and Highways and the Maine Department of Transportation for their cooperation and effort in providing field installations for evaluative purposes. Many thanks are also extended to the Illinois and Georgia Departments of Transportation for allowing the researchers the opportunity to review their current practices.

# PLASTIC PIPE FOR SUBSURFACE DRAINAGE OF TRANSPORTATION FACILITIES


## SUMMARY

This report documents and presents the results of a study of buried plastic pipe for the drainage of transportation facilities. The overall objective of the study was to develop practical guidelines for the selection, design, specification, and installation of plastic pipe for subsurface drainage of transportation facilities.

Design, installation, and performance criteria were developed, analyzed, and evaluated in order to select pipe systems suitable for the application. Ongoing state installations of plastic pipe were monitored to observe installation practice. Full-scale field tests were performed in cooperation with states to obtain realistic data on the effects of installation conditions and on pipe behavior and performance. This information is summarized herein. The documentation developed from this work presents and evaluates criteria for selection of plastic structural materials, design procedures, and installation guidelines. Guide specifications are proposed for corrugated polyethylene (PE) tubing and polyvinylchloride (PVC) pipe. A proposed recommended practice for installation of plastic pipe in transportation drainage applications is also presented.

*Plastic Piping Systems for Transportation Drainage*

Plastic piping systems currently available and appropriate for drainage of transportation facilities and included in this report are listed in the following. Only the PVC pipe, covered by specifications given in the report, is sufficiently well characterized to permit quantitative structural evaluation with a reasonable level of confidence; the other pipe systems listed must be used on the basis of experience, without benefit of rational engineering analysis:

1. *Polyvinyl chloride (PVC) sewer pipe for perforated underdrains, storm drains, and small culverts*—Principal use has been in sanitary sewers, with some application in storm sewers. Maximum diameter currently available is 15 in. (381 mm); much larger pipes are expected in the near future. Users and consultants report satisfactory performance, in some cases better than conventional buried piping systems. Lack of brittleness and resistance to salts and aggressive soils are cited as assets. Available materials standards are in need of improvement to reflect performance requirements for transportation drainage. A specification is proposed in the report that is more stringent than current standards and also contains provisions for perforations in underdrain pipe.
2. *Corrugated polyethylene (PE) drainage tubing for underdrains*—This tubing has been used very extensively for agricultural land drainage and for sanitary leach beds, and is being used increasingly for highway underdrains. Tubing is available in sizes up to 18 in. (457 mm) diameter, but maximum diameter covered by ASTM specifications is 8 in. (203 mm). The very extensive experience in agricultural and sanitary applications demonstrates the potential economy and versatility of this product. Available materials standards are in need of improvement to satisfy the requirements of important transportation facility applications. Some improvements are provided in specifications proposed herein, but development of a specification that is sufficiently restrictive to permit evaluation of long-term performance is beyond the scope of this project.

3. *Acrylonitrile-butadiene-styrene (ABS) composite (trussed wall) pipe for storm sewers*—Principal use is in sanitary sewers, with some application in storm sewers. Maximum diameter is 15 in. (381 mm). Owners and consultants report satisfactory performance. ABS materials are subject to attack by more chemicals than PVC, including gasoline. Structural behavior is complex, hence potential structural performance can not be predicted with any level of confidence by state-of-the-art methods.

4. *Acrylonitrile-butadiene-styrene (ABS) sewer pipe for perforated underdrains*—Principal use has been in sanitary sewers. Available diameter range is from 3 to 12 in. (76 to 304 mm), but standard pipes larger than 6 in. (152 mm) diameter are insufficiently stiff for the transportation drainage application. Unfavorable past economics, rather than technical deficiencies, appear to be the reason for the lack of use in larger sizes. ABS is generally similar in properties to PVC materials, although its overall chemical resistance and its resistance to cracking may not be as good. Current specifications do not characterize materials sufficiently for assurance of long-term performance.

Pipe systems that are not considered in detail in the report, but which may be appropriate for transportation drainage, are as follows:

1. *Polyethylene (PE) gravity or force-main sewer pipe for storm drains and culverts*—Principal use has been in sanitary sewer mains and outfalls. Experience has been mostly in Europe and Canada; U.S. experience, which is more limited, has principally been in sewer relining, force-mains, and outfalls. This pipe is available in sizes up to 48 in. (1,219 mm). This product is not yet covered by ASTM specifications. PE solid wall pipe is tough and rugged with good resistance to attack by many aggressive chemicals. A sophisticated heat welding process is required for joining. This pipe may be highly appropriate in special problem areas where a high degree of chemical or abrasion resistance is needed.

2. *Reinforced plastic mortar (RPM) pipe for storm drains and culverts*—Principal use is in sanitary sewers and water transmission. The pipe is available in sizes from 8 in. to 48 in. (203 to 1,219 mm) diameter. RPM has good resistance to many chemicals including those found in aggressive soils. There has been a significant record of structural failures reported to have resulted from inadequate quality control, stress corrosion in sewer acids, and improper installation practice. The stress corrosion problems have been investigated, and ASTM standards now contain a test and requirements to minimize this problem.

3. *Large diameter corrugated (PE) tubing for secondary culverts*—This is a relatively new product, available in sizes up to 18 in. (457 mm), but no standards are yet developed for diameters above 8 in. (203 mm). Once a suitable base of experience has been developed it should prove useful in small culvert applications.

*Plastic Pipe Performance*

This evaluation of performance is based on an analysis of available literature on plastics and plastic pipe, on personal interviews with researchers and users familiar with plastic pipe, and on the results of laboratory and field tests performed during this program.

*Structural Behavior.* Field tests performed during this program confirm that the behavior of buried plastic pipe is rational and consistent with appropriate extensions of existing theories for flexible metal pipe. The time-dependent (viscoelastic) behavior demonstrated by plastics can be readily accounted for by analytical methods derived herein and presented in the report.

The structural properties of some plastic pipe are not sufficiently characterized or standardized to permit the use of the methods developed for analysis of the system *a priori*. Thus, their structural performance can only be evaluated based on experience in drainage-related applications or on information obtained on specific pipe systems.

*Flexibility*. Available plastic pipe systems appropriate for the drainage application are much less stiff than conventional flexible pipe of the same diameter, such as corrugated metal conduit. This lower stiffness makes plastic pipe much more susceptible to deformation during installation than conventional products used for transportation drainage. This means that available plastic pipe systems require relatively more care during installation than conventional drainage pipe.

Unlike most conventional underground pipe systems, each standard plastic pipe system is usually supplied in one, or perhaps two, stiffness classes. These systems have satisfied the sanitary sewer and agricultural drainage applications, and have performed satisfactorily in project field tests. Stiffer classes of pipe may prove to be more satisfactory in the transportation facilities application, where installation may not be controlled full-time, where high levels of sustained traffic are encountered, or when the consequences of failure are significant.

*Materials*. Present ASTM specifications do not provide assurance that plastic pipe materials can sustain stress or strain for the long term, which is a performance requirement for buried pipe. Specifications for PVC pipe and corrugated PE tubing proposed in the report require the use of available plastic compounds characterized and tested for time-dependent strength.

*Structural Adequacy*. A working strain criterion has been proposed as a basis for the evaluation of structural adequacy of buried plastic pipe. This criterion, although somewhat controversial, provides a rationale for evaluating structural adequacy and for establishing acceptable pipe deflections. The criterion limits strains due to bending and circumferential compression. This is a significant departure from corrugated metal pipe design where yielding is allowed in bending.

An approximate analysis method has been synthesized during this study to evaluate the state of strain in a buried pipe. The PVC plastic pipe investigated by using this method has adequate margins of safety for reasonable burial depths, providing the pipe is embedded in compacted, quality materials. The structural properties of other plastic pipe and corrugated tubing systems are insufficiently characterized by specification to permit other than crude estimates of potential structural performance. Tightening of specifications on the latter products would allow better estimates of performance, but the modifications required are well beyond the scope of this effort.

*Wheel Loads*. Project field tests indicate that buried pipe systems with low cover, which are subjected to sustained heavy traffic, undergo deflections and strains that continue to increase with time and can not be predicted by available methods. This finding is based primarily on tests where the installed pipe is without benefit of pavement structure. A recent FHWA project entitled "Structural Responses of Selected Underdrain Systems" involved tests of plastic pipe buried below pavement, but its results were not available at the termination of the present project. Until more information is available the use of shallowly buried plastic pipe under sustained heavy traffic is experimental.

*Fittings and Connections*. No rationale is available for analysis of fittings and connections, as is the case for most buried pipe systems. No reports of problems have been received. Standards for fitting quality, now under development within ASTM, should be considered for adoption when available.

*Chemical Resistance.* No problems of deterioration are expected from exposure to most aggressive soils, road salts, or "normal" highway runoff. Each generic type of plastic (PE, PVC, and ABS) can be attacked by certain problem chemicals, including oils and greases; effects of exposure can be aggravated by expected sustained strain in the buried pipe. Overall, PVC, PE, and ABS provide chemical resistance in the order listed; the sensitivity of each, however, varies with the specific chemical.

*Biological Attack.* Plastics are generally resistant to both micro- and macro-biological attack. Rodents may chew on corrugated PE tubing; animal guards are needed at pipe ends. Iron bacteria in the soil can clog perforations in underdrains and voids in the drainage envelope. This problem is outside the scope of this project.

*Ultraviolet (UV) Radiation from Sunlight.* Plastic pipe can degrade in sunlight, if not properly stabilized with chemicals. Although proper levels of stabilization can be furnished, such levels have not been standardized. This presents a serious practical problem to the user, because manufacturers and distributors frequently provide no protection from UV radiation during storage and transit. Materials received at the job site should be tested for impact strength, which is a good indicator of UV degradation. Materials should be stored under cover if intended job exposure is more than a few weeks.

*Freezing and Thawing.* Pipe compounds are generally resistant to deterioration from freezing and thawing.

*Abrasian Resistance.* Plastic pipe is resistant to abrasion by water-borne slurries of abrasive materials. Abrasion by heavy aggregates carried at high flow velocities requires special consideration, particularly at locations such as elbows, where the flow changes direction.

*Fire.* Plastics burn; there is a risk of loss by fire in the line or when pipe is exposed without soil cover during storage and construction. Fire-resistant pipe materials should be used to terminate plastic pipe at day-lighted ends.

### *Installation of Plastic Pipe*

The performance of a buried plastic pipe system can not be assessed independent of the design and execution of the installation. Because plastic pipe is very flexible, the density of the embedment material placed around the pipe and the placement and compaction process are the primary determinants of buried pipe behavior and structural performance. Typically, these factors outweigh by far any effects predicted by soil-structure interaction theory (e.g. Spangler's classical formula or more advanced methods).

*Uniformity of Embedment.* Plastic pipe must be surrounded completely by an envelope of quality embedment materials. Any omission or soft spots in the embedment will almost certainly result in excessive deflection of such flexible pipe. Installation procedures must be field monitored to ensure the required uniformity.

*Quality of Embedment.* Crushed stone or other processed angular materials, or clean free drainage gravels, should be used for embedment of plastic pipe in transportation installations, unless specific classes of finer soils are proven suitable.

*Machine Installation.* Plastic pipe, and particularly corrugated polyethylene tubing, can be installed by highly automated equipment that is regularly employed in the installation of agricultural drainage systems. This equipment cuts a trench to accurate grade, frequently by laser control. The equipment used in Illinois DOT shoulder drain tubing installation forms a shaped bedding groove in the trench bottom, it places the tubing in the groove, and it dumps and compacts select material around and above the pipe. The equipment is capable of installing several miles of shoulder drain in one day. It is the preferred method for the installation of corrugated polyethylene tubing that is otherwise difficult to hold straight and in place during installation.

CHAPTER ONE

# INTRODUCTION AND RESEARCH APPROACH

## BACKGROUND

A number of plastic pipe products have become available to the transportation industry that appear to have good potential for economical use as underdrains, storm sewers, culverts, and other drainage structures. Lack of experience with these products in transportation facilities has caused a reluctance to use them as alternates to more conventional pipe products for which in-service performance has been established by long experience in many applications. Accordingly, an evaluation of the theoretical considerations and field performance of buried plastic pipe was deemed necessary to determine under what conditions they can be used in transportation facilities. The research results presented here are the product of a study initiated by the National Cooperative Highway Research Program and conducted under NCHRP Project 4-11, "Buried Plastic Pipe for Drainage of Transportation Facilities."

The study was conducted in two phases. The first phase, completed in September 1975, was a review and evaluation of available plastic pipe systems and candidates for transportation drainage applications. The results of this work were summarized in an Interim Report (*1*). The second phase consisted of laboratory tests, further study, and full-scale field tests that were designed to investigate and evaluate performance of several types of buried plastic pipe in actual transportation installations.

## RESEARCH OBJECTIVES

The overall objective of this project was to evaluate and develop procedures for the selection, design, and installation of buried plastic pipe in transportation facilities.

The specific objectives of Phase I were as follows:

1. Identify the types, sizes, and physical and chemical characteristics of plastic pipe products currently available and considered suitable for use as underdrains, storm sewers, and culverts.
2. Evaluate the current state of the art; appraise the performance with regard to abrasion, frost action, temperature variations, and other environmental considerations; and prepare tentative guideline procedures for design and installation.
3. Design an experimental program to be conducted in Phase II, to improve the understanding of the time-dependent soil-structure interaction of buried plastic pipe subjected to earth and live loads, and to investigate other performance factors in need of further study.

The specific objectives of Phase II were to:

1. Conduct the experimental program outlined in Phase I.
2. Analyze and interpret the information obtained from the experimental program, synthesize the data with other available information, and refine the tentative guidelines prepared under Phase I.
3. Prepare a manual on the use of plastic pipe for subsurface drainage of transportation facilities, with particular attention to permissible loads and deflections, use limitations, material specifications, acceptance tests, construction and maintenance techniques, and inspection criteria.

## RESEARCH APPROACH

The research approach of the Phase I effort was as follows:

1. Questionnaires were prepared and sent to members of the AASHTO Operating Subcommittee on Materials in 50 states, and to other transportation agencies to determine their experience record with plastic pipe, including subsequent performance, and to obtain available specifications and test data.
2. Manufacturers of plastic pipe and plastic materials suppliers were surveyed to obtain product information, back-up test data, and other appropriate information on plastic pipe products.
3. A literature search was made to obtain technical information on such subjects as plastic pipe and plastics materials, soil-structure interaction, and long-term performance factors.
4. Intensive interviews were conducted with those having experience and technical expertise in plastic pipe. These took place at several meetings of ASTM Committee F-17 on Plastic Piping Systems, and in conferences with representatives of manufacturers and materials suppliers, the

National Clay Pipe Technical Institute, The American Concrete Pipe Association, The Plastics Pipe Institute, Uni-Bell Plastic Pipe Association, the Institut für Kunststoffrerarbeitung (Germany), Vattenbyggnadsbyran Consulting Engineers (Sweden), and the States of Georgia, Ohio, and Illinois. Telephone interviews were also conducted with manufacturers and materials suppliers, transportation departments of several states, federal agencies, municipalities, counties, and consulting engineers.

5. State-of-the-art analytical methods for pipe–soil interaction and design approaches for plastic pipe were reviewed, analyzed, and compared. A simplified procedure was synthesized to design and evaluate buried plastic pipe when subjected to vehicle and earth loads.

6. Literature was reviewed to obtain information on performance of plastics and plastic pipe.

7. Several types of plastic pipe were analyzed for stress levels and deformations anticipated in the highway application.

8. Existing standards and specifications for product selection and installation were critically reviewed for adequacy in meeting the needs of the transportation drainage application.

9. On the basis of the foregoing evaluations, certain pipe systems were selected as primary candidates for detailed evaluation in Phase II.

10. A laboratory program was conducted to explore the problem of buried plastic pipe with shallow cover under surface wheel loads and to evaluate instrumentation techniques for Phase II field tests.

11. A field test program was designed for implementation in Phase II.

12. Existing practice for design of underdrain drainage envelopes was reviewed to establish design criteria for pipe perforations (holes, slots) and envelope materials.

13. Tentative guidelines for specification and selection of pipe systems and installation of plastic pipe were prepared.

The research approach of the Phase II effort was as follows:

1. Full-scale field tests were performed in cooperation with the States of Maine and New Hampshire. Installation guidelines developed during Phase I were evaluated, and the performance of several plastic pipe systems was monitored at these sites. Variables examined in the tests included:

Depth of Burial: 2 to 23 ft (0.6 to 7.0) m.
Pipe Types: ABS, PE, PVC smooth-wall pipe, ABS composite-wall pipe, and corrugated-wall PE tubing.
Pipe Diameters: 6 to 16 in. (150 to 400 mm)
Embedment Materials: Coarse sand, sand with fines, and crushed stone.
Bedding Conditions: Shaped grooved bedding with haunching, flat bedding with haunching, and flat bedding with haunching purposely omitted.
Measurements: Diametral changes (or deflection) were measured using deflectometers. Strain gage instrumentation was applied to some pipe at all installations.
Duration of Burial: Six months to two years; one installation is permanent.

2. On-going installations of corrugated-wall PE tubing were monitored in Georgia and Illinois to obtain information on experience and installation details and techniques.

3. Limited exploratory tests were performed to determine the strength behavior of plastic pipe while held under large fixed deflections (strains) in air and water.

4. Information obtained from the states, the industry, and the literature was reviewed and evaluated and incorporated into project findings as appropriate.

5. Several meetings of ASTM Committee F-17 on Plastic Piping Systems were attended to keep abreast of the state of the art and to participate in ongoing standards development that had bearing on the project.

6. A manual, included in this report in Chapter Three, was prepared, which contains selection, design, and installation guidelines as synthesized from project findings; materials specifications; and a recommended practice for pipe installation.

## GLOSSARY

### Abbreviations

ABS = Acrylonitrile butadiene styrene
DR = Dimension ratio
FRP = Fiberglass reinforced plastic
HDB = Hydrostatic design basis
MF = Moment factor, bedding factor for bending stress
PE = Polyethylene
PF = Perforation factor, accounts for strain concentrations
PS = Pipe stiffness
PVC = Polyvinyl chloride
RPM = Reinforced plastic mortar
SDR = Standard dimension ratio
SF = Safety factor
SR = Styrene rubber
USCS = Unified Soil Classification System
UV = Ultraviolet

### Notations

$A$ = Area of pipe wall per unit length (equal to thickness for smooth-wall pipe) (in.$^2$/in.) (mm$^2$/mm).
$B$ = Coefficient in Chelepati buckling formula
$C$ = Coefficient in Chelepati buckling formula
$C_B$ = Coefficient for buckling stress
$C_B = 0.50$ for earth load, and 0.07 for wheel load ($p_w \geqq 0.25 p_s$)
$C_D$ = Correction factor to buckling formula to account for deflection = $(D_{min}/D_{max})^3$
$\tilde{C}$ = Coefficient in Chelepati buckling formula
$D_1$ = Deflection lag factor
$D_{max}$ = Maximum diameter of deflected pipe, in. (mm)
$D_{min}$ = Minimum diameter of deflected pipe, in. (mm)
$E_v$ = Time-dependent viscoelastic modulus of plastic pipe material, psi (MPa)
$E_o$ = Elastic modulus of plastics obtained in short-term tension test, psi (MPa)
$E_s$ = Youngs modulus of soil, psi (MPA)
$E'$ = Modulus of soil reaction of embedment material, psi (kPa)

$F$ = Load on pipe during parallel plates test, lb/in. (N/mm)
$H$ = Height of earth cover above pipe springline, in. (mm)
$I, I_c$ = Moment of inertia per unit length of pipe wall in.$^4$/in. (mm$^4$/mm)
$K$ = Bedding constant for deflection
$M_1$ = Moment at invert, in.-lb/in. (N-mm/mm)
$M_s$ = Constrained modulus of soil, psi (kPa)
$PS_v$ = Time-dependent pipe stiffness, lb/in./in. (kPa)
$PS_o$ = Short-term pipe stiffness, specified value lb/in./in. (kPa/mm)
$PS_{10}$ = Long-term pipe stiffness, 10 years, lb/in./in. (kPa/mm)
$T$ = Springline thrust force in pipe, lb/in. (N/mm)
$W$ = Load on pipe in parallel plate test, lb/in. (N/mm)
$W$ = Pipe shallow burial critical load, lb (n)
$Z$ = Depth of cover over crown of pipe, in. (mm)
$d$ = Mean diameter of pipe, in. (mm)
$d_o$ = Outside diameter of pipe, in. (mm)
$f_{td}$ = Time dependent stress, psi (kPa)
$f_{yp}$ = Tensile yield point stress in plastic material, psi (kPa)
$p$ = Pressure at springline elevation of pipe, psi (kPa)
$p_{cr}$ = Critical buckling pressure on pipe, psi (kPa)
$p_s$ = Pressure at springline elevation of pipe due to earth weight, psi (kPa)
$p_w$ = Pressure at springline elevation of pipe due to surface wheel loads, psi (kPa)
$p_t$ = Pressure at springline elevation of pipe due to wheel and earth loads, psi (kPa)
$r$ = Pipe radius, in. (mm)
$r_o$ = Distance from pipe springline to ground surface, in. (mm)
$t$ = Minimum wall thickness of pipe (equal to area for smooth-wall pipe), in. (mm)
$\Delta$ = Pipe deflection, in. (mm)
$\Delta_{as}$ = Average deflection due to earth weight
$\Delta_{aw}$ = Average deflection due to wheel loads
$\Delta_i$ = Installation deflection
$\Delta_m$ = Allowable deflection
$\Delta_t$ = Total deflection
$\Delta_y$ = Vertical deflection parallel plate test
$\gamma_s$ = Density of earth cover, lb/ft$^3$ (kg/m$^3$)
$\epsilon$ = Strain in pipe wall in./in. (mm/mm)
$\epsilon_b$ = Ring bending strain
$\epsilon_c$ = Maximum combined compression strain (occurs in long term)
$\epsilon_r$ = Short-term ring compression strain
$\epsilon_t$ = Maximum combined tensile strain (occurs in short term)
$\epsilon_{td}$ = Time dependent strain in viscoelastic material
$\epsilon$ = Tentative working strain limit
$\nu_s$ = Poisson's ratio of soil
$\sigma_t$ = Time dependent stress in viscoelastic material, psi (kPa)

CHAPTER TWO

# FINDINGS

The scope of this project on buried plastic pipe was comprehensive in that all appropriate plastic pipe systems were considered, a broad range of performance criteria was developed and evaluated, field observations of ongoing installations and large-scale field-test programs were conducted in cooperation with states, and, finally, specifications for selected pipe and tubing systems and installation guidelines were developed. For the most part, information contained herein is that current in early 1979.

## STATUS OF PLASTIC PIPE IN TRANSPORTATION DRAINAGE

A survey made during the early phases of NCHRP study provided an overview of the status of plastic pipe in transportation drainage in 1975. Response to a questionnaire sent to the 50 members of the AASHTO operating committee on materials revealed that (1) about one-half of the states responding had no experience with plastic pipe, and (2) only seven of the states had installed more than one mile of plastic pipe. Most of these states had installed only corrugated-wall PE tubing for shoulder underdrains, one state had installed ABS composite-wall pipe for storm drains, and one state had installed RPM sewer pipe for the same purpose. One state had used special slotted PVC pipe for horizontal inserted side-slope drains. (The responses are summarized in Appendix H. Copies of the questionnaires and accompanying letters are also given in this appendix.)

The greatest interest in plastic pipe by transportation agencies appears to be for use in underdrain applications, and corrugated-wall PE tubing has been, thus far, the primary candidate for this application. As of 1978, the States of Georgia, Illinois, and Michigan allow perforated corrugated PE tubing as an alternate to other standard materials for underdrains. Pennsylvania allows the use of PVC "half-round" drainage pipe.

Plastic pipe systems that are available and that were considered during the NCHRP Project 4-11 study are summarized and described in Table 1. Typical usages are described, available background on each system is outlined, and the extent to which the system is covered in this report is indicated.

## SELECTED PIPE AND TUBING SYSTEMS FOR TRANSPORTATION APPLICATIONS

The pipe systems considered in detail in this report and summarized in Table 2 were selected in accordance with the following criteria:

1. Good experience record in substantial drainage-related applications (e.g., sanitary sewers, agricultural land drainage) in the United States.
2. Maturity of the product as indicated by availability of ASTM standards covering the system.
3. Adequate expected performance based on experience and analytical evaluation.
4. Adequacy of performance in field tests conducted during the NCHRP study.

Some of the selected systems covered in this report do not fully satisfy these criteria. Other plastic piping systems that are available include PE and RPM smooth-wall pipe for storm drains and small culverts, and large diameter corrugated-wall PE tubing for secondary culverts. These systems are not covered in detail herein primarily because either the experience record in the United States is limited, ASTM specifications are not available, or, for RPM pipe, past performance has not been consistent.

### Acrylonitrile Butadiene Styrene (ABS) Composite Wall Pipe

Acrylonitrile butadiene styrene (ABS) composite wall sewer pipe was first installed about 1963. The principal manufacturer and licenser of this pipe system states that several thousand miles of sewer lines have been installed. The Illinois Department of Transportation has used a small quantity of this material for storm sewers, and an evaluation made by them indicates satisfactory performance (*2*). Most use of ABS composite pipe has been in municipalities. Users report satisfactory performance for installations installed up to about 12 years, although most experience has been for shorter periods. The city of New Orleans, La., for example, first used ABS composite sewer pipe in very poor soil to correct continuing failures of conventional sewer pipe. They have used this type of pipe increasingly for sewers, mainly because it has proven durable. Furthermore, the field-bonded joints have resulted in low infiltration from high water tables.

ABS composite-wall pipe (also referred to as ABS composite pipe) derives its name from the construction of the wall. The plastic portion of the wall consists of two concentric tubes, connected by longitudinal webs arranged in a triangular pattern across and around the annual space between tubes; this forms a circular ring-truss configuration (Table 2). The annular cavity is filled with a lightweight foamed cement; other inert filler materials are allowed by ASTM standards. The cement filler stabilizes the thin web sections of the extruded plastic against local buckling, and imparts a ruggedness to the pipe during handling.

Despite the widespread acceptance, use, and apparently successful experience record of the ABS composite piping system, insufficient information is available either to characterize its structural performance or to verify its potential performance in the long term. Overall, selection of this system must necessarily be based on its "track record" in municipal sewers. Limited study indicates that this pipe should not be perforated.

### Acrylonitrile Butadiene Styrene (ABS) Smooth Wall Pipe

ABS was one of the first plastics to be used in smooth-wall sewer pipe in the United States. Since then, it has been used primarily as service lines in diameters of 6 in. (150 mm) or less, in conjunction with larger diameter ABS composite-wall collector lines. Its use in larger sizes in primary municipal installations appears to be extremely limited, at least in recent years, relative to ABS composite and PVC smooth-wall pipe. (This appears to be for economic rather than technical reasons.)

The experience record of generic ABS smooth-wall pipe, while longstanding, is not extensive in major installations, particularly in the larger sizes. Furthermore, present specifications provide insufficient structural characterization of materials for either short-term or long-term properties. Overall, selection of this system must be based on its "track record" in small-diameter sewer service lines. The use of the more flexible pipe supplied in larger diameters may invite field problems of overdeflection.

### Corrugated Polyethylene (PE) Tubing

Corrugated polyethylene tubing was developed in Europe in the early 1960's and since 1967 has seen major application in agricultural land drainage in the United States. Reportedly, well over 100,000 miles (160,000 km) of this tubing have been used for arid and humid agricultural drainage. Both the Bureau of Reclamation (U.S. Department of Interior) and the Soil Conservation Service (U.S. Department of Agriculture) have endorsed the use of corrugated tubing in these applications. Several state transportation agencies have installed corrugated tubing in highways either on a trial basis or as an alternate to other underdrain systems. Other applications are in sanitary leach beds and foundation drains.

The major use and apparent success of corrugated PE tubing in agricultural drainage applications render this system an attractive candidate for transportation underdrains. Existing specifications for the product remain much too broad to permit an *a priori* engineering evaluation of a product conforming to the specifications. Hence, selection must be based on experience rather than on engineering rationale.

### Polyvinyl Chloride (PVC) Pipe

Polyvinyl chloride (PVC) pipe has been widely used in

TABLE 1

SUMARY OF PLASTIC PIPE AVAILABLE FOR SUBSURFACE DRAINAGE APPLICATIONS (AS OF DEC. 1978)

| | Material(1) | Wall Type | Available(2) Diameter Range (in.) | Standard Specification(3) Number | Typical Current Usage | Comments | Included in guidelines |
|---|---|---|---|---|---|---|---|
| PERFORATED UNDERDRAINS | ABS | Smooth | 3 - 12 | ASTM D 2751 | Foundation drains, leach beds. | Very limited experience record. Perforations non-standard. | Yes |
| | PE | Corrugated | 3 - 8 | AASHTO M 252 ASTM F 405 | Highway underdrains, agricultural drainage, leach beds, building foundation drains. | Very extensive acceptance in agricultural drainage. Some states allow use for underdrains. Much interest shown by many state transportation agencies. | Yes |
| | PVC | Smooth | 4 - 15 | ASTM D 3033 & D 3034 | Trial installations in Illinois as highway shoulder underdrains; main use has been in sanitary leach beds and building foundation drains. | Significant usage but experience record difficult to obtain because of limited size of most projects Perforations non-standard. | Yes |
| | PVC | Corrugated | – | None | Possible usage as above. | New product in U.S.A. Used in Europe. No recent activity in ASTM standards development. | No |
| | SR | Smooth | 2 - 6 | ASTM D 3298 | Building foundation drains, leach beds. | Very brittle material; no significant highway related experience record. | No |
| | SR | Corrugated | 4 | None | Building foundation drains, leach beds. | Same as solid wall type; extremely brittle; no present manufacturers of this product known to us, no recent activity in ASTM. | No |
| SMALL CULVERTS AND STORM DRAINS | ABS | Smooth | 2 - 12 | ASTM D 2751 | Sanitary sewers and storm drains, building sewers. | Very limited experience record in sizes larger than 6 in. | No |
| | ABS | Composite | 8 - 15 | ASTM D 2680 AASHTO M 264 | Sanitary and storm sewers. | Good experience record for 12 years. Owners and consultants satisfied. | Yes |
| | FRP | Smooth & Ribbed | 2 - 144+ | ASTM D 2996 & D 2997 | Outfalls, chemical handling, sub-aqueous lines, sewers, power plant discharges, storm sewers. | Appropriate for aggressive soils and corrosive applications. Pipe may be very flexible. | Limited treatment |
| | PE | Smooth | 3 - 48 | None | Sewer force-mains, relining existing sewers, outfalls, abrasion/corrosion applications | Most experience in Europe, Canada. Tough rugged pipe. Appropriate for special problem areas, with corrosive or abrasive conditions. | Limited treatment |
| | PE | Corrugated | 3 - 18 | ASTM F 405 AASHTO M252 | Drainage, small culverts. | Still experimental. Other ASTM standards are under development. | Limited treatment |
| | PVC | Smooth | 4 - 15 | ASTM D 3033 & D 3034 | Sanitary and storm sewers. | Good experience record for 12 years or more. Owners and consultants satisfied. | Yes |
| | RPM | Smooth | 24 - 78 | ASTM D 3262 | Sewers, irrigation, and water distribution. | Significant record of failures attributed to stress corrosion in sanitary sewers, manufacture and installation. Very flexible pipe. | Limited treatment |
| | SR | Smooth | 2 - 6 | ASTM D 2852 | Septic tank connectors, storm drains. | Material is brittle, size range too small for sewers and culverts. | No |

(1) KEY

ABS = Acrylonitrile-Butadiene-Styrene
FRP = Fiberglass Reinforced Plastic
PE = Polyethylene
PVC = Polyvinyl Chloride
RPM = Reinforced Plastic Mortar
SR = Styrene-Rubber

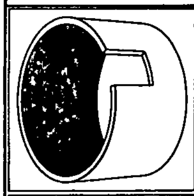
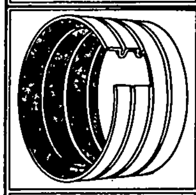
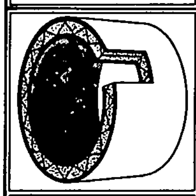
Note: 1 in. = 25.4 mm

(2) Diameter range covered by specification is frequently less than that which is commerically available.

(3) AASHTO = American Association of State Highway and Transportation Officials
ASTM = American Society for Testing and Materials

TABLE 2

PLASTIC PIPE AND TUBING FOR DRAINAGE OF TRANSPORTATION FACILITIES

| Wall Construction | Material | Diameter Range (in.) | Perforation Option | Specifications | |
|---|---|---|---|---|---|
| | | | | Reference | Proposed* |
|  a. Smooth Wall | ABS | 8-15 | Holes | ASTM D 2751 | None |
| | PVC | 4-15 | Holes | ASTM D 3033 or D 3034 | SGH PVC-TD |
|  b. Corrugated Wall | PE | 3-8 | Slots or Holes | ASTM F 405 AASHTO-M 252 | SGH PE-TD |
|  c. Composite Wall | ABS | 8-15 | None | ASTM D 2680 AASHTO-M 264 | None |

* Proposed by SGH and presented in Appendix A

Note: 1 in. = 25.4 mm

sanitary sewers and storm drains, drain waste vent, water supply, chemical transmission, underground telephone conduit, and in some crude oil and salt-water lines. One of the greatest uses has been in municipal sewers, an application which closely relates to transportation drainage. Users and consultants report satisfactory performance in both sanitary sewer and storm drainage applications. Thousands of miles have been installed, most of which have been in place for 12 years or less. Users cite lack of brittleness, resistance to road salts and aggressive soils, and competitive installed costs as reasons for use.

Perforated PVC pipe has been used on a limited basis for shoulder drains on the New York Thruway, and Illinois has installed several miles of PVC shoulder drains in trial installations. Principal use of perforated PVC pipe has been in sanitary leach beds and in foundation drainage for buildings.

Pipe systems (covered by ASTM D 3033 or D 3034, which are identical specifications except for overall dimensions) have a substantial record of good performance in municipal sewer applications. Nonetheless, the specifications alone are too broad to categorize the basic materials within reasonable engineering limits, and they do not address strength capacity under long-term sustained stress or strain. Thus, although the track record has been good, these existing standards provide neither a high level of assurance of long-term performance nor a sound basis for engineering design. Selection of PVC pipe which meets these standards is necessarily based on experience with transportation drainage-related applications such as sewers rather than on engineering rationale.

A modified form of the foregoing standards could provide reasonable assurance of long-term performance and a reasonably sound basis for engineering design and evaluation of PVC smooth-wall pipe for transportation drainage applications. Proposed specification SGH PVC-TD (see App. A2) is intended to achieve these objectives and also to incorporate provisions for perforations in underdrain pipe. Thus, the proposed specification is recommended for transportation drainage applications in which long-term performance is critical and technical evaluation is required.

## PERFORMANCE OF PLASTIC PIPE

This section identifies important criteria for the selection, design, and evaluation of plastic pipe for the transportation drainage application. Neither cost nor cost-benefit analysis is within the scope of this report.

### Structural Criteria

A primary objective in evaluating pipe performance is to determine the conditions under which the pipe will or will not break, or deflect to a point where function is impeded. This performance must be estimated for the long life of transportation installations, which is taken here as 50 years and which far exceeds the duration of the experience base of a decade or more. Thus, evaluation of structural performance of buried plastic drainage pipe encompasses both theoretical and practical considerations.

At the outset it should be recognized that the pipe is only one component of the buried structural systems. The other component, which usually has major controlling influence on pipe performance as installed, is the envelope of embedment material which surrounds and supports the pipe. The embedment system will be considered in more detail later.

The transportation drainage application places significant demands on structural performance of the installed piping system. Pipes must be stiff enough and strong enough to resist a variety of loads including those imposed during the process of installation, those applied by earth cover, and those applied by either construction traffic or by vehicular traffic during service. These demands may be more critical than those imposed in other applications where plastic pipe has been used successfully. Significant considerations are:

1. *Consequences of failure*—The consequences of failure of a drainage system vary widely. Failures can lead to stoppages and loss of intended function, with subsequent flooding, washouts, or accelerated deterioration of pavements because of poor drainage. Replacement and repair can involve interruption of traffic at best and, if extensive, extremely expensive dig-ups involving removal and replacement of portions of the pavement.

2. *Installation conditions*—For new construction, the drainage piping is installed part way through the construction of the facility. The trench is frequently trafficked with heavy construction vehicles before embankment construc-

tion, finished grading and paving, base, or subbase is completed. Thus, it is likely that the trench containing pipe and embedment material will be subjected to large and frequent wheel loads without benefit of the maximum protective cover which may be provided subsequently in the finished installation.

3. *Shallow burial*—Economics of construction, topography, or the requirements imposed by gravity flow drainage design frequently dictate shallow burial of the pipeline. Depending on location with respect to the roadway, the installation may receive occasional to frequent cyclic loads because of traffic.

4. *Monitoring and supervision*—The construction of underdrains and small storm sewer lines may receive low priority in the overall construction of major works such as transportation facilities. Attention of field monitors is frequently directed to the major components such as the pavement structure, the bridge construction, and the like, as well as to the inevitable construction problems. There is a likelihood that the installation of the drainage system may not receive full-time monitoring.

The foregoing should provide a perspective in any structural evaluation, selection, and design of buried plastic pipe for drainage of transportation facilities.

For the most part, both experience of others and this study show no serious structural problems with most buried plastic pipe. In spite of this, there are significant difficulties in translating this "experience" into an engineering approach that can be used in the evaluation of past successful installations of existing products or in the design of new installations of plastic pipe.

Buried pipe systems for subsurface drainage are structures that support significant loads. For example, a 12 in. (300 mm) pipe buried 8 ft (2.4 m) deep carries a nominal load of 1,000 lb (455 kg) per ft (30 cm) of length. In the transportation application, the pipe must be both stiff and strong enough to resist such significant levels of earth load, and also a variety of loads imposed during the process of installation, and applied by either construction traffic or by vehicular traffic during service.

Despite this, many design methods for plastic pipe do not even consider strength as a design criterion, even though the strength of plastics is sensitive to such factors as load duration and cyclic loading. Furthermore, most standard specifications for plastic pipe written in the United States contain no provisions relating to structural properties other than short-term strength and stiffness.

### *Stiffness*

The stiffness of plastic pipe is determined by short-term tests in which a ring of pipe is compressed across a diameter; the resistance to diametral compression is called pipe stiffness (PS) or ring stiffness. Stiffness, rather than strength, is the common and accepted measure of the structural properties of plastic pipe. Historically, this follows from the technology of buried flexible metal conduit, which recognizes the significance of flexural (or ring) stiffness of the pipe in determining the structural interaction between the pipe and its embedment (*3*).

The stiffness of plastic pipe systems considered herein is markedly less than that provided in corrugated flexible metal pipe of equivalent diameter. Thus, a key consideration in the use of plastic pipe for transportation drainage is that it is much less stiff than conventional flexible pipe products of the same size.

Parametric pipe-soil studies, using theories for pipe-soil interaction, reveal that the stiffness of most plastic pipe is sufficiently low that it can be neglected for its effect on deflection response, provided that the pipe is embedded in high quality, well-compacted, granular materials as are typically used in transportation drainage applications. Thus, practically, it is the quality or stiffness of the embedment material, and not the pipe, which dominates the structural response of the system to earth and live loads. This theoretical result was confirmed in field tests performed during NCHRP Project 4-11.

A major finding from the NCHRP field tests was that the magnitude of pipe deflections induced by or resulting from the very process of installing the pipe was much larger than the deflections predicted by pipe-soil interaction theory. The former deflections, termed installation deflections, were highly dependent on the stiffness of the pipe. While the field tests demonstrated that it is possible to install pipe having low stiffness with negligible deflection, in most practical field installations deflection resulting from the installation process is expected to increase as pipe stiffness decreases.

Pipe stiffness is a significant consideration in deflection control when an installation with low depth of cover is trafficked by repetitive wheel loads. That is, a certain level of stiffness must be provided in order to restrain cumulative movement of the embedment materials under the cyclic stresses caused by wheel loads. Quantitative determination of minimum stiffness levels required to prevent significant cumulative movement under prolonged heavy traffic is beyond the state of the art.

Pipe stiffness is also an important consideration in controlling buckling. Buckling, however, is seldom critical when most types of plastic pipe are installed in quality embedment materials. Specifications for some types of plastic pipe, especially corrugated PE tubing, do not provide sufficient information on materials or section properties to permit calculation of buckling resistance *a priori*. Buckling should be considered when an installation is subjected to very high earth fills, when surface wheel loads applied to an installation with very shallow cover (not recommended), or when large external fluid pressures act on the pipe.

The stiffness of all plastics, as measured by the ratio of stress to strain at a given time, decreases with the duration of the stress or strain. Most nonmetallic construction materials exhibit similar behavior. This behavior can be accounted for by reasonably simple methods provided that stresses and strains are held within certain limits (*4*, Chap. 2 and 3). The use of an acceptable level of strain is proposed to provide such a limit; this will be discussed in more detail subsequently.

The stiffness of thermoplastics used for pipe varies significantly with changes in temperature. Stiffness properties obtained in tests at room temperature (73 F, 23 C) are normally used in design. An accurate analysis of pipe behavior in the buried condition requires knowledge of such variations; however, this information is not usually available for plastic pipe.

*Strength*

The strength of all plastics depends on both the magnitude and the duration or frequency of loading. It also depends on the temperature and the chemical environment to which the material is exposed. The effects of temperature are frequently neglected in the design of buried plastic pipe. As is the case for stiffness properties, strength properties obtained at room temperature (73 F, 23 C) are usually the only properties available and they are used in design. Strength typically increases with decreasing temperature, and vice versa. The effects of chemical environment on strength are extremely important and will be discussed later. The effects of load and load duration are discussed in the following.

*Short-Term Strength.* Short-term strength of most plastic pipe used for transportation drainage is obtained both directly and indirectly in tests required by ASTM standards. First, the short-term tensile strength of the materials used in the manufacture of the pipe is specified. Second, adequacy of strength of the pipe itself is established by specified requirements for sustaining large diametral deflections in "flattening" tests (i.e., parallel-plate tests). Third, most standards contain a requirement for an arbitrarily defined impact strength of both the pipe material and the pipe itself. Impact tests are used mostly for quality control.

Flattening tests for smooth-wall pipe involve deflecting the pipe between parallel plates (see ASTM D 2412) in the range of 30 to 60 percent of the original pipe diameter with no failures allowed. Manufacturers of smooth-wall plastic pipe, however, frequently use a "100% flattening test" as an internal check on pipe quality, and a modification of this has been introduced as a requirement in specification SGH PVC-TD (App. A2).

Specifications for flattening of ABS composite-wall pipe, which is the stiffest, by far, of all plastic drainage pipe, require that the pipe sustain deflections up to only 7.5 percent without rupture of either the inner or outer wall of the pipe (ASTM D 2680); failure of the diagonal webs is permitted at any point during the test. The pipe can be deflected to significant levels in the test, during which the webs usually fail, but the inner and outer walls remain intact, while they gradually flatten against the loading plates at the crown and invert.

There is no practical flattening test available to determine the ultimate strength of corrugated PE tubing. The maximum deflection required in ASTM F 405 is 10 percent, and the load at this deflection is used in calculations for specified stiffness. The low modulus and high elongation capabilities of most quality polyethylenes, combined with the flexibility and buckling characteristics of the thin corrugated sections, usually result in gross distortions and local buckling, without any rupture during short-term flattening tests. Thus, flattening is an unsuitable measure of tubing strength, and, unfortunately, no other methods are available to make strength determinations.

*Long-Term Strength.* A simple model of a buried pipe under earth load depicts a stable, ovalled pipe, held indefinitely in a state of constant flexural strain. This behavior pattern was verified in NCHRP Project 4-11 field tests. A primary strength criterion for buried plastic pipe, then, is its capacity to resist sustained constant strain without fracture. This criterion is not recognized in most U.S. design methods for plastic pipe; it is the subject of significant controversy. Highly exploratory long-term tests performed in this study were designed to investigate the long-term strain capacity of two pipe materials. No failures were observed when pipe samples were subjected to high strain levels in air and water. Crazing was produced in one pipe material, however, and this increases potential for rupture in aggressive environments because aggressive environments accelerate failure at high strain levels. For these and other reasons, the formation of crazing has been frequently proposed as a strength criterion for thermoplastics. It is a primary strength criterion for buried RPM pipe, which is comprised of a thermosetting plastic as well as sand and fiberglass.

At present, there is no standardized method to characterize a thermoplastic material for its capacity to resist sustained constant strain. Short-term strength tests required in ASTM standards for thermoplastic sewer and drainage pipe do not provide any assurance of sustained strain capacity. Until a sutiable test for long-term strain capacity can be developed, thermoplastic compounds used in gravity flow drainage pipe should be the same as those used in plastic pressure pipe which have a demonstrated capacity to resist sustained stress, and hence sustained strain. This somewhat conservative requirement, in view of present specifications, has been introduced in proposed specifications SGH PE-TD and SGH PVC-TD (App. A1 and A2).

It is possible that some plastics used presently in non-pressure pipe intended for burial can be held at high levels of sustained strain indefinitely without failure, providing they are not exposed to aggressive environments. In this case, strength criteria for buried plastic pipe would follow that used for the design of flexible metal pipe, where the material is allowed to yield and form hinges in bending. This, in fact, is implicit in state-of-the-art design methods for both metal and plastic pipe systems which address deflection but not flexural stress or strain (*5, 6*). Field experience of a decade or more for plastics bears this out—there are no reports of significant failures by breakage of thermoplastic sewer and land drainage pipe of the type considered herein. (In contrast, early RPM pipe showed premature failure in sewer acids because of excessive strains, but the composition of this material is very different from that of thermoplastics.) While a post-yield criterion may eventually prove to be acceptable in design of thermoplastic pipe, there is insufficient documentation to justify its applicability to design for short-term and sustained stresses and strain. Thus, the use of a working or limiting strain concept is proposed here as a strength criterion until the acceptability of using higher strain limits is fully demonstrated.

*Strain Limit.* Limiting strain criteria have been widely proposed for use in designing plastics for conditions of sustained constant strain (*8*). With few exceptions (*7, 9*), such criteria have not been widely accepted for the design of nonpressurized buried thermoplastic drainage pipe in the United States. Limiting strain is now a recognized design criterion for RPM pipe (ASTM D 3262), and this stems from experience gained in early failures of this pipe. This strain limit is proposed herein as the principal design criterion for strength.

The strain limit for static loads is taken as one-half of the strain at the short-term yield stress of the material. This is an adaptation of a criterion proposed earlier for buried plastic pipe (*7*). A less restrictive post-yield criterion as used for buried metal pipe may eventually prove to be acceptable in design, but there is insufficient documentation of the effects of environmental exposures, scratches, and gouges on strength to justify its use at present.

*Fatigue.* Strength capacity under cyclic loading is subject to many of the same variables of time, temperature, and environment as previously discussed for other stress modes. In addition, fatigue strength varies with frequency, stress amplitude and mean stress, shape of the stress input, and the time interval between stress applications.

Fatigue properties for specific compounds used in buried plastic pipe are usually not available. For this and other reasons, the structural adequacy of plastic pipe under sustained repetitive traffic loads can not be evaluated within the state of the art.

In the case of buried plastic pipe, cyclic stresses resulting from occasional traffic loads are superimposed on stresses developed in the ovalled pipe—this is called a ripple loading. A criterion for this loading condition is given in Chapter Three under "Structural Design of the Pipe–Soil System."

*Strength and Stiffness of Embedment.* Any consideration of structural behavior of a buried plastic pipe must necessarily deal with the quality of the embedment materials surrounding the pipe. This subject is treated in detail in Chapter Three. The quality of the embedment material is, in most respects, more important than the properties of the pipe itself in determining in-service performance of the installation. The key considerations are as follows:

1. A primary criterion for a buried plastic pipe is that embedment materials should provide a uniform and continuous support for the pipe wall for its entire length. Deflection or strain limits may be exceeded unless the critical nature of this support is recognized in selecting materials for the embedment system and in installing these materials in the field.

2. Plastic pipe is much more flexible than conventional flexible metal pipe of the same diameter. This means that relatively more care is required during installation of plastic pipe so that the installation process itself (e.g., dumping materials, improper compaction methods) does not result in deflections that are in excess of those specified.

### Drainage Criteria

Design criteria for a drainage installation should include characteristics of the in-situ material, the drainage envelope surrounding the underdrain, and the perforations in the underdrain. If a filter fabric is used, it constitutes a fourth important component of the drainage system.

#### *Drainage Envelope*

In addition to providing structural support for the pipe underdrains, the drainage envelope should be proportioned to minimize migration of fines in the envelope through perforations and migration of fines from the in-situ material into or through the envelope. This minimizes chances for clogging of the pipe or envelope, and loss of structural support of the pipe as material is removed from the envelope.

#### *Perforations*

Perforations for plastic underdrain systems are in the form of either elongated slots or circular holes. Both corrugated tubing and smooth-wall pipe are provided with holes. Slotted perforations are seldom used in smooth-walled products considered herein, although slotted smooth-wall PVC pipe has been used for horizontal side-slope drains. Slots in smooth-wall pipe may cause severe stress concentrations, and they seriously weaken the longitudinal bending strength ("beam strength") of the pipe. Slots in corrugated PE tubing do not weaken the tubing significantly because the corrugation configuration minimizes stresses developed during normal longitudinal bending.

AASHTO specifications (*13*) require standard hole sizes and arrangements for all types of conventional perforated underdrains. Proposed specification SGH PVC-TD includes provision for hole sizes and patterns similar to those called for in AASHTO specifications. The standard patterns consist of two or more rows of holes, $\frac{3}{16}$ to $\frac{3}{8}$ in. (4.7 to 9.4 mm) in diameter, with rows distributed over the lower 180 deg, or less, of the pipe circumference. Holes and slots for corrugated PE tubing are, as yet, not standardized. Generally, they are located in the valleys of the corrugations, frequently, 120 deg apart around the circumference.

#### *Filter Fabrics*

A variety of plastic fiber filter fabrics has become available in recent years as an accessory to conventional drainage systems. These fabrics allow water permeation into the pipe, and restrict the infiltration and migration of fine materials that are smaller than the perforations in the pipe wall. Corrugated polyethylene drainage tubing is sometimes provided with a prewrapped sleeve of this material; alternatively, the sleeve may be applied in the field.

The plastics used in the fibers of filter fabrics are frequently not stabilized against UV attack by sunlight. Hence, they should be protected from sunlight when exposed for more than a few days. Furthermore, filter fabrics are frequently nonwoven, and very thin; thus, they can be torn when handled carelessly.

### Abrasion Resistance

Drainage pipe should be resistant to excessive gouging, scratching, or wear caused by rough handling, water-borne debris, and cleaning equipment. In general, plastic pipe has good to excellent resistance to water-borne abrasive materials.

Rate of erosion in piping carrying a slurry is proportional to the rate of flow, quantity, size, and shape of particles in the slurry. Hence, abrasion resistance is a function of both design flow rates and characteristics of debris expected at the installation, as well as of the materials that make up the pipe wall and inner surface.

Plastics of the same generic types used in buried pipe have been tested for abrasion resistance to either a continuous or an oscillating flow of abrasive slurry within the pipe. These tests indicate that PVC, ABS, and PE pipe systems frequently show less wear than conventional pipe materials; however, this depends on the specific conditions of test. Smooth-wall polyethylene pipe, in particular, is being used extensively in the transport of mine tailings, which are very abrasive.

Overall, plastic pipe should withstand exposure to waterborne abrasives such as fine sands that are transported at normal flow rates. Special consideration and study are required when either rapidly flowing streams containing aggregate change direction, such as at fittings, or if large stones or rocks are transported in streams having high velocity.

#### UV Resistance and Protection

Plastic pipe should withstand exposure to ultraviolet (UV) radiation during storage, handling, transportation, and installation, without significant loss of properties. Resistance of plastics to UV degradation varies widely, depending on the generic type of plastic and the extent to which the particular formulation is stabilized against UV deterioration. Plastics used in buried pipe may contain some stabilizers to minimize UV deterioration, but most standard specifications do not contain any specific requirement for level of stabilization. An exception to this is corrugated PE tubing, which normally contains carbon black to improve resistance to UV radiation; however, gradation requirements for the carbon black may not lead to long-term UV resistance.

An early sign of UV degradation is a change in color, usually towards a yellowish or brownish shade; this may be accompanied by a dulling or chalking. Early degradation is a surface effect that usually manifests itself in decreased impact resistance or elongation at failure. If allowed to continue, degradation can result in severe embrittlement, crazing, and cracking of the plastic, and a lowered strength under sustained stress. The rate of such deterioration depends on the generic type of plastic and the stabilizer used, if any. Proper formulation can result in extremely good UV resistance, which, for example, is provided in polyethylene telephone cable covering and in PVC siding for buildings.

The potential for UV degradation must be recognized for both storage and service conditions. It is not uncommon for pipe to be stored in manufacturers' yards for several months before shipment. Then, the pipe may receive more exposure during storage in a distributor's yard, and finally at the job site.

A good check for the extent of UV degradation is to require impact tests for acceptance of materials received at the job site, and to further require that materials be protected from sunlight if they are exposed to UV radiation for more than a few weeks. Research by industry is presently underway to better define acceptable storage times.

Obviously, plastic pipe should be protected from prolonged exposure to sunlight after installation (e.g. at "daylighted" ends) unless positive assurance of long-term UV resistance is obtained.

#### Animal, Insect, and Microbiological Attack and Protection

Buried plastic pipe should be resistant to deterioration or destruction by animals, insects, and microbiological organisms during storage and in service.

Rodents may chew on plastic if it restricts them from access to food, water, or mates. Pocket gophers are considered the animal most destructive to buried plastic cable sheathing. It has been shown that access of rodents from the soil side is not prevented by compaction of soil around the pipe (*14*).

Pipe systems under consideration here are much larger than the jaw opening of rodents, and, in general, no significant attack is expected. However, thin-walled, corrugated PE tubing with its small radius corrugation remains vulnerable to attack. Rodent guards should be installed at open ends of tubing to prevent entry by animals (see Fig. 2, App. A3, for details).

Most known insect attack of buried plastics is by termites, even though plastics offer no food value. Tests performed in areas of severe termite infestation indicate that attack is minor and is restricted to nibbling of corners and edges, not on general surface areas (*14*).

The base resins used in plastic pipe provide no food value to support growth of fungi or other microorganisms. Fungus can grow on the surfaces of plastics, but no damage to the material has been observed after burial tests (*15*).

Growth of iron bacteria, which are found in some soils, can clog filter fabrics, the perforations in drainage pipe, and the drainage envelope itself. Where such bacterial growth is common, a clean drainage envelope, chemical treatment, and water jet cleaning are required.

#### Resistance to Chemicals

Buried plastic pipe should be resistant to chemical compounds found in the earth and in runoff water that may contact either the inside or the outside of the pipe.

Resistance of plastics to particular chemicals depends on polymer formulation, effects of processing, intensity of stress or strain, and duration and concentration of the aggressive media. Information is not available to determine behavior under all possible combinations of these parameters. In general, pipe compounds are highly resistant to a wide range of chemicals. In fact, chemical and corrosion resistant qualities have been a chief reason for the use of plastics in preference to conventional materials.

Determination of the resistance of plastic pipe to the soil environment is complicated by the extremely wide variation in soils chemistry (e.g., pH = 2 to 10). In general, however, pipe compounds are resistant to alkalies and all but the strongest acids. Burial tests (pH 5.3 and 8.1) for 8 years reveal no degradation of the generic plastics used in pipe. Chemical attack by particularly aggressive soils may need further evaluation.

Tests on highway runoff water indicate that it can contain trace quantities of oil, lubricants, hydraulic fluids, tire rubber, fuel residue, asphalt decomposition products, silt, soil stabilizers, growth control materials, heavy metals, and feces. Measured concentration of oils is typically 0.01 percent by weight or less. Road deicing salts are expected in runoff in northern climates.

A sampling of the types of aggressive agents that can attack, degrade, or destroy generic materials used in pipe compounds is given in the following. Those agents that also enhance brittle fracture (stress cracking) when the plastic is exposed to both sustained stress or strain and the contaminant are designated by a plus (+) symbol.

- ABS—concentrated oxidizing acids, ketones, esters, chlorinated hydrocarbons, gasoline+, vegetable oils+, glacial acetic acids+, kerosene+, aromatic hydrocarbons, and alcohols+.
- PE—strong oxidizing acids, oils, polar reagents such as detergents+, silicones+, alcohols+, esters+, and ketones+.
- PVC—ketones, esters, aromatic and chlorinated hydrocarbons+, and vegetable oils+.

With the exception of oils or petroleum derivatives, such aggressive agents as noted, are not common to "normal" transportation drainage, and hence the principal risk is that of exposure to accidental spills. The effects of possible deposits of deleterious oils and aromatic hydrocarbons on pipe surfaces are somewhat lessened by flushing from storm and drainage waters and the small initial concentration of problem contaminants.

Plastic pipe compounds considered here are resistant to road deicing salts. Many types of plastic pipe have had a history of successful use in the transport of brine.

#### Thermal Effects

The coefficients of thermal expansion of plastic pipe materials are much greater than those of conventional piping materials (*16*). For example, the coefficients for PVC and PE, respectively, are 5 and 12 times that of steel. Thus, thermal expansion of plastic pipe materials can result in movements of 3½ to 9 in. (89 to 229 mm) per 100 ft (30 m) of pipe per 100 F (55.6 C) temperature change. The effects of large movements resulting from significant temperature excursions must be accounted for in design and particularly during field installation.

Once plastic pipe is buried, temperature excursions, and hence thermal movements, are significantly less than previously. However, accumulated thermal movements still may be significant and hence should be accounted for in design details.

The flexible gaskets provided in some bell-and-spigot pipe and the corrugations in long lengths of polyethylene tubing can accommodate thermal movements normally expected in buried pipe. ABS composite and smooth-wall pipe systems, which may be connected by solvent-bonding, deserve special consideration because rigid connections can not absorb movement.

As indicated earlier, all plastics undergo significant changes in strength and stiffness with changes in temperature. The decrease in impact strength that occurs at low temperatures, in particular, should be recognized in handling of pipe during installation. In addition, pipe being installed in hot climates may deflect more during the installation process because of the decreased stiffness accompanying high temperatures.

No deterioration of plastics is expected because of freezing and thawing. Limited studies on ABS composite pipe by Illinois indicate good resistance of cement filler materials to such effects. Since standard specifications for ABS composite pipe (ASTM D 2680) contain no requirements for core filler materials, freeze-thaw test requirements should be specified if ABS composite pipe is to be used where the potential for freezing exists.

#### Fire

Plastic pipe burns. A risk of destruction exists if flaming materials are introduced into a drainage system or if a fire occurs during storage.

A common maintenance practice has been to burn off grass and brush on areas adjacent to highways. Plastic pipe should be terminated underground, and noncombustible pipe should be installed from this terminus to areas that may be exposed to these or other accidental fires.

#### Cleaning

A wide variety of devices can be used to clean clogged pipe. Some manufacturers and users have performed tests using rotary routers and other conventional cleaning equipment in PVC and ABS composite pipe, and they report no significant abrasion or gouging. Nonetheless, equipment should be carefully selected and inspected to ensure that there are no sharp edges or projections that could damage the pipe.

High-pressure water-jet cleaning devices are being used increasingly for cleaning buried pipe, and this is the preferred method to minimize damage to plastic pipe. Water jet cleaning is the only method recommended for corrugated PE tubing that has thin walls that might be damaged by other types of cleaning equipment.

#### Handling and Storage

The service performance of plastic pipe should not be affected by handling and storage. This subject is covered in more detail in Chapter Three and Appendix A.

Generally, plastic pipe is considered rugged, but dropping, sliding, or scraping can damage the pipe and possibly affect long-term performance. Plastic pipe need not be handled gingerly as if fragile, but it should be treated with an appropriate level of care.

As indicated under UV resistance and protection, plastic pipe should be protected from sunlight when stored outdoors for more than a few weeks. This is not standard practice at present, but this measure appears prudent until some level of UV resistance is included in specifications.

During storage, pipe should be supported in such a manner that the pipe does not warp or oval significantly.

### Repair

PVC and ABS plastic pipe is easy to cut using hand or power saws. Replacement of sections can be performed using available conventional sleeves. For PVC, gasketed sleeves should be used; for ABS, sleeves can be readily bonded using available adhesives.

Corrugated PE tubing is readily cut for repairs with snips or saws. Mating connections can be made with standard fittings.

CHAPTER THREE

# APPLICATION

The results of the research performed under NCHRP Project 4-11 have been used to develop guidelines on the selection design, and installation of plastic pipe for subsurface drainage of transportation facilities. This chapter, which is developed for the practicing transportation engineer and for construction personnel, adapts state-of-the-art information to the special requirements of the transportation drainage application. Proposed product specifications for corrugated PE tubing and PVC pipe and a proposed standard practice for installation of plastic pipe in transportation applications are included in this report in Appendix A (Sections 1, 2, and 3) as submitted by the research agency.

## SELECTED PIPE SYSTEMS

This section presents systems that are considered appropriate for use in buried transportation drainage applications. The experience record of each system and recommendations for use are given in Chapter Two. Existing ASTM specifications, available engineering information, and possible limitations are summarized in the following. Proposed specifications for corrugated-wall PE tubing and smooth-wall PVC systems are given in Appendix A1 and A2, respectively.

### Acrylonitrile Butadiene Styrene (ABS) Composite Wall Pipe

*Specifications*

The standard specifications for ABS composite pipe are:

ASTM D 2680, AASHTO M264: Standard Specification for Acrylonitrile Butadiene Styrene (ABS) Composite Sewer Piping.

These standards are very broad in their requirements for materials properties and wall construction. Furthermore, the required short-term strength tests on the pipe actually permit failure of webs during the test; the actual strength at which webs fail is not determined. These reasons, combined with the complex configuration and construction of the wall, render it impossible to evaluate the structural performance of the pipe by simple state-of-the-art analysis methods.

*The Pipe System*

ABS composite pipe is available with inside diameters of 8, 10, 12, and 15 in. (203, 254, 304, and 381 mm). Standard lengths are 6 ft 3 in. and 12 ft 6 in. (1.9 and 3.8 m). A wide range of fittings such as tees, wyes, elbows, and reducers is available. Table 3 summarizes the key characteristics and available information on this pipe system.

ABS composite pipe is usually provided with a sleeve coupling that is bonded to one end of the pipe at the factory. The sleeve forms a bell that is solvent cemented to the spigot end in the field. Gasketed bell and spigot connections are also available, and should be used when significant differential settlements are anticipated along the length of the installation or where field bonding is impractical or uneconomical.

Available fittings include saddles, tees, wyes, elbows, and reducers. Standard specifications cover materials and laying lengths only.

*Limitations*

Perhaps the primary limitation on ABS composite-wall pipe is the lack of structural characterization of this pipe in terms of wall construction and structural behavior, and materials properties such as modulus of elasticity and long-term strength. Other limitations include a sensitivity of ABS to more aggressive environments (stress-cracking and softening agents) than other pipe materials considered herein. Materials used in this pipe appear to be highly sensitive to deterioration under UV exposure.

### Acrylonitrile Butadiene Styrene (ABS) Smooth Wall Pipe

*Specifications*

The standard specification for smooth-wall ABS pipe is:

ASTM D 2751: Standard Specification for Acrylonitrile Butadiene Styrene (ABS) Sewer Pipe and Fittings.

TABLE 3

DESIGN AND SELECTION GUIDELINES—ABS COMPOSITE-WALL PIPE

These guidelines are assembled from specifications covering the products, from data furnished by pipe manufacturers, and from information available in the technical literature on generic plastics used in the pipe. Some properties are estimated. As such, the information contained herein is not intended as a specification, nor should it be used in design without verification by the manufacturer of the product.

**Reference Specification**

ASTM D 2680 / AASHTO M264 — Standard Specification for Acylonitrile-Butadiene-Styrene (ABS) Composite Sewer Piping

**Nominal Pipe Properties**

| Diameter (in.) | 8 | 10 | 12 | 15 |
|---|---|---|---|---|
| Unit Weight (lb/ft) | 7 | 9 | 14 | 23 |
| Pipe Stiffness (lb/in./in.) | 200 | 200 | 200 | 200 |
| Wall Dimensions (in.) | | | | |
| Overall depth | 0.83 | 1.00 | 1.16 | 1.44 |
| Inner plastic shell | 0.060 | 0.068 | 0.079 | 0.096 |
| Outer plastic shell | 0.035 | 0.038 | 0.048 | 0.059 |
| Plastic webs | no spec. | no spec. | no spec. | no spec. |
| Section Modulus (Est.) ($in.^3/in.$) | | | | |
| Inner fiber | 0.043 | 0.058 | 0.079 | 0.120 |
| Outer fiber | 0.027 | 0.034 | 0.051 | 0.078 |
| Moment of inertia (Est.) ($in.^4/in.$) | 0.014 | 0.022 | 0.036 | 0.068 |
| Hydraulic Coefficient-Manning (n) | 0.01 | 0.01 | 0.01 | 0.01 |

**Nominal Properties of ABS Pipe Material**

| | |
|---|---|
| Specific Gravity (excludes inorganic filler in annulus) | 1.1 |
| Modulus of Elasticity at 73°F (estimate only, no spec.) | |
| Short-term test (minutes) (psi) | 320,000 |
| Long-term (10 years sustained stress or strain) (psi) | 110,000 |
| Tensile Strength at 73°F | |
| Short-term test (psi) | 5,000 |
| Long-term (10 years sustained stress) (psi) | unknown |
| Coefficient of Thermal Expansion (in./in./°F) | $55 \times 10^{-6}$ |
| Fire Properties | burns |
| Chemical Resistance | |
| Stress-crack agents | gasoline, kerosene, vegetable oils, glacial acetic acids, ketones, aromatic hydrocarbons and alcohols |
| Other aggressive agents | oxidizing acids, ketones, esters, chlorinated hydrocarbons |
| UV Resistance | low |
| Biological | |
| Microbiological degradation | nil |
| Rodents | unlikely |
| Insects | unlikely |

**Connections and Fittings**

| | |
|---|---|
| Connection mode | solvent-cement bonded or gasketed bell and spigot |
| Fittings | tees, wyes, elbows, couplings, saddles, and reducers |

Note: 1 in. = 25.4 mm; 1 lb/ft = 1.49 kg/m; 1 lb/in./in = 1 psi = 6.9 kPa; $T_{^oF} = 1.8\, T_{^oC} + 32$

This specification is limited in its structural characterization of plastic compounds used in the pipe. Modification of specifications to reflect requirements of the transportation drainage application are not feasible within the scope of this report because major changes in materials would be required.

ASTM D 2751, which covers sewer pipe, does not contain specifications for perforations that are needed for underdrain applications.

### *The Pipe System*

Table 4 summarizes the key characteristics of ABS smooth-wall pipe. Specifications for this pipe cover diameters in the range of 3 to 12 in. (76 to 305 mm), but ready and widespread availability of all pipe listed has not been verified. A variety of pipe stiffnesses is provided, depending on wall thickness and diameter.

Smooth-wall pipe systems are classified by the ratio of outside diameter to wall thickness. The usual term used to define this ratio is standard dimension ratio (SDR). For most nonpressure pipe intended for burial, the dimension ratios specified are not "standard" as defined in ASTM F 412. The proper term for such ratios is dimension ratio (DR). The term DR will be used here for all ratios of outside diameter to wall thickness because DR is more general and also because the question of whether or not the ratio is standard has no significance in the buried drainage pipe application.

The minimum pipe stiffness of standard ABS smooth-wall pipe varies significantly, from 20 to 150 lb/in./in. (138 to 1034 kPa). The former stiffness is much lower than that of any other thermoplastic pipe considered in detail in this report.

ABS smooth-wall pipe is available with either tapered or gasketed bell and spigot joints. The tapered slip-fit joint mates snugly and is intended to be made watertight with the application of solvent cement. The joint can be "tacked" with cement, or left "dry" if desired, for perforated underdrain connections where watertight connections are not needed.

Gasketed connections in ABS smooth-wall pipe usually use elastomeric O-rings. The O-ring is slipped over the spigot and the bell end is slid over the O-ring to compress the gasket and seal the pipe.

A wide range of fittings is covered by specifications, including saddles, tees, wyes, bends, sweeps, reducers, and caps. The extent to which these fittings are readily available has not been established.

### *Limitations*

The experience record with buried ABS smooth-wall pipe, although long, has not been extensive. A further limitation on the use of this pipe is that ASTM specifications are not sufficiently comprehensive to characterize the material properties, particularly for modulus and for long-term strength. Other limitations include a sensitivity of ABS to more aggressive environments (stress-cracking and softening agents) compared to other pipe systems considered. Furthermore, the ABS materials used in this pipe appear to be highly sensitive to rapid deterioration under UV exposure. Finally, the stiffness of standard pipe in the larger sizes is low, and such pipe should not be used without detailed evaluation in transportation drainage applications; the 150-lb/in./in. (1034-kPa) stiffness provided in smaller sizes is preferred for shallow burial.

## **Corrugated Polyethylene (PE) Tubing**

### *Specifications*

Existing standard specifications for corrugated PE tubing are:

ASTM F 405: Standard Specification for Corrugated Polyethylene (PE) Tubing and Fittings.
AASHTO M252: Specification for Plastic and Polyethylene Corrugated Drainage Pipe or Tubing.

The proposed specification for corrugated PE tubing is SGH PE-TD, Proposed Standard Specification for Class PS 50 Corrugated Polyethylene (PE) Tubing Systems for Subsurface Drainage of Transportation Facilities (see App. A1).

The ASTM F 405 specification for corrugated polyethylene tubing was adopted in 1974. This specification covers standard and heavy-duty tubing in the diameter range of 3 to 8 in. (76 to 203 mm) in 1-in. (25-mm) increments. The scope of the specification includes materials, marking, dimensions, workmanship, stretch resistance, environmental stress cracking, pipe stiffness, and perforations.

AASHTO M252 specification is similar in most respects to ASTM F 405. The significant requirements of the AASHTO specification that do not appear in ASTM F 405 (e.g., "Low Temperature Flexibility" and "Storage and Handling") are included in SGH PE-TD.

SGH PE-TD proposed specification contains a provision for material tests to evaluate long-term performance under sustained stress, which appears to be the only way at present to provide some assurance that the product can withstand a specific sustained strain in the buried condition. It appears feasible that a method can be developed to standardize and/or classify the present infinite variation in properties resulting from the extremely broad range of materials and cross sections allowed in present specifications. Finally, the specification requires a pipe stiffness of 50 lb/in./in. (345 kPa), which, although higher than existing standards, has been verified as feasible in Illinois DOT tests. A higher pipe stiffness may eventually be required to improve resistance to installation deflections.

### *The Tubing System*

Corrugated polyethylene tubing is available in sizes that range from 3 to 18 in. (76 to 457 mm) in diameter. ASTM F 405 covers the 3- to 8-in. (76- to 203-mm) diameter range; specifications that cover larger sizes are under development. Key characteristics of corrugated PE tubing systems are given in Table 5.

The wall configuration of corrugated PE tubing is not standardized, although several manufacturers use similar molds ("corrugators") to form the pipe wall. The shape is chosen, in part, to accommodate the manufacturing

TABLE 4

DESIGN AND SELECTION GUIDELINES—ABS SMOOTH-WALL PIPE

These guidelines are assembled from specifications covering the products, from data furnished by pipe manufacturers, and from information available in the technical literature on the generic plastics used in the pipe. Some roperties are estimated. As such, the information contained herein is not intended as a specification, nor should it be used in design without verification by the manufacturer of the product.

**Reference Specification**

ASTM D 2751: Standard Specification for Acrylonitrile-Butadiene-Styrene (ABS) Sewer Piping

**Nominal Pipe Properties**

| Diameter (in.) | 3 | 4 | | 6 | | 8** | 10** | 12** |
|---|---|---|---|---|---|---|---|---|
| Unit Weight (lb/ft) | 0.51 | 1.10 | 0.73 | 2.38 | 1.65 | 2.46 | 3.84 | 5.54 |
| DR | 32.5 | 23.5 | 33.5 | 23.5 | 35 | 42 | 42 | 42 |
| Pipe Stiffness (lb/in./in.) | 50 | 150 | 45 | 150 | 45 | 20 | 20 | 20 |
| Wall Thickness (in.)* | 0.10 | 0.18 | 0.12 | 0.26 | 0.18 | 0.2 | 0.25 | 0.3 |
| Manning Coefficient | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |

* Section properties may be calculated directly from wall thickness.
** Not recommended for use in the transportation drainage application.

**Nominal Properties of ABS Pipe Material**

| | |
|---|---|
| Specific Gravity | 1.1 |
| Modulus of Elasticity at 73°F (estimate only, no spec.) | |
| Short-term test (minutes) (psi) | 350,000 |
| Long-term (10 years sustained stress or strain) (psi) | 90,000 |
| Tensile Strength at 73°F | |
| Short-term (minutes) (psi) | 4,000 or 5,000 |
| Long-term (10 years sustained stress or strain) (psi) | unknown |
| Coefficient of Thermal Expansion (in./in./°F) | $55 \times 10^{-6}$ |
| Fire Properties | burns |
| Chemical Resistance | |
| Stress-crack agents | gasoline, kerosene, vegetable oils, glacial acetic acids, ketones, aromatic hydrocarbons and alcohols |
| Other aggressive agents | oxidizing acids, ketones, esters, chlorinated hydrocarbons |
| UV Resistance | low |
| Biological | |
| Microbiological degradation | nil |
| Rodents | unlikely |
| Insects | unlikely |

**Connections and Fittings**

| | |
|---|---|
| Connection mode | solvent-cement bonding or O-ring gasket |
| Fittings | tees, wyes, bends, sweeps, saddles, reducers and caps |

Note: 1 in. = 25.4 mm; 1 lb/ft = 1.49 kg/m; 1 lb/in./in. = 1 psi = 6.9 kPa; $T_{°F} = 1.8\ T_{°C} + 32$

TABLE 5

## DESIGN AND SELECTION GUIDELINES—PE TUBING

These guidelines are assembled from specifications covering the products, from data furnished by pipe manufacturers, and from information available in the technical literature on generic plastics used in the pipe. Some properties are estimated. As such, the information contained herein is not intended as a specification, nor should it be used in design without verification by the manufacturer of the product.

**Reference Specifications**

| | |
|---|---|
| AASHTO M252: | Specification for Plastic and Polyethylene Corrugated Drainage Pipe or Tubing |
| ASTM F 405: | Standard Specification for Corrugated Polyethylene (PE) Tubing and Fittings |
| SGH PE-TD: | Proposed Standard Specification for Class PS 50 Corrugated Polyethylene (PE) Tubing for Subsurface Drainage of Transportation Facilities |

**Nominal Pipe Properties**

| Specification | ASTM F 405 or AASHTO M252 | | SGH PE-TD |
|---|---|---|---|
| Tube Diameter (in.) | 3, 4, 5, 6, 7, 8 | | 3, 4, 5, 6, 7, 8 |
| Class | Standard | Heavy Duty | PS 50 |
| Pipe Stiffness (lb/in./in.) | | | |
| at 5% Deflection | 24 | 30 | 50 |
| at 10% Deflection | 19 | 24 | 40 |
| Elongation, % | 10 | 5 | 5 |
| Unit Weight (lb/ft) | varies; not specified | | varies; not specified |
| Wall Dimensions | | | |
| Wall Thickness (in.) | varies; not specified* | | 0.025 in. min. |
| Corrugation Depth (in.) | varies; not specified | | varies; not specified |
| Wall Area (in.$^2$/in.) | varies; not specified | | varies; not specified |
| Section Modulus (in.$^3$/in.) | varies; not specified | | varies; not specified |
| Moment of Inertia (in.$^4$/in.) | varies; not specified | | varies; not specified |
| Hydraulic Coefficient-Manning (n) ** | 0.13 to 0.18 | | 0.13 to 0.18 |
| Perforations | Holes and Slots | | Holes and Slots |

* ASHTO requires 0.025 in. min.
** Approximate value; not specified. Consult manufacturer.

**Nominal Properties of PE Tubing Material**

| | |
|---|---|
| Specific Gravity | 0.91 - 0.96 |
| Modulus of Elasticity at 73°F (estimated range) | |
| Short-term test (minutes) (psi) | 50,000 - 100,000+ |
| Long term (10 years sustained stress or strain) (psi) | 16,000 - 33,000+ |
| Tensile Strength at 73°F | |
| Short-term test (psi) | 1,800 or 3,200 |
| Long-term (10 years sustained stress) (ASTM F 405) (psi) | unknown |
| Long-term (10 years sustained stress) (SGH PE-TD) (psi) | 1,000 to 1,250 |
| Coefficient of Thermal Expansion (in./in./°F) | $80 \times 10^{-6}$ |
| Fire Properties | burns |
| Chemical Resistance | |
| Stress-crack agents | detergents and polar reagents, silicones, alcohols, esters, ethylene glycol, and some oils and solvents |
| Other aggressive agents | strong oxidizing acids, some oils |
| UV Resistance | moderate |
| Biological Degradation | |
| Microbiological | nil |
| Rodents | possible |
| Insects | minor |

**Connections and Fittings**

| | |
|---|---|
| Connection mode | external couplings or snap-lock connectors |
| Fittings | couplings, reducers, tees, wyes, and end caps |

Note: 1 in. = 25.4 mm; 1 lb/ft = 1.49 kg/m; 1 lb/in./in. = 1 psi = 6.9 kPa; $T_{°F} = 1.8\, T_{°C} + 32$

method. Sections are proportioned to meet stiffness requirements. The corrugated wall construction provides an extremely efficient bending cross section, which, when coupled with the low specific gravity of the material, results in a very lightweight product.

The low weight of corrugated tubing is not always an advantage, because the lightweight pipe can be easily moved out of alignment during the placement and compaction of embedment materials. This problem is significant, and it is aggravated by the high longitudinal flexibility (low "stretch" resistance) of this product. Installation by automated equipment tends to minimize these problems.

Corrugated polyethylene tubing is connected by various proprietary external split sleeves or integral snap-lock connections. Coiled tubing, available in diameters up to 6 or 8 in. (152 to 203 mm), is provided in long lengths and therefore the number of connections is minimized, compared to all other systems considered. Smaller diameter tubing can be supplied in continuous lengths of 1 mile or more.

Some transportation agencies specify the long lengths available in coiled tubing because chances for a disconnected pipe are minimized. This solves a recurring field problem experience with all types of buried pipe. Obviously, field labor required for connecting tubing is also minimized when long lengths are used.

Despite the advantages of coiled tubing, some transportation agenices prefer shorter straight lengths, particularly in larger diameters. Experience has shown that it is difficult to maintain line and grade with coiled tubing, which may not straighten sufficiently on uncoiling.

A variety of fittings is available for the corrugated PE tubing system, including couplings, reducers, tees, wyes, and end caps. These fittings are installed by snap-on, screw-on, or wrap-around methods. The configuration of most fittings is proprictary, and hence one brand of fittings may be compatible only with the same brand of tubing.

*Limitations*

The proposed specification (App. A1), although more restrictive than existing standards, still does not permit engineering evaluation of corrugated PE tubing, for the following reasons. Section properties (area, section modulus, moment of inertia) that are essential to any rational analysis and prediction of performance are not defined. Thus, these properties may vary widely even in a product that is made in accordance with the proposed standard. Also, materials specifications given in the proposed standard remain extremely broad because they allow short-term yield strengths that vary from 1800 to 3200 psi (12 to 22 MPa). Furthermore, there is no requirement for modulus of elasticity. The adequacy of tubing of the proposed stiffness (PS = 50 lb/in./in. (345 kPa)) has not been fully verified under conditions of shallow burial and heavy, sustained repetitive traffic. In sum, it is not possible within the scope of this report to develop specifications that are sufficiently restrictive to permit an *a priori* evaluation of product capabilities.

Additional characteristics that should be considered in the selection of PE corrugated tubing are as follows:

1. Some tubing is supplied with a filter fabric envelope. This material may degrade very rapidly in sunlight—reportedly some materials degrade after exposure of a few days. Extreme care must be taken to limit exposure to sunlight. Also, filter fabrics are easily damaged by rough treatment.
2. Tubing may be gnawed by rodents. Animal guards may help to prevent animal entry (Fig. 2, App. A3).
3. Automated machine installation is the preferred method for installing tubing. At present, such equipment may not be readily available or economical outside of agricultural regions.

**Polyvinyl Chloride (PVC) Pipe**

**Specifications**

Standard specifications that describe PVC sewer pipe are:

ASTM D 3033: Standard Specification for Type PSP Poly (Vinyl Chloride) (PVC) Sewer Pipe and Fittings
ASTM D 3034: Standard Specification for Type PSM Poly (Vinyl Chloride) (PVC) Sewer Pipe and Fittings

The proposed specification for transportation drainage use is SGH PVC-TD, Proposed Standard Specification for Class PS 50 Polyvinyl Chloride (PVC) Plastic Piping Systems for Subsurface Drainage of Transportation Facilities.

The difference between the two ASTM standards is mainly one of dimensions of the pipe. The terms PSP and PSM are used solely to distinguish between systems described by the two specifications. Commercially, PSP pipe is frequently referred to as plastic sewer pipe, and PSM pipe is referred to as plastic sewer main.

For simplicity, ASTM D 3034 will be used as a basis for the tabulations (Table 6). This specification appears to be gaining acceptance over ASTM D 3033; however, there is no technical reason to cite one in preference to the other, because the only difference between the two relates to small differences in overall dimensions.

*The Pipe System*

Tables 6 and 7 summarize key characteristics of smooth-wall PVC pipe that is available in the diameter range of 4 to 15 in. (102 to 381 mm).

The minimum pipe stiffness defined by the ASTM specifications is either 28 or 46 lb/in./in. (193 or 317 kPa). The stiffer pipe is less subject to possible overdeflection during the installation process, but deflection resulting from earth loads is not significantly different for the two pipes. The proposed specification SGH PVC-TD requires a stiffness of 50 lb/in./in. (345 kPa), but a higher stiffness may eventually be required to improve resistance to installation deflections.

ASTM specifications for PVC pipe classify wall thickness (and indirectly pipe stiffness) by the ratio of outside diameter to wall thickness. As explained for ABS smooth-wall pipe, commercial practice has been to use SDR to define this ratio even though, for the DR 35 pipe, the terminology is not in accordance with ASTM F 412. The term DR is used here exclusively because it is more general.

TABLE 6

DESIGN AND SELECTION GUIDELINES—PVC PIPE

These guidelines are assembled from specifications covering the products, from data furnished by pipe manufacturers, and from information available in the technical literature on generic plastics used in the pipe. Some properties are estimated. As such, the information contained herein is not intended as a specification, nor should it be used in design without verification by the manufacturer of the product.

**Reference Specification**

ASTM D 3033: Standard Specification for type PSP Poly (Vinyl Chloride) (PVC) Sewer Pipe and Fittings

ASTM D 3034: Standard Specification for Type PSM Poly (Vinyl Chloride) (PVC) Sewer Pipe and Fittings

**Nominal Pipe Properties ASTM D 3034 Pipe ****

| | Diameter (in.) | 4 | 6 | 8 | 10 | 12 | 15 |
|---|---|---|---|---|---|---|---|
| DR 41 | Pipe Stiffness (lbs/in./in.) | - | 28 | 28 | 28 | 28 | 28 |
| | Unit Weight (lb/ft) | - | 1.9 | 3.5 | 5.3 | 7.3 | 11.3 |
| | Wall Thickness (in.)* | - | 0.153 | 0.205 | 0.256 | 0.305 | 0.375 |
| DR 35 | Pipe Stiffness (lbs/in./in.) | 51 | 46 | 46 | 46 | 46 | 46 |
| | Unit Weight (lbs/ft) | 1.1 | 2.2 | 4.2 | 6.4 | 8.9 | 13.2 |
| | Wall Thickness (in.)* | 0.120*** | 0.180 | 0.240 | 0.300 | 0.360 | 0.437 |
| Hydraulic Coefficient-Manning (n) | | | | 0.007 to 0.011 | | | |

* Section properties can be computed directly from wall thickness
** D 3033 Dimensions and properties are nearly identical to those listed. Only one set of values is listed for simplicity.
***DR 33.5

**Nominal Properties of PVC Pipe Material**

| | |
|---|---|
| Specific Gravity | 1.4 |
| Modulus of Elasticity at 73°F (psi) | |
| Short-term | 400,000 or 500,000 |
| Long-term (10 years under sustained stress or strain) | 133,000 or 170,000 |
| Tensile Strength at 73°F (psi) | |
| Short-term (minutes) | 7,000 or 6,000 |
| Long-term (10 years sustained stress) | unknown |
| Coefficient of Thermal Expansion (in./in./°F) | $30 \times 10^{-6}$ |
| Fire Properties | burns |
| Chemical Resistance | |
| Possible stress-crack/softening agents | ketones, esters, aromatic hydrocarbons, some oils |
| UV Resistance | low |
| Biological | |
| Microbiological degradation | nil |
| Rodents | unlikely |
| Insects | unlikely |

**Connections and Fittings**

| | |
|---|---|
| Connection mode | bell and spigot, tapered sleeve and solvent cement, or gasketed. |
| Fittings | bends, saddles, wyes, crosses, reducers, saddles, couplings, caps and plugs, adaptors |

Note: 1 in. = 25.4 mm; 1 lb/ft = 1.49 kg/m; 1 lb/in./in. = 1 psi = 6.9 kPa; $T_{^oF} = 1.8\ T_{^oC} + 32$

TABLE 7

DESIGN AND SELECTION GUIDELINES—PVC UNDERDRAINS

These guidelines are assembled from specifications covering the products, from data furnished by pipe manufacturers, and from information available in the technical literature on generic plastics used in the pipe. Some properties are estimated. As such the information contained herein is not intended as a specification, nor should it be used in design without verification by the manufacturer of the product.

**Reference Specification**

SGH PVC-TD Proposed Standard Specification for Class PS 50 Polyvinyl Chloride (PVC) Piping Systems for Subsurface Drainage of Transportation Facilities

**Nominal Pipe Properties**

| Diameter (in.) | 4 | 6 | 8 | 10 | 12 | 15 |
|---|---|---|---|---|---|---|
| Pipe Stiffness (lb/in./in.) | 50 | 50 | 50 | 50 | 50 | 50 |
| Unit Weight (lb/ft) | 1.1 | 2.2 | 4.2 | 5.3 | 7.3 | 11.3 |
| Wall Thickness (in.)* | 0.120 | 0.180 | 0.240 | 0.300 | 0.360 | 0.437 |
| Hydraulic Coefficient-Manning (n) | 0.007 to 0.011 | | | | | |
| Perforation option | 3/16 to 3/8 in. Diameter Holes | | | | | |

* Section properties can be computed directly from wall thickness.

**Nominal Properties of PVC Pipe Material**

| | |
|---|---|
| Specific Gravity | 1.4 |
| Modulus of Elasticity at 73°F (psi) | |
| Short-term test (minutes) | 400,000 |
| Long-term (10 years sustained stress or strain) | 130,000 |
| Tensile Strength at 73°F (psi) | |
| Short-term test (minutes) | 7,000 |
| Long-term (10 years sustained stress) | 4,000 |
| Stain Limit (%) (Tentative) | 1.0 |
| Coefficient of Thermal Expansion (in./in./°F) | $30 \times 10^{-6}$ |
| Fire Properties | burns |
| Chemical Resistance | |
| Possible stress-crack/softening agents | ketones, esters, aromatic hydrocarbons, some oils |
| UV Resistance | low |
| Biological | |
| Microbiological | nil |
| Rodents | unlikely |
| Insects | unlikely |

**Connections and Fittings**

| | |
|---|---|
| Connection mode | bell and spigot, tapered sleeve and solvent-cement, or gasketed. |
| Fittings | bends, salddles, wyes, couplings, caps and plugs, adaptors |

Note: 1 in. = 25.4 mm; 1 lb/ft = 1.49 kg/m; 1 lb/in./in. = 1 psi = 6.895 kPa; $T_{^\circ F} = 1.8\,T_{^\circ C} + 32$

In the case of the proposed specification for transportation drainage, pipe stiffness (PS) is used in preference to the dimension ratio system to classify pipe. Pipe stiffness is the key performance parameter that controls installation deflections and to a lesser extent deflection due to earth and live loads.

ASTM D 3033 and D 3034 are incompatible at connections. The outside diameter of each system is different and, hence, they will not mate at connections and special adaptors are required.

Several modes of connection are available in PVC pipe. Bell and spigot joints having either O-ring or internally captivated elastomeric seals are the most common form of joint for the sewer application. This type of joint is preferred in sizes greater than 6 in., because it is difficult to properly connect the larger diameter pipe in the field using solvent-cement bonding techniques.

Smaller sizes of PVC pipe may be furnished in bell and spigot joints, where the bell socket is tapered to receive and fit snugly with the spigot. In this case, solvent-cement bonding techniques are used to make up the joint. For perforated underdrain systems, where minor joint leakage is tolerable, such joints may be either "tacked" with solvent cement to hold successive lengths of pipe in place, or they may be left "dry."

A wide variety of fittings is available for the smooth-wall PVC pipe system. As is the case for conventional buried pipe systems, specifications cover only dimensions and materials requirements for fittings. Standards are under development that address the problem of quality control of fittings, and these should be considered when they become available.

*Limitations*

PVC pipe made in accordance with existing standards can not be evaluated on an engineering basis, *a priori,* because of the significant differences in materials properties allowed by specifications, and because the materials are not characterized for long-term strength.

Proposed specification SGH PVC-TD is more specific and restrictive on materials properties, and hence this provides some level of confidence in the evaluation of performance.

Potential limitations of PVC pipe include its brittleness at low temperatures and its potential for deterioration on prolonged exposure to UV radiation. The adequacy of pipe of the proposed stiffness (PS = 50 lb/in./in. (345 kPa)) has not been fully verified under conditions of shallow burial in heavy repetitive traffic.

## STRUCTURAL DESIGN OF THE PIPE–SOIL SYSTEM

This section presents a tentative method for determining the structural adequacy of a buried plastic pipe installation or for use in designing such installations. The effects of loading conditions imposed on the installation by earth weight and vehicle wheels are considered. In addition, the effects of pipe distortions, which are imposed during installation, or which result from the installation process, are taken into account. The method is considered tentative because some parts of the design procedure are based on theory and on very limited substantiating data that remain to be verified by tests and experience.

The method is directly applicable to buried smooth-wall pipe systems that are sufficiently characterized to permit structural evaluation. Thus, presently it applies to PVC pipe systems that are defined in proposed specification SGH PVC-TD (App. A2). Some of the needed material properties and section properties of the other piping systems covered in this report are not assured by standard specifications, and must be estimated, assumed, or obtained from the pipe manufacturer in order to use the methods proposed herein. Concepts for treating pipe having other wall configurations are given elsewhere in Appendix D, but they are not developed in detail. It is hoped that a valid technical development of the required information on materials and wall configurations will be undertaken by the pipe system manufacturers in the near future.

The approach to the design of buried plastic pipe differs from that used in design of conventional buried pipe systems, which usually involve selection of a structural section drawn from a wide variety of available sections. For example, concrete pipe is provided in a wide range of strength classes, and flexible metal pipe is provided in a range of corrugation configurations and material gages. In contrast, a plastic pipe system is frequently provided in only one or, perhaps, two stiffness classes. Because there is little or no choice of structural characteristics within a given plastic pipe system, design of a plastic pipe installation primarily involves selection of the soil embedment system to satisfy structural performance limits set for the installation.

The proposed procedure is actually an evaluation method that follows in part from traditional buried flexible pipe design and focuses on control of pipe deflection. Design conditions and performance limits are first established, and trial pipe and embedment systems are selected. Calculations are made to determine whether or not the installation meets the performance limits. The embedment is varied, as necessary, by trial and error (for a selected pipe system) until performance limits are met.

This procedure recognizes the importance of installation deflections. With good quality installations of the type considered here, classical soil-structure interaction methods predict average deflections due to earth loads with reasonable accuracy, but, typically, these are small. Installation deflections, which are a function of both level of soil compaction and pipe stiffness, frequently dominate the design problem. Installation deflections, as defined in this report, are potential deflections that result from variability of the combined pipe-soil installation and that are not normally accounted for in conventional design/analysis procedures. These deflections are largely related to workmanship and the high flexibility of typical plastic pipe; they are highly variable and difficult to predict.

A simplified procedure is presented later in this section for determining the maximum deflection limit of a pipe system. This deflection limit can be used in specifications for the installation as well as for the evaluation of present or emerging plastic pipe systems.

Although the procedure is based on existing methods, field tests performed during NCHRP Project 4-11, and recent work on the structural design of plastics, more work is needed to enhance the reliability of predicting structural performance of the complex soil-plastic pipe system. Installation deflection variability and lag factors achieved in the field need significant further study. The structural behavior under wheel loadings should be further studied, and the strain limit criterion that forms a basis for the suggested approach needs refinement to establish the range of conditions under which it provides appropriate safety against long-term failure.

**Performance Limits for Plastic Pipe**

The two basic requirements for the performance of any structure are strength and serviceability. In the case of plastic drainage pipe, these two requirements are met primarily by control of maximum strain and deflection. Because buried pipe systems are subject to ring compression forces, stability against buckling must also be evaluated to preclude overall collapse.

*Deflection*

"Deflection" is defined herein as the change in the base vertical diameter of the pipe from that calculated from specified dimensions. The base vertical diameter is the diameter at the neutral axis of the pipe walls; in the case of smooth-wall pipe barrels, this is equal to the inside diameter plus the wall thickness. For all practical purposes, deflection is the change in specified inside diameter of the pipe.

A traditional limit on deflection of flexible metal pipe under earth loads has been a 5 percent change in either vertical or horizontal diameter. This derives from observations on early installations of corrugated metal pipe where collapse in the buried condition was generally imminent at deflections of about 20 percent; therefore, a limit of 5 percent provided a safety factor of 4 against failure by collapse.

A deflection limit of 5 to 10 percent has also been commonly proposed for most flexible plastic pipe based on much the same reasoning. However, rationale for such limits does not recognize the structural characteristics peculiar to plastics, particularly the important role of the time dependence of structural properties.

The magnitude of allowable deflections should be based on the following performance limits:

1. *Function*—Large deflections near or at the pipe spigot may cause loss of seal of gasketed joints; information on allowable deflections for this case should be available from the manufacturer. The reduced diameter associated with excessive deflection may restrict standard-sized cleaning equipment. The reduced area of a deflected pipe also reduces flow capacity, but no significant loss occurs until deflections are very gross and unacceptable for other reasons.

2. *Loss of pavement support*—If a buried pipe deflects excessively, it can result in pavement deterioration due to loss subgrade support.

3. *Strength*—The deflection of a pipe is indicative of the flexural stress and strain in the pipe wall. Thus, by selecting a deflection limit for a plastic pipe, an approximate limit is indirectly placed on stress and strain. Since excessive stress or strain may result in failure, the deflection limit is related to the strength limit of the pipe.

Deflections resulting from earth load, from surface wheel load, and from conditions imposed during the installation process should all be considered.

*Ring Bending*

Ring bending moments arise from any loads that are not applied as uniform radial pressure on the periphery of the pipe. Ring bending, which can be related, approximately, to deflection by simple methods, produces stress and strain in the pipe wall, and hence it is a primary consideration in strength design.

*Ring Compression*

Ring compression forces result from external loads applied to the pipe. Ring compression stress or strain is not a major contribution to total stress or strain in the smooth-wall pipe considered, unless such pipe is buried extremely deep. However, the effects of ring compression may be very important in corrugated and composite-wall pipe. In the case of corrugated tubing, circumferential shortening due to ring compression strain can result in diametral changes that comprise a substantial component of total deflection.

*Strength/Maximum Strain*

Strength is a primary structural design criterion. In the case of plastics, strain rather than stress proves to be a convenient measure of strength. For some materials, a working strain criterion is taken as a strength criterion for short- and long-term stresses and strains and for infrequent superimposed cyclic loads due to surface-applied vehicle wheels.

*Buckling*

Stability against buckling is a performance limit for plastic pipe; however, the buckling criterion rarely governs wall thickness for smooth-wall pipe. Both local buckling and general instability may govern the design of corrugated tubing.

**Requirements for Embedment Systems**

The following are important requirements that relate to the embedment soil or aggregate surrounding the buried plastic pipe (see later section under "Installation Guidelines" for terminology and for discussion of the embedment system components).

*Bedding/Haunching*

The pipe must receive uniform and continuous support, particularly along its lower half, in order to minimize deflections, stresses, and strains at the pipe invert. The bedding and haunching must be designed and constructed to provide this support. It is especially critical to provide well-compacted material in the haunch zone to ensure that the full bottom of the pipe is supported.

*Side Support*

The pipe must receive uniform lateral support along its sides. This support provides reactions that allow ring compression stress resultants to develop and carry a significant share of the vertical loads applied to the pipe-soil system. If such reactions are not provided, ring bending and shear become the primary but structurally inefficient load paths, and the result is large deflections, stresses, and strains.

*Embedment Materials*

The behavior of a buried plastic pipe is largely dependent on the type and density of the embedment material in which it is buried. The classes of materials appropriate for embedding plastic pipe in transportation applications are defined and covered in more detail later (section under "Installation Guidelines" and App. A3). They include Class A aggregates that are angular and well graded and Class B soils that include clean gravels and coarse sands. Properly designed drainage envelope materials used around underdrains generally fall within these two classes. These classes of embedment materials offer the following properties, which are extremely important to the performance of plastic pipe installations: (1) stiffness, or capacity, when compacted, to provide structural support to a buried pipe; and (2) compactibility, or the ease with which a soil can be placed at or compacted to the desired density.

Because Class A and Class B embedment materials are inherently stiff and compactible over a wide range of field conditions, they provide a high degree of reliability in field installations. This is true provided the gradation of these materials is made compatible with that of the in-situ soil.

Other types of embedment soils have a lower stiffness at a given density, they may require considerable effort to achieve proper compaction, or their compactibility may be very sensitive to moisture content. The risk of exceeding performance limits under field conditions is increased when the latter materials are employed.

**Structural Evaluation Procedure**

The detailed procedures for the design and evaluation of buried smooth-wall plastic pipe are summarized in Table 8. A thumb-nail description of the various steps given in the table is presented in the following to illustrate the method. Design examples that illustrate its use are given later in this section.

*Establish Pipe Properties*

Pipe stiffness and section properties are required for initial calculations. Pipe strength (working strain) will be determined later. The short-term pipe stiffness, $PS_o$, is calculated or obtained from the pipe specification. Section properties are calculated from the specified minimum wall dimensions given in the specification (e.g. SGH PVC-TD, App. A2, Table 7).

$$PS_o = \frac{F}{\Delta} = 53.7\frac{E_o I}{d^3} \qquad (1)$$

where $F$ equals load per unit length on pipe at 5 percent deflection, lb/in. (N/mm); and $\Delta$ equals pipe deflection (change in vertical diameter), in. (mm). For pipe stiffness calculation $\Delta$ equals 0.05 $d$ by definition. See Table 8 for additional notation.

*Estimate Embedment Stiffness*

Values of $E'$ are estimated from Table 9. These values are used directly for calculating the effects of earth loads (Eqs. 4 and 10).

The values of $E'$ given in Table 9 should be reduced tentatively by a factor of 2, for calculating the effects of surface wheel loads at shallow burial (Eqs. 4 and 10 are also used in these calculations). This reduction accounts for the lack of confinement of shallow cover and the nonuniformity of confinement arising from the localized nature of the soil stresses associated with concentrated surface loadings.

The constrained modulus, $M_s$, may be used as an alternative to the $E'$ values given in Table 9. $M_s$ is calculated from the stress-strain curve for the embedment material, as obtained in a confined compression test.

*Loads*

The "soil prism" theory, which is receiving increased acceptance, is proposed for use in determining earth loads on the pipe (Eq. 2). Alternatively, the Marston-Spangler method, which accounts for the effects of geometry of the trench embedment characteristics and the relative stiffness of pipe and soil, may be used (*17*). The soil-prism theory is usually the more conservative of the two methods. Earth load is expressed in terms of free-field soil stress, if no pipe were present. This is not the same as the pressure at the pipe-soil interface.

Soil pressures applied to the pipe by surface-applied wheel loads are determined from Figure 1 for a single H-20 vehicle wheel. The effects of wheels of adjacent vehicles may also be significant and can be evaluated by superposition. The beneficial effects of the pavement structure, if any, are neglected in Figure 1. Other concentrated load conditions and the effects of pavements can be taken into account by available methods (*17, 18, 19*). Pressures from concentrated truck wheel loads are usually neglected for depths of cover exceeding 96 in. (2.5 m).

*Calculate Deflection Due to Earth and Live Loads*

*Earth Loads.* The Iowa formula, Eq. 4, is used to calculate the deflection due to earth load. (This has also been called the "average" deflection elsewhere in this report. Values of $E'$ are obtained from Table 9. Use of the Iowa formula requires selection of values for the deflection lag factor and the bedding constant, as follows:

1. *Deflection lag factor, $D_l$*—The deflection lag factor accounts for increases in deflection that result from the time-dependent stiffness response of the embedment soil surrounding a pipe. This response may be accelerated by traffic during construction, as found in NCHRP Project 4-11 field tests. The amount of deflection lag depends on soil type, level of compaction, water conditions, trench

TABLE 8

DESIGN PROCEDURE FOR BURIED PLASTIC PIPE

| Purpose | Design Parameter | Formula | Eq. | Comment |
|---|---|---|---|---|
| Determine Total Applied Soil Pressure Due to Loads | Pressure at Springline Due to Soil Load | $p_s = \gamma_s H$ (or Fig. 1) | 2 | Soil prism theory. Marston-Spangler theory is alternate method. |
| | Pressure at Springline due to H20 Surface Live Load | $p_w$ from Fig. 1 | | Boussinesq theory may be applied for other load conditions |
| | Total Applied Pressure | $p_t = p_s + p_w$ | 3 | |
| Determine Deflection Level | Average Deflection | $\frac{\Delta_a}{d} = \frac{D_l K p}{0.149 PS_o + 0.061 E'}$ | 4 | E' from Table 9. Use for earth load and vehicle load. Use reduced E' for vehicle loads. $PS_o$ specified or calculated from Eq. 1 |
| | Installation Deflection | $\frac{\Delta_i}{d}$ from Table 11 | | Varies with $PS_o$, and embedment quality. |
| | Total Deflection | $\frac{\Delta_t}{d} = \frac{\Delta_{as}}{d} + \frac{\Delta_{aw}}{d} + \frac{\Delta_i}{d}$ | 5 | |
| Determine Critical Strain Levels | Ring Bending Strain | $\varepsilon_b = 4.27\left(\frac{t}{d}\right)\left(\frac{\Delta_t}{d}\right)$ MF | 6 | See Table 12 for MF. For smooth-wall pipe only. See Ref. 1 for general equation. |
| | Short Term Ring Compression Strain | $\varepsilon_r = \frac{p_{do}}{2 A E_o}$ | 7 | |
| | Critical Compression Strain | $\varepsilon_c = 2\,\varepsilon_r + \varepsilon_b$ | 8 | |
| | Critical Tension Strain | $\varepsilon_t = \left(\bar{\varepsilon}_b - \bar{\varepsilon}_r\right)$ PF | 9 | Calculate only at perforation locations. See Table 13 for PF |
| Determine Critical Buckling Pressure | Critical Buckling Pressure | $p_{cr} = C_B C_D \sqrt{E' PS_v}$ | 10 | Use $PS_o$ for wheel loads<br>Use $PS_{10}$ for earth loads<br>PS from specification or calculated from Eq. 1. |
| Evaluate Strain Levels | Compression Strain | $\varepsilon_c \leq \bar{\varepsilon}$ | 11a | $\bar{\varepsilon}$ from Eq. 13, Fig. 2 |
| | Tension Strain | $\varepsilon_t \leq \bar{\varepsilon}$ | 11b | $\bar{\varepsilon}$ from Eq. 13, Fig. 2 |
| Evaluate Buckling Capacity | Wheel Loads | $p_w \leq \frac{p_{cr}}{SF}$ | 12a | |
| | Long Term Loads | $p_s \leq \frac{p_{cr}}{SF}$ | 12b | |
| Estimated Installed Deflection Requirement | Field Deflection for Typical Installations | $\frac{\Delta_m}{d} = 0.23 \frac{d}{t} \bar{\varepsilon} \frac{1}{MF} \frac{1}{PF}$ | 14 | For maximum field deflection, add allowance for manufacturing tolerances for smooth-wall pipe only. |

TABLE 8—(*Continued*)

NOTATIONS

| | | |
|---|---|---|
| $A$ | = | Area of pipe wall per unit length (equal to thickness for smooth-wall pipe) in.$^2$/in. (mm$^2$/mm). |
| $C_B$ | = | Coefficient for buckling stress<br>$C_B$ = 0.50 for earth load, and 0.07 for wheel load ($p_w \geq 0.25\ p_s$) |
| $C_D$ | = | Correction factor to account for deflection = (D min./D max.)$^{3/2}$ |
| $D_l$ | = | Deflection lag factor |
| D max. | = | Maximum diameter of deflected pipe in. (mm) |
| D min. | = | Minimum diameter of deflected pipe, in. (mm) |
| $E_v$ | = | Time-dependent viscoelastic modulus of plastic pipe material, psi (MPa) |
| $E_o$ | = | Elastic modulus of plastics obtained in short-term tension test, psi (MPa) |
| $E_{10}$ | = | Elastic modulus of plastics after 10 years under constant stress or strain, psi (MPa) |
| E' | = | Modulus of soil reaction of embedment material, psi (kPa) (See Table 9) |
| F | = | Load on pipe during parallel plates test, lb/in. (N/mm) |
| H | = | Height of earth cover above pipe springline, in. (mm) |
| I | = | Moment of inertia per unit length of pipe wall in.$^4$/in. (mm$^4$/mm) |
| K | = | Bedding constant for deflection (See Table 10) |
| MF | = | Moment factor; bedding factor for bending stress (See Table 12) |
| $M_s$ | = | Constrained modulus of soil, psi (kPa) |
| PF | = | Strain concentration factor (See Table 13) |
| $PS_v$ | = | Time-dependent pipe stiffness, lb/in./in. (kPa) |
| $PS_o$ | = | Short-term pipe stiffness, specified value, lb/in./in. (kPa) |
| $PS_{10}$ | = | Long-term pipe stiffness, 10 years, lb/in./in. (kPa) |
| SF | = | Safety Factor |
| $d$ | = | Mean diameter of pipe, in. (mm) |
| $d_o$ | = | Outside diameter of pipe, in. (mm) |
| $f_{yp}$ | = | Tensile yield point stress in plastic material, psi (kPa) |
| $p$ | = | Pressure at springline elevation of pipe, psi (kPa) |
| $p_{cr}$ | = | Critical buckling pressure on pipe, psi (kPa) |
| $p_s$ | = | Pressure at springline elevation of pipe due to earth weight, psi (kPa) |
| $p_w$ | = | Pressure at springline elevation of pipe due to surface wheel loads, psi (kPa) |
| $p_t$ | = | Pressure at springline elevation of pipe due to wheel and earth loads, psi (kPa) |
| $t$ | = | Minimum wall thickness of pipe (equal to area for smooth-wall pipe) in. (mm) |
| $\gamma_s$ | = | Density of earth cover, lbs/in.$^3$ (kg/m$^3$) |
| $\Delta$ | = | Pipe deflection in. (mm)<br>$\Delta_{as}$ = Average deflection due to earth weight<br>$\Delta_{aw}$ = Average deflection due to wheel loads<br>$\Delta_i$ = Installation deflection (Table 11)<br>$\Delta_m$ = Allowable deflection<br>$\Delta_t$ = Total deflection |
| $\varepsilon$ | = | Strain in pipe wall in./in. (mm/mm)<br>$\varepsilon_b$ = Ring bending strain<br>$\varepsilon_c$ = Maximum combined compression strain (occurs in long term)<br>$\varepsilon_r$ = Short-term ring compression strain<br>$\varepsilon_t$ = Maximum combined tensile strain (occurs in short-term)<br>$\bar{\varepsilon}$ = Tentative working strain |

TABLE 9

AVERAGE VALUES OF MODULUS OF SOIL REACTION—E' (AFTER REF. 6)

| Embedment Class | Embedment Material per Unified Soil Classification System ASTM D 2487 | Average E' for Degree of Compaction of Bedding (lb/in.$^2$) | | | |
|---|---|---|---|---|---|
| | | Dumped | Less than 85% of Max. Dry Density [3] | 85 to 95% of Max. Dry Density [3] | Greater than 95% of Max. Dry Density [3] |
| A | Crushed Rock [1] | 1,000 | 3,000 | 3,000 | 3,000 |
| B | Coarse-grained Soil with Little or No Fines<br>GW, GP, SW, SP contains less than 5 percent fines | 200 | 1,000 | 2,000 | 3,000 |
| - | Coarse-grained Soils with Fines<br>GM, GC, SM, SC contains more than 12 percent fines<br>Fine-grained Soils (LL <50) [2]<br>Soils with medium to no plasticity CL, ML, ML-CL, with more than 25 percent coarse-grained particles | 100 | 400 | 1,000 | 2,000 |
| - | Fine-grained Soils (LL <50) [2]<br>Soils with medium to no plasticity CL, ML, ML-CL, with less than 25 percent coarse-grained particles | 50 | 200 | 400 | 1,000 |
| - | Fine-grained Soils (LL> 50) [2]<br>Soils with medium to high plasticity CH, MH, CH-MH | No data available | | | |

Notes:

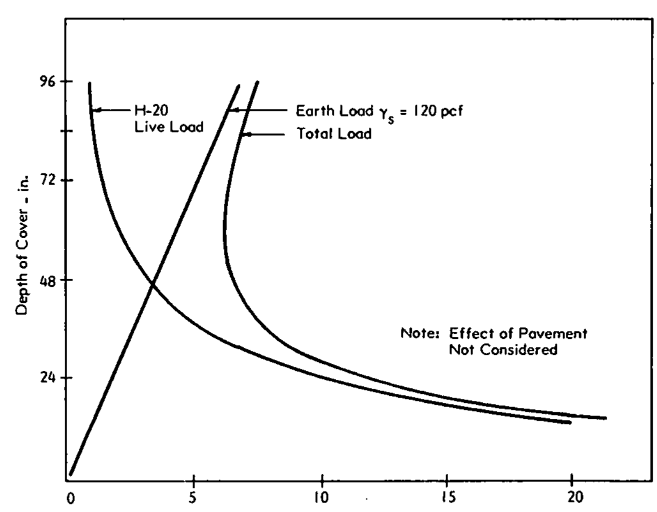
1. This classification is not given in ASTM D 2487.
2. LL = Liquid limit.
3. Maximum Dry Density determined in accordance with AASHTO T-99.
4. Shaded area is appropriate for transportation drainage applications.
5. Values applicable only for fills less than 50 feet (15 m).
6. If embedment falls on the borderline between two compaction categories, select Lower E' value or average the two values.

1 psi = 6.9 kPa

geometry, and other factors. The lag factor should be in the range of 1 to 1.5, providing the materials and values of $E'$ shown shaded in Table 9 are used in deflection calculations. Values of deflection lag can be much greater than this, but more work is needed to better define conditions under which these large increases occur.

2. *Bedding constant, K*—The bedding constant accounts for the effects of bedding and haunching conditions on pipe deflections. Spangler recommended values from 0.083 for 90 deg bedding (uniform support) to 0.11 for 0 deg bedding (line support at invert) (*21*). Project 4-11 field tests show that the omission of haunching can have a significantly greater effect on pipe deflection than predicted by Spangler for the 0 deg bedding case and that the bedding constant is as high as 0.13 for unhaunched pipe (0 deg bedding).

Tentative bedding constants for various installation conditions are given in Table 10. A common value used in design of an installation with haunching has been $K = 0.10$. An installation should not be intentionally designed without haunching because the absence of haunching causes high stress, strain, and deflection as well as an installation of unreliable quality.




Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 lb/in.$^3$ = 0.028 g/mm$^3$

*Figure 1. Variation in soil pressures with increasing depth of cover.*

*Surface Wheel Loads.* Deflection due to surface-applied wheel loads can be calculated in the same manner as for earth loads. $E'$ given in Table 9 should be reduced by a factor of 2 for concentrated surface loadings. The magnitude of cumulative deflections that occur in shallow installations under long-term sustained traffic loadings can not be estimated within the state of the art.

*Estimate Installation Deflection Allowance*

The allowance for variability in deflection of the pipe-soil installation, called installation deflection, is estimated from Table 11. This allowance accounts for deflections associated with densification of embedment resulting from construction traffic, normal variations in embedment density, and deflections imposed on the pipe during placement of both the pipe and the embedment material surrounding the pipe. Deflections arising from these sources are largely dependent on workmanship, and, thus, the allowances given in Table 11 are intended only as a guide. Furthermore, they are tentative because they are based on limited data.

*Estimate Maximum Deflection*

The maximum deflection is the sum of the earth and live-load deflection and the installation deflection allowance (Eq. 5).

*Calculate Bending Strain in the Pipe Wall*

Equation 6 is used to calculate the maximum ring bending strains at either the invert or the springlines due to earth and surface wheel loads and the installation deflection allowance. Examples 2 and 4 illustrate these calculations. The moment factor, *MF*, required for Eq. 6 accounts for the effects of bedding on the bending moment and strain at the invert. In this respect, it serves the same purpose as does $K$, the bedding factor, in the deflection equation. Tentative values for the moment factor are given in Table 12.

For determination of springline bending strains, MF can be taken as 0.75. Effects of stress or strain concentrations from perforations are considered in the following.

*Calculate Ring Compression Strain*

Equation 7 is used to calculate the initial ring compression strains in the pipe. These strains are assumed to be constant around the full pipe circumference.

*Calculate Critical Strains in Pipe Wall*

Governing strains are calculated using Eq. 8 for compression and Eq. 9 for tension. Maximum compression strain occurs at the invert, while maximum tension strain occurs either at the invert or at perforations, if present. Calculations for maximum tension strains due to strain concentrations around perforations are discussed next.

In perforated pipe, stress or strain concentrations due to perforations can be significant. Strain concentrations can be neglected in compression because they do not provide a site for crack propagation. Table 13 provides perforation factors, PF, to be applied to the maximum tensile stress or strain calculated at the perforation location.

The effects of perforations are most serious when they are located at maximum moment points. If the perforations occur at or near the invert, the invert bending strain is used in Eq. 9. If the perforations are located near the springline (Table 6, App. A2, for PVC pipe), the springline strain may be critical. Finally, if the perforations are located near the inflection points, where moments are small or zero, the effects of perforations can be neglected. Inflection points are located at about ±45 deg from crown and invert.

*Estimate Critical Buckling Pressure*

Critical buckling load under either earth or surface vehicle loads is calculated using Eq. 10. The coefficient, $C_B$, is taken as 0.50 for earth load and 0.07 for surface wheel loads. This equation is conservative for cover depths greater than about 3 ft (0.9 m). If the actual cover is less, or if buckling is shown to be critical, a more detailed analysis is warranted.

*Estimate Strain Capacity*

Strain capacity is estimated using Eq. 13 in Figure 2. If strains are maintained below this limit, the elastic equations in Table 8 can be used to estimate stresses and strains in the viscoelastic plastic pipe material with reasonable accuracy. The strain limit is taken here as a working strain capacity as well. Although the strain limit calculation may be used to estimate strain capacity in most types of rigid thermoplastics, it is judged appropriate only for those materials that have proven long-term strength.

*Determine Structural Adequacy*

The maximum strain in the pipe wall determined from earlier steps is compared with the strain capacity, using either Eq. 11a or Eq. 11b, to assess structural adequacy. The working strain as calculated by Eq. 13 (Fig. 2) is used directly in these equations, without any further safety factors. The use of an unfactored strain limit provides deflection limits for smooth-wall pipe that are generally consistent with those currently specified in practice. Additional margins of safety may be applied depending on the design situation.

To evaluate potential fatigue effects, a separate check should be made to determine whether the strain due to wheel loads comprises a significant portion of the total strain in the pipe wall. Very limited data on one PVC pressure pipe compound indicate that fatigue effects become significant when the cyclic strain amplitude becomes greater than 25 percent of the total strain (*10*). The PVC compound specified in proposed specification SGH PVC-TD is a pressure pipe compound and it is tentatively assumed that this behavior is exhibited by this material. Of course, the total strain should not exceed the working strain. Other pipe materials are insufficiently characterized to permit evaluation of fatigue strength limits. The conditions under which cumulative deflections occur during heavy long-term repetitive traffic above pipe with shallow cover have not been established, and hence the use of plastic pipe under such conditions remains experimental.

TABLE 10

TENTATIVE BEDDING CONSTANTS FOR DEFLECTION

| Construction Condition | Bedding Constant (K) |
|---|---|
| Haunched, and field monitored | 0.09 |
| Haunched, and not monitored | 0.11 |
| No Haunching (for information only; not recommended) | 0.13 |

TABLE 11

TENTATIVE DESIGN INSTALLATION DEFLECTIONS FOR HAUNCHED PIPE

| | Installation Deflection (%) (1) | | |
|---|---|---|---|
| Pipe Stiffness (lb/in./in.) | 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 12

TENTATIVE MOMENT FACTORS FOR RING BENDING STRAIN

| Construction Condition | Moment Factor (MF) |
|---|---|
| Haunched, and field monitored | 0.75 |
| Haunched, and not monitored | 1.0 |
| No haunching (for information only; not recommended) | 1.5 or greater |

TABLE 13

PERFORATION FACTORS FOR STRAIN CONCENTRATIONS

| Condition | Perforation Factor (PF) |
|---|---|
| Circular hole in smooth-wall pipe in bending | 2.3 |
| Circular hole, uniform tension (e.g. one shell of ABS Composite, or in flanges of corrugated tubing) | 3.0 |
| Circumferential slot, rounded ends, assume aspect ratio = 8:1 (e.g. 1 inch circumferential slot, 1/8 in. wide); factor varies with actual aspect ratio | 1.3 |

Finally, the critical buckling pressure is compared to the calculated maximum applied pressure on the pipe wall, in accordance with Eq. 12. The safety factor selected is a matter of judgment. A safety factor of 3 has been recommended for buckling resistance to earth loads. This appears appropriate for wheel loads as well.

The maximum deflection estimated from Eq. 5 should be compared to nonstructural performance limits set for the project, which may be based on such considerations as gasket tightness and access for cleaning equipment.

### Simplified Method for Estimating Deflection Limits

The preceding design procedures can be used to demonstrate that deflections due to earth and traffic loads are generally low when compared to deflections caused by the variability expected in actual installations (see Examples 1 to 3 under "Design Examples"). This is true at least for most smooth-wall flexible plastic pipe, when installed in stiff, compacted embedment materials. Thus, provided that burial is neither very shallow nor very deep, as is typical for most installations, stresses due to earth and traffic loads may be neglected.

In light of the foregoing, a simplified approach can be taken to establish a maximum level of installed deflection, which can be used as a specification requirement or a field check on the quality of installation. It can also be used to review deflection limit criteria for existing or new products.

In this simplified method, pipe stiffness, section properties, and strain limits are first determined in the same fashion as described earlier. Wall section properties are calculated from the specified minimum wall dimensions given in the specification (e.g. SGH PVC-TD, App. A2; see Table 7 also). Working strain limits are determined from Eq. 13 (Fig. 2).

The deflection limit is determined from the following equation:

$$\frac{\Delta_{max}}{d} = 0.23\,\bar{\epsilon}\,\frac{d}{t}\,\frac{1}{MF \times PF} \qquad (14)$$

in which:

$\frac{\Delta_{max}}{d}$ = maximum installed pipe deflection relative to average diameter;

$t$ = minimum wall thickness of pipe, in. (mm);

$\bar{\epsilon}$ = working strain, in./in. (mm/mm);

MF = moment factor (Table 12); and

PF = perforation factor (Table 13).

This equation provides a maximum value for installed deflection.

The foregoing approach is extremely simple and yet very useful. It provides a guide in the selection of maximum acceptable limits for installed deflection. They are guideline limits that the designer may choose to increase or reduce, depending on the specific design situation.

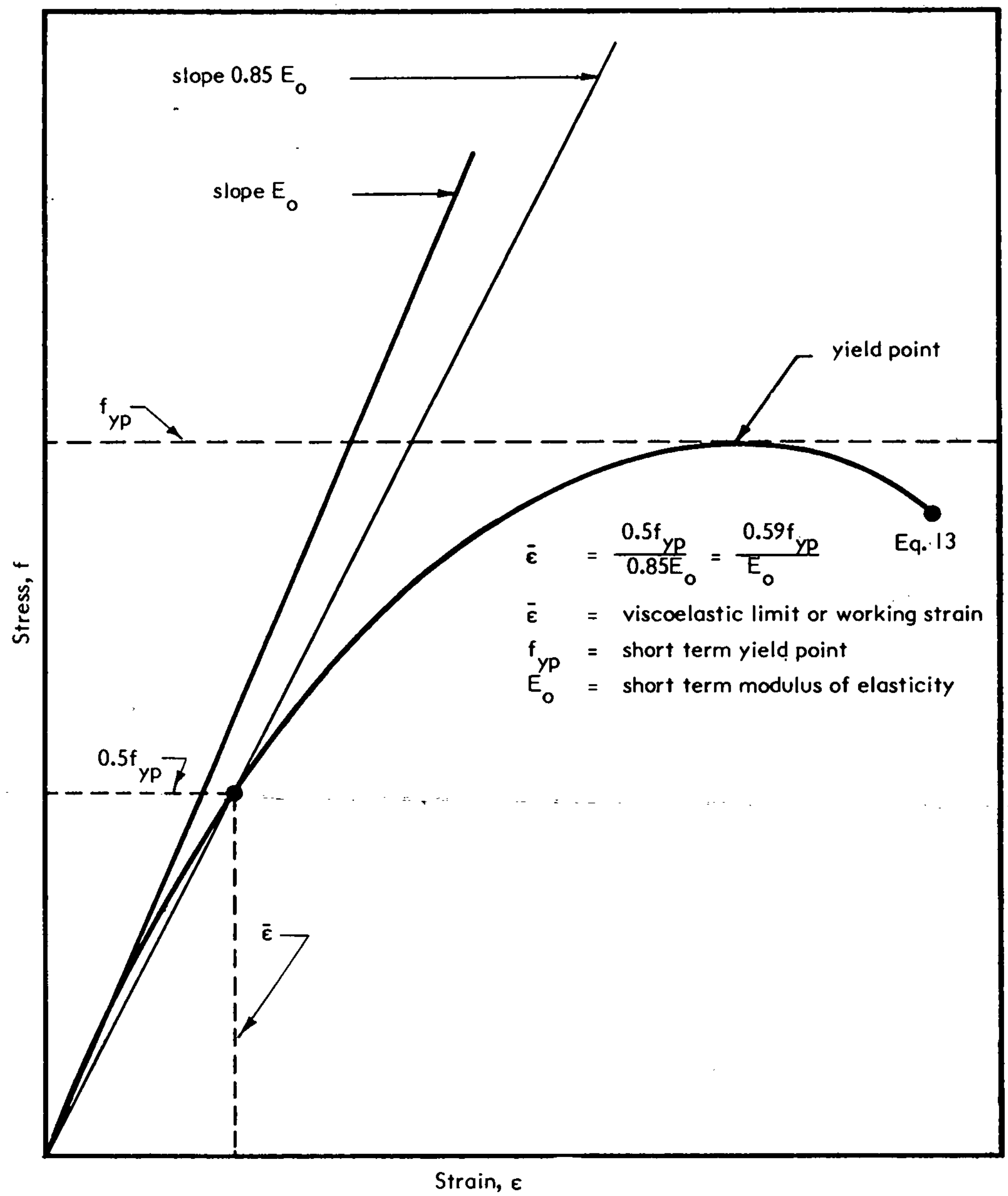



*Figure 2. Short-term stress-strain relations for plastics.*

**Connections and Joints**

Like most structural design procedures for plastic pipe, the previous approaches consider only the structural behavior and adequacy of the pipe barrel. Joints and connections may display stiffness, strength, and stiffness-to-strength relationships that are significantly different from those provided in the barrel. Thus, any comprehensive structural evaluation method for plastic pipe should consider the effects of joints.

The foregoing methods, or adaptations thereof, may be used to obtain approximate estimates of structural adequacy of joints and connections and to establish deflection limits for these components of the pipe system. For the most part, however, accurate determination of structural adequacy of such components awaits an advance in the state of the art.

**Design Examples**

Design Examples 1 to 4, which follow, illustrate implementation of the design procedures discussed earlier.

*Example 1—Deflection of a Deeply Buried Pipe*

Determine the maximum estimated deflection of a PVC pipe, specification SGH PVC-TD, under the following design conditions (*Note:* 1 psi = 1 lb/in./in. = 6.9 kPa; 1 in. = 25.4 mm; 1 lb/in.$^3$ = 0.028 g/mm$^3$):

Pipe: 15 in. diameter SGH PVC-TD, unperforated, PS = 50 lb/in./in.
Cover height: 20 ft of 120 pcf earth
Embedment: Class B well-graded gravel (GW)· 90 percent of maximum dry density (AASHTO T-99)
Installation specification: SGH RP-TD

1. Loads:

$$P_s = \gamma_s H \text{ (Eq. 2)}$$
$$\gamma_s = 120 \text{ pcf} = 0.069 \text{ lb/in.}^3$$
$$H = 20' = 240''$$
$$p_s = 0.069\ (240) = 16.6 \text{ psi}$$

2. Embedment stiffness:

$$E' = 2000 \text{ psi (Table 9)}$$

3. Average deflection:

$$\frac{\Delta_a}{d} = \frac{D_l K p_s}{0.149\ \text{PS}_o + 0.061\ E'} \text{ (Eq. 4)}$$

Assume $D_l = 1.2$

$$K = 0.11 \text{ (Table 10)}$$
$$\frac{\Delta_a}{d} = \frac{1.2\ (0.11)\ 16.6}{0.149\ (50) + 0.061\ (2000)}$$
$$= 0.017, \frac{\Delta_a}{d} = 1.7\%$$

4. Installation deflection:

$$\frac{\Delta_i}{d} = 3.0\% \text{ (Table 11)}$$

5. Total deflection:

$$\frac{\Delta_t}{d} = \frac{\Delta_{as}}{d} + \frac{\Delta_{aw}}{d} + \frac{\Delta_i}{d} \text{ (Eq. 5)}$$
$$\frac{\Delta_t}{d} = = 0.017 + 0 + 0.030 = 0.047 \quad \frac{\Delta_t}{d} = 4.7\%$$

The estimated deflection, assuming reasonable workmanship, is about 5 percent. Note that the installation deflection is twice the earth load deflection even with 20 ft of earth weight applied to the pipe.

*Example 2—Strains in a Deeply Buried Pipe*

Determine the maximum strain in the deeply buried PVC pipe examined in Example 1 (*Note:* 1 psi = 1 lb/in./in. = 6.9 kPa; 1 in. = 25.4 mm; 1 lb/in.$^3$ = 0.028 g/mm$^3$):

1. Pipe properties (from SGH PVC-TD, App. A2):

$$d_o = 15.3 \text{ in.}$$
$$t = 0.438 \text{ in.} = A \text{ (in.}^2\text{/in.)}$$
$$d = d_o - t = 14.86 \text{ in.}$$
$$f_{yp} = 7000 \text{ psi}$$
$$E_o = 400{,}000 \text{ psi}$$

2. Strain limit:

$$\bar{\epsilon} = \frac{0.5 \times f_{yp}}{0.85 \times E_o} \text{ (Eq. 13)}$$
$$\bar{\epsilon} = \frac{0.5 \times 7000}{0.85 \times 400{,}000} = 0.0103 \qquad \bar{\epsilon} = 1.0\%$$

3. Ring bending strain (maximum at invert for nonperforated pipe):

$$\epsilon_b = 4.27 \left(\frac{t}{d}\right)\frac{\Delta_t}{d} \times \text{MF (Eq. 6)}$$

MF = 1.0 (assumes average bedding) (Table 12)

$$\frac{\Delta_t}{d} = 0.047 \text{ (solution from Ex. 1)}$$
$$\epsilon_b = (4.27)\ \frac{0.438}{14.86}\ (0.047) = 0.0059 \qquad \epsilon_b = 0.59\%$$

4. Ring compression strain:

$$\epsilon_r = \frac{Pd_o}{2A\ E_o} \text{ (Eq. 7)}$$
$$P = p_s = 16.6 \text{ psi (from Ex. 1)}$$
$$\epsilon_r = \frac{16.6\ (15.3)}{2\ (0.438)\ (400{,}000)}$$
$$= 0.00072 \qquad \epsilon_r = 0.07\% \text{ (small)}$$

5. Total strain:
Unperforated Pipe—check compression only

$$\epsilon_c = 2\epsilon_r + \epsilon_b \text{ (Eq. 8)}$$
$$\epsilon_c = 2\ (0.0007) + 0.0059 = 0.0073 \qquad \epsilon_c = 0.73\%$$

6. Evaluate strain level:

$$\epsilon_c = 0.73\% < \bar{\epsilon} = 1.0\% \qquad \text{ok}$$

The strain at the invert is below the strain limit. If the pipe contained perforations, a check should be made for tensile strain at springline.

*Example 3—Deflection of a Pipe with Shallow Cover*

Determine the estimated deflection of a perforated underdrain, specification SGH PVC-TD, under the following design conditions (*Note:* 1 psi = 1 lb/in./in. = 6.9 kPa; 1 in. = 25.4 mm; 1 lb/in.$^3$ = 0.028 g/mm$^3$):

Pipe: 6 in. diameter, perforated, PS = 50 lb/in./in.
Cover height: 3 ft
Traffic: H20 vehicle
Embedment: Drainage envelope of sand (SP) compacted to 90 percent of maximum dry density (AASHTO T-99)
Installation Specification: SGH RP-TD

Earth: $p_s = 2.5$ psi (Eq. 2)
Live: $p_w = 5.3$ psi (Fig. 1)

1. Embedment stiffness (reduce by a factor of 2 for wheel load):

$$E' = 2000 \text{ psi} \times 0.5 = 1000 \text{ psi (Table 9)}$$

2. Deflections:
Assume $D_l = 1.2$; $K = 0.11$ (Table 10)

$$\frac{\Delta_a}{p} = \frac{D_l K p}{0.149\ PS_o + 0.061\ E'} \text{ (Eq. 4)}$$
$$\frac{\Delta_{as}}{d} = \frac{1.2\ (0.11)\ 2.5}{0.149\ (50) + 0.061\ (1000)} = 0.005, \frac{\Delta_{as}}{d} = 0.5\%$$
$$\frac{\Delta_{aw}}{d} = \frac{1.2\ (0.11)\ (5.3)}{0.149\ (50) + 0.061\ (1000)} = 0.010, \frac{\Delta_{aw}}{d} = 1.0\%$$
$$\frac{\Delta_i}{d} = 3.0\% \text{ (Table 11)}$$
$$\frac{\Delta_t}{d} = \frac{\Delta_{as}}{d} + \frac{\Delta_{aw}}{d} + \frac{\Delta_i}{d} = 0.5 + 1.0 + 3.0 = 4.5\% \text{ (Eq. 5)}$$

The estimated deflection, assuming reasonable workmanship, is 4.5 percent. The installation deflection is three times the surface wheel load deflection.

*Example 4—Strains in Pipe with Shallow Cover*

Determine the maximum strain in the perforated PVC pipe examined in Example 3 (*Note:* 1 psi $\doteq$ 1 lb/in./in. = 6.9 kPa; 1 in. = 25.4 mm; 1 lb/in.³ = 0.028 g/mm³):

1. Pipe properties (SGH-PVC-TD, App. A2):

$$t = 0.180 \text{ in.} = A \text{ (in.}^2\text{/in.)} \quad f_{yp} = 7000 \text{ psi}$$
$$d_o = 6.275 \text{ in.} \quad E_o = 400{,}000 \text{ psi}$$
$$d = d_o - t = 6.095 \text{ in.} \quad PS_o = 50 \text{ psi}$$
$$\bar{\epsilon} = 0.01 = 1.0\% \text{ (see Ex. 2 for calculation)}$$

2. Ring bending strain (critical perforation location is at springline, Table 6, App. A2):

$$\epsilon_b = 4.27 \left(\frac{t}{d}\right)\left(\frac{\Delta_t}{d}\right) \text{MF (Eq. 6)}$$

MF = 0.75 @ springline; MF = 1.0 @ invert (assumes good bedding)

$$\frac{\Delta_t}{d} = 0.045 \text{ (Ex. 3)}$$

$$\epsilon_b = 4.27 \left(\frac{0.180}{6.095}\right) (0.045) \text{ MF} = 0.0057 \text{ MF}$$

$$\epsilon_{bs} = 0.0057\ (0.75) = 0.0043 \qquad \epsilon_{bs} = 0.43\%$$
$$\epsilon_{bi} = 0.0057\ (1.0) = 0.0057 \qquad \epsilon_{bi} = 0.57\%$$

3. Ring compression strain:

$$\epsilon_r = \frac{Pd_o}{2A\,E_o} \text{ (Eq. 7)}$$

$$P = P_s + P_w = 2.5 + 5.3 = 7.8 \text{ psi (see Ex. 3)}$$

$$\epsilon_r = \frac{7.8\ (6.275)}{2\ (0.18)\ (400{,}000)} = 0.00034 \qquad \epsilon_a = 0.03\% \text{ (small)}$$

4. Total strains:

Maximum compression strain (at invert)

$$\epsilon_c = 2\,\epsilon_r + \epsilon_{bi} \text{ (Eq. 8)}$$
$$\epsilon_c = 2\ (0.0003) + (0.0057) = 0.0063 \qquad \epsilon_c = 0.63\%$$

Tension strain (at perforations at springline)

$$\epsilon_t = (\epsilon_{bs} - \epsilon_r) \text{ PF (Eq. 9)}$$

PF = 2.3 (circular hole in smooth-wall pipe in bending) (Table 13)

$$\epsilon_t = (0.0043 - 0.0003)\ 2.3 = 0.0092 \qquad \epsilon_t = 0.92\%$$

5. Evaluate strain levels:

$$\epsilon_c = 0.63\% < \bar{\epsilon} = 1.0\%$$
$$\epsilon_t = 0.92\% < \bar{\epsilon} = 1.0\%$$

6. Evaluate fatigue: Strains are proportional to deflection, therefore, compare deflections due to wheel load with total deflection

$$\frac{\Delta_{aw}/d}{\Delta_t/d} = \frac{0.010}{0.045} = 0.22 = 22\% \text{ (Ex. 3)}$$

Fatigue effects become significant when the cyclic strain amplitude becomes greater than 25 percent of the total strain; therefore, fatigue in this example should not be critical for occasional repetitive loads.

The maximum strain criterion is met at perforations at the springline, and at the invert where no perforations are present. Furthermore, because the calculated strain just meets the fatigue criterion, the 3-ft burial depth is about the minimum burial depth for occasional repetitive traffic unless a rigid pavement or higher quality embedment is provided.

## INSTALLATION GUIDELINES

The objectives when installing a buried plastic pipe are to minimize pipe deflections induced by, or resulting from, the installation process, and to provide a firm, stable, permanent support for the pipe when the installation is subjected to loads. This section deals with factors that are especially critical in obtaining such an installation. A recommended practice developed from these installation considerations is contained in Appendix A3.

### Terminology

Terminology used to describe buried pipe installations varies among regions of the country and also among various specifying authorities. The terminology that follows is used throughout this report. A general arrangement of the pipe embedment system describing the terminology is shown in Figure 3.

*Foundation*—A foundation is an imported material used under the bedding. It may be required when trench bottom instability, rock, or excess water is encountered.

*Embedment System*—The embedment system, which also may be the drainage envelope for perforated underdrains, includes bedding, haunching, and initial backfill.

*Bedding*—Bedding is that portion of the embedment that is prepared and in place prior to installing the pipe. Where in-situ soil conditions and drainage characteristics permit, the in-situ trench bottom may serve as bedding. Bedding may or may not contain a groove conforming to the pipe curvature, depending on installation requirements.

*Haunching*—This is a layer of embedment material that extends from the top of the bedding to the springline of the pipe.

*Haunch Zone*—This zone is defined as the area between the invert and the springline of the pipe (haunches).

*Initial Backfill*—Initial backfill is the portion of the embedment system that extends from the top of the haunching to 6 to 12 in. (150 to 300 mm) above the crown of the pipe.

*Final Backfill*—Final backfill is that portion of the installation that lies between the top of the initial backfill and the top of the trench.

*Pipe Zone*—This zone lies adjacent to the pipe over its full height.

### Pipe-Embedment System

The objectives that must be achieved in the installation of a flexible buried plastic pipe for transportation drainage are as follows:

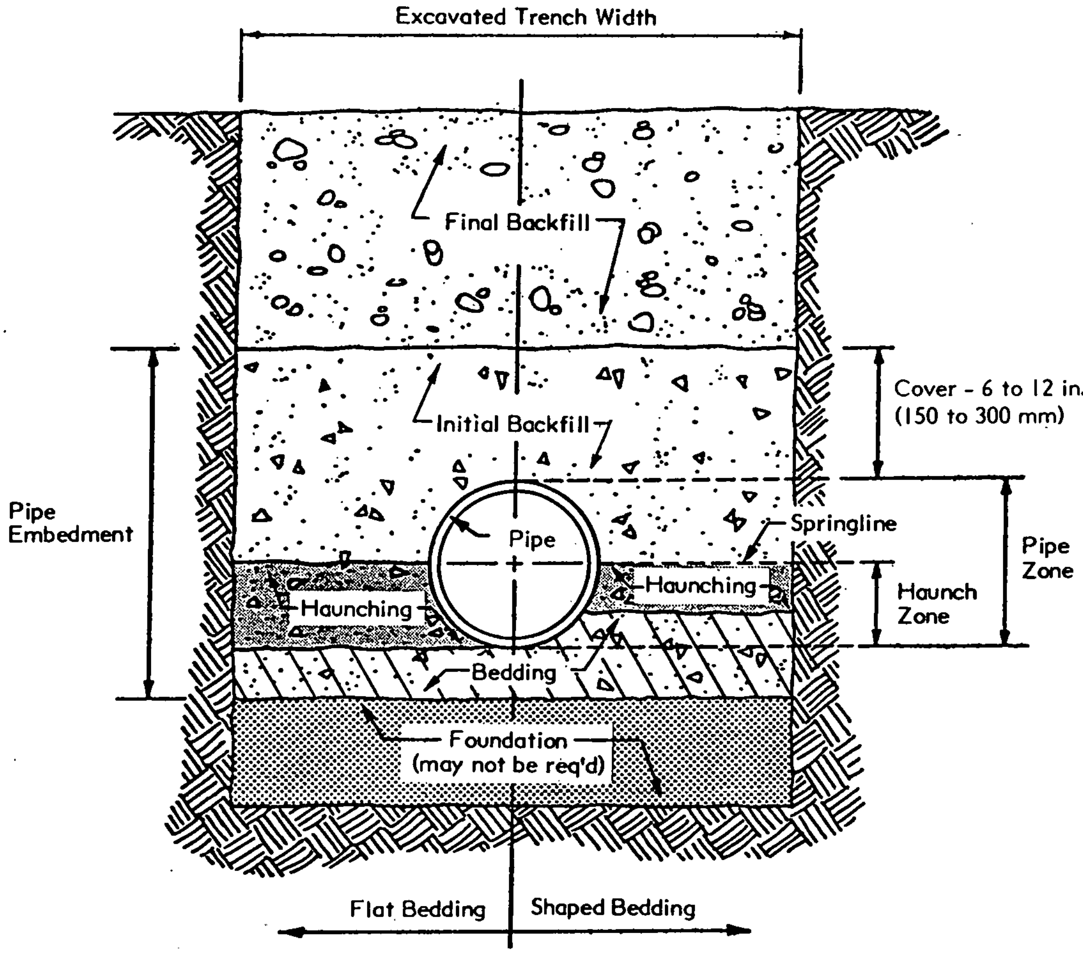



*Figure 3. Trench cross section showing terminology.*

1. The line and grade of a drainage piping system should be constructed to provide the gravity flow requirements anticipated in design.
2. The cross section of the installed pipe should be within specified deflection limits immediately after construction and remain reasonably circular for the indefinite future. This means that distortion built in during installation, or caused by construction, service traffic, or earth loadings, should remain within tolerable limits. Overdeflection is an indication of excessive strain in the pipe wall; it may restrict cleaning devices and cause gasketed joints to leak.
3. When buried pipe is used for underdrains, the embedment system also serves as a drainage envelope, and must permit free drainage for the design life of the installation. This means that the envelope must be designed and constructed to allow passage of water, with minimum transport of fines into or through the pipe-envelope system. Movement of fines from the in-situ trench may clog the envelope. Movement of fines into the pipe through perforations can clog the pipe or cause loss of structural support by embedment materials.

An acceptable installation results from the proper choice of materials and construction techniques that recognize the factors that contribute to both successful and unsuccessful installation performance.

*Key Structural Considerations*

Deflection is a practical indication of the state of stress or strain in the wall of a flexible pipe. Most design methods and design criteria for flexible pipe are based on deflection and its control. Deflection is easy to measure and it has been traditionally used as a measure of adequacy of flexible pipe installations. The objective of the installation, then, is to ensure that the pipe is installed with tolerable deflections and that deflections do not increase significantly during the lifetime of the system.

There are many sources of deflection in a buried flexible pipe. The two primary sources are those resulting from installation and those arising from subsequent earth and traffic loads.

Plastic pipe is flexible and can be deformed rather readily during the installation process. If suitable methods and materials are not used in the installation, the excessive deflections that may result can seriously detract from, or even exceed, the overall design deflection budget. Generally, installation deflections reduce with increasing pipe stiffness. Improper construction, however, can result in overdeflection of stiff pipe, whereas proper construction can result in negligible deflection of very flexible pipe.

Plastic pipe depends on the embedment or envelope material for its support. Theory, laboratory and field tests, and experience with failures, all point to the necessity of providing uniform and continuous support around the flexible pipe. The properties of the surrounding embedment material have more influence on pipe behavior under earth and wheel loads than the stiffness of the pipe itself.

The design and execution of the installation must recognize that a primary part of the pipe-soil structure is being constructed in the field. Field conditions are usually difficult, particularly in trenches where ledge, boulders, frozen material, water, and unstable conditions are encountered. Materials used for embedment may be inherently variable by nature. Handling and feasibility of obtaining required density and uniformity of embedment can vary widely depending on properties such as grain size and moisture content. Obviously, the more that can be done to improve the reliability of the construction under difficult field conditions, the greater the chances for a successful installation. Reliability is a function of both the materials specified and furnished and the procedures used in construction of the embedment envelope.

*Key Drainage Considerations*

There is an increasing emphasis on providing adequate drainage of transportation facilities. Past experience shows that water which permeates pavements must be removed quickly. Otherwise, pavement support is lost and premature deterioration develops under heavy and repetitive wheel loads.

The underdrain pipe is only one component of the drainage system. A second component is the drainage envelope surrounding the pipe and its filter sleeve, if any. The third component is the material to be drained, such as in-situ material in the trench bottom and walls, backfill over the pipe, or drainage courses beneath the pavement. These components must work together to provide suitable drainage.

Drainage theory is outside the scope of this report. Qualitatively, the key functions to be considered are the following. The system should carry water to the underdrain conduit as rapidly as possible. Flow rate should be restricted, however, to minimize transport of fines into either the envelope or the underdrain, or both. Holes or slots in the underdrain pipe wall should be small enough such that significant quantities of fines do not enter the pipe and obstruct flow. Nonwoven fabric filter sleeves may be used in certain instances to minimize entry of fines into the pipe.

Clearly, the requirements of the system dictate that there is no universal drainage envelope suitable for all soils and underdrain perforations. Careful attention should be given to this in the design and construction stages of the project (*11, 12*).

**Functions and Requirements of Pipe Installation**

The key requirements governing success of a buried plastic pipe installation have been previously discussed. This section is devoted to the various components of the pipe installation and their principal roles in achieving satisfactory performance.

*Foundation*

A specially constructed foundation layer may or may not be required depending on subsurface conditions. When used, the foundation provides a sound, firm base both in the event that the trench bottom is unstable and in the case of overexcavation. It serves to level out the bottom of trenches cut in rock and provides a cushion layer above a rock or hard earth trench bottom. It may also serve as a drainage layer to drain ground water entering the trench near the work, or water flowing into the work area from adjacent trench sections. Where water conditions are severe, underdrains may be incorporated into this layer to speed drainage to sumps, drainage ditches, or other means of water removal. As discussed later, foundation materials must be carefully selected to be compatible with both in-situ and embedment materials and to facilitate removal of flowing water in the trench, if present.

*Embedment*

The embedment material consists of the bedding, haunching, and the initial backfill. Material placed in the haunch zone below the springline, and which may be comprised of either the bedding or the haunching, or both, is a vital part of the installation. This whole zone supports the pipe wall under vertical loads applied to the pipe, and hence it plays a significant role in structural performance of the installation. It also provides a significant portion of the lateral support to the pipe wall.

Judgment, theory, tests, and evaluation of field failures all lead to the conclusion that the support at the haunches of any buried pipe should be uniform rather than concentrated, and plastic pipe provides no exception to this. The desired support in the haunch zone is a uniform "cradle" of embedment material extending over the entire haunch zone for the full pipe length. Undesirable support is a line reaction applied to the invert only. The least desirable support results if this line support is absent along portions of the pipe length or, even worse, if this support reduces to a point load caused by a cobble or boulder in the bedding. These principles hold for any pipe, and any means used in the field to provide uniform bedding is acceptable.

Clearly then, the installation design should recognize the importance of supporting the haunches of plastic pipe. A shaped bedding groove that closely conforms to the bottom of the pipe may be provided prior to installation. Alternately, it may prove more convenient to tamp embedment material underneath the pipe haunches to provide the desired uniform support, as is practice for embedment of some types of conventional pipe. Granular embedment materials can be compacted readily and are desirable as materials for the haunch zone.

The embedment materials placed in the pipe zone at the sides of the pipe are also critical to the success of a flexible plastic pipe installation. This material, including that in the haunch zone, must provide uniform lateral support for the pipe wall to minimize ovalling or deflection. Like the bedding, material adjacent to the pipe should provide a continuous uniform cradle extending for the full height and length of the pipe, and any discontinuities in density of materials or the presence of cobbles or other debris may result in erratic or excessive deflections.

The upper portion of the initial backfill material above the crown of the pipe is also important in installations where significant wheel loads may be applied at the top of the trench. In this case, the maximum stresses in the pipe are at the crown. Thus, the initial backfill directly above the pipe can be considered as an inverted bedding. The quality of this part of the embedment must be similar to that previously described for bedding and haunching.

*Final Backfill*

The final backfill material applied above the embedment system usually has little practical importance in pipe performance. It should, of course, be free of boulders and debris to prevent high localized loads on the pipe embedment system, because such inclusions are a known source of overdeflection and failure. In installations located under pavements, the backfill material should be compacted as required for the adjacent materials below pavements to minimize differential settlement of the trench and subsequent loss of support to the pavement.

**Considerations in Materials Selection**

Because the nature and placement of embedment materials may have more influence on pipe deflection than the pipe itself, selection of embedment materials is a primary consideration in installation design. Key factors in this selection are discussed in the following.

*Reliability*

Theoretically, a wide variety of soils and processed aggregates can be used for founding and embedding of plastic pipe. Furthermore, depending on the loadings applied to the pipe embedment system, density requirements for these soils could also be varied to meet design deflection control criteria. From the standpoint of practicality and reliability, however, the choice becomes somewhat limited.

Reliability is a major consideration in the drainage of transportation facilities, which are typically important civil works. However, full time monitoring of such projects, although highly desirable, may not always be feasible. Furthermore, installations may be subjected to substantial wheel loads during construction. Finally, the pipe may be buried under pavements, where implications of dig-up of an installed pipe are enormous. For these reasons, clean, angular materials such as coarse sands, gravels, and crushed stone are traditionally used for embedment of pipe in transportation drainage installations.

Properly designed drainage envelope materials are granular and free of fines, and hence are highly satisfactory for structural embedment. Clean, angular embedment materials can be readily compacted, and compaction can be achieved over a wide range of moisture contents. Although omission of compaction is not recommended, these materials reach rather high densities even if not compacted by positive means. Specific materials meeting these requirements are:

1. *Class A*—Angular, ½-in. (13-mm) maximum size, well-graded crushed stone, coral, slag, cinders, and crushed shells. (ASTM D 2321 allows the use of 1½ maximum size aggregates, but the use of such large sizes is not consistent with the requirements for haunching and embedment, and reliability.)
2. *Class B*—Clean coarse sands and gravels with maximum particle size of ½ in. (12 mm) including variously graded sands and gravels containing small percentages of fines, generally granular, and noncohesive, when either wet or dry. Soil types GW, GP, SW, and SP are included (See ASTM D 2487 for meanings of these symbols.)
3. *Drainage Envelope*—Drainage envelope materials may be either processed or natural soils with characteristics of either Class A or Class B embedments.

Unless there is a problem of migration of in-situ materials, Class A materials are preferred for embedment. These materials display high density and stiffness even when not compacted. Density achieved is largely independent of moisture content. They drain rapidly and help drain water from the trench, and they may serve as the drainage envelope for underdrains.

Some specifications permit the use of embedment materials such as fine sands, clayey gravels, sand clay mixtures, silt, silty clays (e.g. soil types GM, GC, SM, SC, MH, ML, CH, and CL as classified in accordance with ASTM D 2487). Although NCHRP Project 4-11 field tests show that specific materials drawn from this categorization may be appropriate for a particular installation, overall they do not provide the reliability expected in important transportation drainage applications, and they require detailed evaluation and perhaps some experimentation. Frozen materials and rock or ledge should never be used for bedding or backfilling.

*Compaction or Density*

Theoretically and practically, the component of deflection of the pipe that results from applied load decreases with increasing stiffness or density of the embedment material. In one simple sense, the applied load tends to densify the embedment, and the pipe deflects to accommodate the associated change in volume. Conversely, the lower the installed density, the higher the amount of pipe deflection that takes place under superimposed loads.

In installations subject to surface traffic, the repetitive, concentrated wheel loads tend to densify embedment materials. Hence, original specified density should be high to minimize the amount of subsequent deformation. A minimum density of 95 percent of maximum dry density (AASHTO T-99) is appropriate. It is impractical to measure the density of Class A materials. Such materials should be tamped or compacted by positive means to minimize subsequent deformation for the reason just given.

Field tests performed during this study demonstrated that dumped initial backfill, although meeting a density requirement of 80 percent of the maximum dry density (AASHTO T-99), results in highly variable deflections. Pipe embedded in the same material compacted by positive means (vibratory compactor) to a slightly higher density of 85 percent of the maximum dry density (AASHTO T-99) displayed much less variability. This finding is also consistent with laboratory tests. As a rule, any installation should receive positive compaction, and a density of 90 percent of maximum dry density (AASHTO T-99), or higher, should be considered in specifications for transportation installations. Higher densities may be called for depending on design or field conditions.

*Compatibility of Materials*

A point deserving special emphasis results from field experiences with flexible plastic pipe that have shown excessive deflection or failures. Failure to meet performance requirements can frequently be traced to a migration of fine materials into the voids in open-graded imported materials, particularly when water is present to encourage flow of fines. This causes loss of structural support of the pipe, which, in turn, results in excessive deflection, rupture, or collapse. This demonstrates the need for compatible gradations of in-situ soils and imported embedment materials.

The potential for migration of fines is a particularly important consideration when open-graded crushed stones or other processed or manufactured Class A materials are used as foundation or embedment. If gradation is sufficiently open, fines can migrate from either the trench wall or possibly from Class B materials placed above or below a layer of Class A materials. Thus, when open-graded Class A materials are used as a bedding or foundation to stabilize an unstable trench bottom, for example, Class B materials should not be used as pipe embedment, unless compatibility of gradation is verified.

Consideration of compatibility is extremely important, and, although applicable to the embedment of any pipe, the need for compatibility appears to have surfaced during research and examination of failures of plastic pipe that are very flexible. The use of crushed stone as the "preferred" embedment should not be applied indiscriminately.

**Construction Considerations**

For the most part, trench proportions and construction procedures for plastic pipe follow practice for conventional piping installations. There are several important considerations bearing on the flexible pipe installation that deserve emphasis.

*Trench Width*

It is generally considered good practice to keep the trench width as narrow as possible. Long standing theories have held that friction that develops between the trench wall and the backfill relieves the pipe of some vertical load. The theoretical amount of load reduction varies with properties of the soils involved, water conditions, depth-to-width ratio of the trench, and pipe stiffness. Although, as a rule, minimizing trench width remains good practice, it is much less important in typical shallow buried transportation drainage applications where other factors can prove more critical.

The trench must be wide enough to allow elbow room for mechanics to place and compact material into the haunch zone. Placement can also be done by shovel. A trench width that allows a clearance of 12 in. (300 mm) on either side of the pipe at springlines is generally the minimum space needed to work in the trench and place haunching material. This clearance depends somewhat on pipe size and depth and, in any event, should be made large enough to accommodate compaction equipment. Care should be used to avoid damaging pipe when pneumatic compactors are used.

*Use of Shields and Sheeting*

Shields, sheeting, and other supports may be required to support trench walls for safety of personnel or if the walls are unstable. A key consideration in flexible plastic pipe installations is to ensure that these devices allow room to place and compact materials. Thus, they should provide working room and the clearances previously discussed for trench width.

Portions of sheeting in the embedment zone should be left in place, unless methods are employed that allow for its removal without disturbing the embedment system. Sheeting that is left in place must be selected to survive for the lifetime of the installation; otherwise, deterioration may cause gradual loss of support of the pipe.

Movable shields should be positioned and moved in a manner that will minimize disturbance of embedment materials and uncoupling of the pipe.

*Bedding the Pipe*

An ideal bedding for any pipe is a firm but not rigid shaped bedding groove that conforms closely to the lower half of the pipe. A bedding groove provides advantages over the use of tamped material in the lower part of the haunch zone. The bedding groove can be prepared from above and inspected before the pipe is laid. The groove is practically a necessity in holding corrugated PE piping true to line and grade during installation.

When a bedding groove is used, it must fit the pipe within close tolerances. If the radius of the groove is significantly greater than that of the pipe, the gap between the pipe and the bedding may be difficult or impossible to fill during subsequent tamping or compaction operations. For this reason, it is possible that an oversize bedding groove may do more harm than good. Obviously, the use of a standard shovel to provide curvature of the bedding groove is inappropriate unless the curvature of the shovel bottom conforms closely to that of the pipe. Field experiments in Illinois show that the radius of the bedding groove should be no greater than one-half of the diametral deflection limit set for the pipe plus the outside radius of the pipe.

Many types of plastic pipe have belled ends. A small pocket should be made in the bedding to accommodate the bell and to prevent localized large reactions from point support at the thickened bell.

If the bedding is not grooved, haunching material should be tamped into the lower part of the haunch zone. But tamping is a blind operation, the degree of compaction is not readily controlled or measured, inspection is nearly impossible, and tamping below lightweight pipe may displace the pipe. Despite these shortcomings, field tests performed during this project and general field experience indicate that tamping material in the haunch zone, if done properly, can provide good deflection control and nearly ideal bedding conditions.

*Haunching and Initial Backfill*

Placement of haunching and initial backfill materials around plastic pipe follows procedures used in installing more conventional pipe. The key special consideration is that plastic pipe systems are very flexible compared to conventional pipe systems, and, hence, they may experience excessive deflection during installation unless proper procedures are followed. Some plastic pipe is brittle, particularly in cold weather, and this also must be recognized during installation of the backfill.

The following are important considerations related to installation of the initial backfill and haunching materials:

1. Material should be carefully placed and tamped into the entire haunch zone of the pipe, uniformly, over the whole length of the pipe.
2. Material should not be dumped onto the pipe from the top of the trench. Chutes or other means should be used to direct or divert the flow of material to the sides of the trench and to prevent impact on the pipe. The pipe should be stabilized by mounding material at intervals along its length, during placement of embedment material, or by other suitable means, as required to minimize lateral movements of the pipe during placement of the critical backfill.
3. For pipe 8 in. (203 mm) in diameter and larger, embedment material should be placed to the springline and compacted by tamping, vibratory compactors, or other means. Compaction equipment should not be allowed to contact the pipe to avoid gouging, impact, and possible excessive deflection. Lift thickness should be compatible with the compaction method to achieve required compaction through the entire thickness of the lift. The remainder of the initial backfill should be compacted in appropriate lift thicknesses. Material at the sides of the pipe should be compacted before compacting material lying directly above the pipe, and this material should not be compacted until sufficient cover is provided. These steps tend to minimize deflections induced during installation.
4. Lift thicknesses become impractically thin when material is placed to the springline of pipe less than 8 in. (203 mm) in diameter. Furthermore, small diameter pipe is easily displaced when embedment material is compacted at this level. Thus, embedment of smaller pipe should be placed to the level of the top of the pipe before the sidefill is compacted. Precautions given previously for larger pipe should be observed.

*Final Backfill*

Final backfill installation is similar in most respects to that for conventional pipe. A key consideration, however, is to avoid excessive deflection of the pipe caused by placing and compacting the backfill. Large boulders and other debris should be eliminated from the backfill, and material should not be dumped onto the embedment from a significant height.

A protective earth cover should be provided over the top of the pipe before heavy equipment is allowed either in or on the top of the trench. Most state transportation agency specifications require that the contractor furnish a suitable cover depth to protect pipe from construction damage. Where construction traffic is anticipated, the final backfill should be compacted to a density sufficient to minimize rutting. Deep ruts can seriously diminish the actual earth cover provided to shallowly buried pipe, and the pipe installation may be seriously disturbed if not protected by adequate cover.

*Special Considerations for Corrugated PE Tubing*

Corrugated PE tubing has several characteristics that deserve special consideration during installation. They are related to the longitudinal flexibility of the tubing introduced by the corrugations and the light weight of the tubing.

Corrugated tubing in diameters up to 6 or 8 in. (152 or 203 mm) is available in coils for convenience in shipping and handling. It may be difficult to obtain straight lengths of tubing after uncoiling, particularly at the larger pipe diameters. This is aggravated by cold weather. This problem can be minimized by only allowing coiling of pipe that is 4 in. (101 mm) in diameter or less; larger sizes should be furnished in straight lengths (usually 20 ft (6 m)). Even "straight" lengths, however, may exhibit significant residual warping or undulations.

The inherent longitudinal variations discussed earlier, combined with the low weight of corrugated tubing, present some problems of obtaining tolerances of line and grade that are more readily obtainable with smooth-wall pipe. Once laid in place and straightened, warped tubing will tend to return to its warped configuration unless it is either warmed by the sun, anchored in place with wire hoops located at intervals along its length, or held in a tight fitting bedding groove. Furthermore, the process of tamping material in the haunch zone tends to both lift the lightweight tubing and shove it laterally. Wire hoops help to prevent this shifting, and shaped bedding minimizes or eliminates the necessity for tamping material in the haunch zone.

The use of a shaped bedding groove, where practical, is the preferred method for achieving uniformity of line and grade in a corrugated pipe installation. Where the gradation of the bedding does not permit accurate shaping, as in Class A materials, closely spaced wire hoops should be used to hold the pipe in place until initial backfill is installed. Shaped bedding is readily obtained with specially equipped automated installation equipment.

The corrugation pattern interrupts the longitudinal structural continuity of corrugated tubing. This makes the tubing vulnerable to longitudinal "stretch" during installation. That is, the tubing can be elongated significantly by axial forces applied during uncoiling, dragging the pipe, or by excessive drag within automated installation equipment. Elongation results in deformations in the corrugation configuration and lowers pipe stiffness. Thus, field installation procedures should ensure that longitudinal elongation of the installed pipe is within tolerable limits, which is typically set at 5 percent.

Highly automated installation equipment has been developed to install conventional agricultural drainage tile and smooth-wall or corrugated plastic pipe and tubing. Because corrugated PE tubing has received the most use in U.S. agricultural applications, most U.S. experience with this equipment pertains to installing corrugated tubing rather than smooth-wall plastic pipe.

The automated installation equipment is comprised of several main components, the details of which vary depending on machine manufacture and application. A machine used to install shoulder underdrains in Illinois has the following features (Fig. 4):

1. A tractor located at the front end provides locomotion.
2. A chain-type trencher is mounted on a "floating" boom. The depth of the trench can be controlled automatically by a mechanism activated by a remote laser bench mark, or the trench can be made a fixed depth below grade.
3. Either spiral worm screws or conveyor belts are mounted below the trencher chain to deflect the excavated spoil falling from the scoops to each side of the trench.
4. A "boot" functioning as a trench shield fits into the trench, supports the trench walls, and excludes crumbs while the tubing feeds through it.
5. The Illinois installation design calls for a bedding groove in the trench bottom. A "groover," located on the leading edge of the boot, forms a semicircular (180 deg) bedding groove in the bottom of the trench.
6. A hopper that retains and distributes select materials for the drainage envelope is mounted on the trailing edge of the boot. A small vibrating compactor located within the hopper compacts the embedment material at a level 5 in. (127 mm) above the crown of the pipe.
7. A second compactor located on the trailing edge of the boom compacts the top of the trench. Alternately, the top of the trench can be compacted in a separate operation.

This machine installed tubing at a rate of about 3 miles (4.8 km) per day in the Illinois installation.

Other variations in the equipment used in agricultural drainage installations employ gravel hoppers behind trenching equipment. The tubing is fed through a metal sleeve as select envelope material is placed completely around the tubing. These devices do not compact the embedment material.

Overall, it appears that automated machine installation, in addition to being efficient, is the preferred method for installing corrugated PE tubing. Mainly, the difficulties of installing, bedding, and embedding lightweight and flexible tubing by hand methods are minimized, and, as Illinois measurements show, deflection control can be closely maintained.

#### Handling of Pipe

Each type of plastic pipe has different handling characteristics that should be familiar to the qualified installation contractor. As with any pipe materials, specific limits can not be placed on how plastic pipe is handled in the field or on how any misuse may affect subsequent performance. Hence, the following is offered only as guidelines that may prove helpful in field control.

*Rough Handling*

By many standards, plastic pipe is rugged. However, there are a number of reasons why rough treatment should be avoided in spite of this desirable characteristic.

A primary concern relates to impact. If impact stresses are sufficient, the pipe will fracture, and this is aggravated by cold weather and extended prior exposure to sunlight. Fractured pipe can be detected readily and replaced. Impact damage possibly may reduce the capacity of the pipe to resist sustained stress or strain in the buried condition, although this has not been specifically validated for buried nonpressure pipe.

Rough handling can also gouge and scratch the plastic pipe. Most plastics used in buried pipe are "notch-

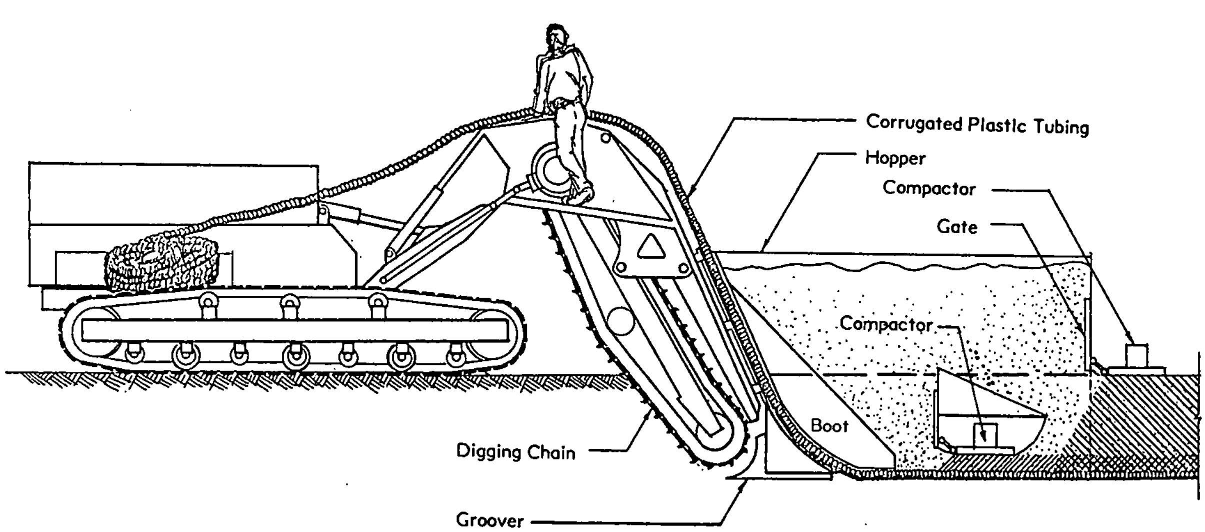



*Figure 4. Automated equipment for installing PE tubing in Illinois.*

sensitive," and therefore such damage can lower impact strength and general durability of the product. Fatigue resistance is also compromised, and badly gouged pipe should not be used in installations where significant traffic loads are expected.

*Storage in Sunlight*

Sunlight can cause significant reductions in impact strength and elongation to failure from those properties measured immediately after manufacture. The effects of UV deterioration, if extensive, can be detected by a chalking of the surface and/or a color change towards a brownish or yellowish shade. Such changes are most readily detected by comparing the color of pipe that has received UV exposure, such as outer pipe in a stack, to that of pipe stored in a protected location within the stack.

UV deterioration can be minimized if appropriate ingredients are included in the pipe formulation. This is seldom done in practice, however, and hence plastic pipe and tubing should be protected from extended exposure to sunlight. As a guideline, pipe should be covered if it is exposed to the sun for periods greater than a few weeks. This period should be reduced in arid regions or elevated locations where UV intensity may be high. More information is becoming available on specific acceptable time limits for UV exposure.

*Distortions During Storage*

Plastic pipe can distort severely if not properly stored. One type of distortion is longitudinal bowing. Bowing makes it difficult to achieve specified line and grade. Furthermore, bowed pipe may not properly conform to straight bedding grooves provided, if any. Pipe that is bowed to an extent that line and grade tolerances or proper bedding can not be achieved should be rejected.

Bowing can be minimized by proper storage. Stored pipe should be supported at intervals spaced to prevent visible sagging. Sag will increase with storage time and with temperature of storage.

Another type of distortion resulting from improper storage is out-of-roundness or ovalling. Ovalling makes it difficult to achieve proper fit at connections. Furthermore, if the minor axis of the oval is oriented in a vertical direction during installation, the ovalling will deduct from the vertical deflection budget. This may cause expensive problems of rejection of the buried pipe if deflection criteria are exceeded.

Ovalled pipe meeting the following conditions should be acceptable:

1. The deflection resulting from ovalling should not exceed one-half of the deflection limit specified for the installation.
2. Pipe should be installed with the major axis of the oval in a vertical position.
3. Joint integrity should not be affected.
4. The installation must meet specified deflection limits.

Otherwise, ovalled pipe should be rejected before installation.

**Field Tests for Deflection**

Traditionally, deflection or vertical diameter change has been used as an indication of the potential performance of buried flexible plastic and metal pipe. In the case of plastics, deflection measurements provide a valuable quality control check on field work. The requirements of the approach to deflection testing of plastic pipe depend on the experience and philosophy of the specifying authorities, as follows:

1. The agricultural industry does not require field measurements of deflection for corrugated PE drainage tubing.
2. Some municipal users of PVC and ABS sewer pipe do not require deflection measurements, but full-time monitoring of the installation is frequently provided.
3. Some municipal users of PVC and ABS sewer pipe provide inspection and also require complete deflection testing for the full length of the installation.
4. In transportation drainage, the State of Illinois, for example, uses sophisticated deflectometers in their research to develop and refine installation techniques. They find it impractical to specify or measure deflection in actual installations, because there is no practical access in their underdrain installations.

Overall, field measurements of deflection on installed pipe are a highly desirable check of installation quality. Such measurements may not be feasible in underdrain pipe, where access for testing is not normally provided. It seems prudent that at least the first section installed on a contract should be tested for deflection to verify that the construction method produces the desired result. Once the method has been shown to be satisfactory, it must be consistently maintained throughout the job.

*Deflection Devices*

Practical methods of field testing buried plastic pipe installations include go-no-go plugs, deflectometers, and video systems. These devices represent different levels of sophistication of field instrumentation and of information provided.

*Go-no-go plugs.* The simplest device used in deflection measurement is the go-no-go plug, which consists of a more or less cylindrical mandrel that is pulled through the pipe. The plug is sized to a diameter that corresponds to the minimum specified deflected diameter of the pipe. Thus, the plug will not pass an area of overdeflected pipe. Mandrels can also be made adjustable, so that many sizes of pipe can be measured with the same device. The major advantage of this system is that no instrumentation is required other than the mandrel, itself, which can be constructed to withstand field abuse.

*Deflectometers.* The second form of deflection testing is by deflectometer, which is a device that measures pipe diameter continuously or intermittently, while it is drawn through the pipe. Deflectometers have been made with numerous levels of sophistication, from devices that read only vertical diameter and are manually pulled through the pipe and read at selected intervals, to devices that provide continuous readout of both vertical and horizontal diameter. The type of transducer, the instrumentation required, and associated reliability vary significantly. All are nonstandard.

Advantages of the deflectometer are that the measuring operation can be completed without interruption for repair of overdeflected regions (most deflectometers can tolerate high deflections without damage) and that a profile of the entire pipeline is obtained for analysis. Deflectometers that read both vertical and horizontal diameters have the added benefit of a self-check. That is, if an area of pipe shows a reduced vertical diameter and an increased horizontal diameter of about equal magnitudes, the reading is assumed to be accurate. If the measured vertical diameter is reduced, however, while the horizontal diameter is unchanged, a deposit of soil in the invert may be present, which affects only the vertical reading.

Deflectometers generally involve some form of electronic instrumentation and must be operated by qualified technical personnel. Adequate checkout procedures must be performed both prior to and after each use to ensure that the instrument is operating properly. Tests are required to determine that the deflectometer maintains the proper orientation within the pipe. This can be a problem in measuring pipe systems that have horizontal sweeps.

Overall, the features of deflectometer devices are that the actual field deflections are known and that they provide good background for the assessment of overall quality of the installation. In addition, a statistical distribution of deflections can be established, which provides a desirable base for evaluation and acceptance of the installed system.

*Video Systems.* The most sophisticated form of pipe inspection involves video systems, generally closed circuit television. These devices require operation by qualified technical personnel. They provide a fairly good first-hand view of the inside of the pipe for detection of defects such as major breaks or leaking joints. Their resolution and angle of view do not allow detection of any small cracks and the like. Video systems can also be used to record changes in scale of deflectometers that are drawn through the pipe in tandem with the video unit. Furthermore, a picture of the deflectometer provides a check on the orientation of the probe and allows evaluation of the readings, such as whether or not the invert is filled with soil.

### *Considerations in Deflection Measurement*

There are several important considerations involved in obtaining reliable deflection measurements.

Any soil or other debris in the pipe may be seen by a deflection measuring device as an area of reduced diameter or excessive deflection. This may cause rejection of an otherwise properly installed section of pipe. Thus, it is desirable to clean the pipe using water jet or other means prior to obtaining measurements.

The period of time that elapses between the installation of a pipe and the deflection check can be very important, because deflections increase with time after installation. Most research indicates that deflections stabilize within a year of installation; however, it is impractical to wait this long prior to evaluating an installation. In general, the period of time required for an installation to stabilize varies with the quality of backfill. Crushed stone or well-compacted granular backfill will normally exhibit a very small increase in deflection after the installation is completed, while finer grained soils with low density and poorly compacted fills can show significant increases. Trench geometry also may affect rate of development of the final deflection. It is generally assumed that the final deflection will not exceed 1.5 times the deflection at installation, although much higher values have been recorded, and lower values are possible. Judgment must be used in the selection of the length of time between installation and deflection measurements. The longer the time, the more likely the installation has approached its maximum deflection. Thirty days appears to be a reasonable minimum period. In any event, deflections should be determined prior to installing paving or other permanent structures to avoid costly dig-up of pipe that does not meet performance criteria.

While conceptually elementary, practically it is not a simple task to establish a reference diameter for the pipe that can be used as a base for deflection measurements. For example, for most pipe the outside diameter is controlled, and the inside diameter is allowed to vary below a maximum value set by the minimum wall thickness. An oversize wall deducts from the deflection control limit, even while providing more material than specified. The problem becomes more serious with corrugated PE tubing, where the inside diameter is controlled to ±3 percent according to specifications; this 6 percent gross variation may be about the same as the deflection limit set for the tubing.

In recognition of the foregoing problems, the following approach, as used by the State of Wisconsin (*20*) appears appropriate for establishing the reference diameter as a base for deflection measurements. The reference diameter is taken either as the minimum average diameter obtained in conformance tests or as the following diameters obtained from specified dimensions, whichever is less.

1. *ABS and PVC smooth-wall pipe*—the average specified outside diameter of the pipe minus the specified tolerance on the specified diameter minus two times 110 percent of the specified minimum wall thickness.
2. *ABS composite pipe*—the specified average minimum inside diameter.

There does not appear to be a practical solution to the dilemma offered by corrugated PE tubing, where the permitted variation in manufactured diameter may exceed the deflection limit established.

Although plastic pipe is manufactured in a reasonably circular configuration, it can oval permanently during shipment and storage. Overall, ovalling may detract from the deflection budget. Theoretically, if the working strain criterion is used as a guideline for determining deflection control limits, the permanent strains induced during ovalling should be deducted from the working strain. Thus, no allowance for ovalling induced after manufacture should be taken in the deflection limit budget.

## Field Monitoring

Field monitoring of installations of plastic pipe should be given high priority.

Deflection limits established on the basis of working strain criteria are fairly stringent, particularly for perforated underdrain pipe and tubing. This means that good construction practice must be maintained throughout the job to maintain deflection control. Monitoring is particularly important if deflection control is not required for the complete installation.

Also, performance of the flexible plastic pipe installation as measured by deflection depends to a major extent on embedment quality. The embedment structure is constructed in the field, using variable materials, under typically difficult trench conditions. Thus, there is further justification for field monitoring the installation.

Obviously, the contractor retains responsibility for construction of the installation as specified. However, experience shows that competent field monitoring helps to prevent costly construction problems in systems where success depends strongly on field workmanship quality. Plastic pipe installations, unfortunately, provide no exception to this rule.

CHAPTER FOUR

# CONCLUSIONS AND SUGGESTED RESEARCH

## CONCLUSIONS

Several plastic pipe and corrugated tubing systems are appropriate for subsurface drainage of transportation facilities. Plastic pipe has been used extensively and successfully in significant municipal works such as sanitary sewers and in storm drains; corrugated perforated tubing has been used in large quantities in agricultural land drainage applications. These applications provide an experience base of more than a decade in underground use, although most use has been more recent.

Guidelines for the selection, design, and installation of plastic pipe for subsurface drainage of transportation facilities have been provided (Chap. Three) for the practicing engineer interested in the use of buried plastic pipe for transportation drainage and for engineering and construction personnel responsible for installing such pipe in the field. These guidelines incorporate information obtained from the state of the art and findings of significance from this study. Product specifications for PVC (polyvinyl chloride) pipe and corrugated PE (polyethylene) tubing and a standard recommended practice for the installation of buried plastic pipe have been proposed.

### Selected Pipe Systems

Specific plastic piping systems that are considered appropriate for the transportation drainage application are as follows:

1. *PVC smooth-wall pipe for small storm drains and for perforated underdrains*—This pipe has been used extensively and successfully mostly in sanitary sewers and less frequently in storm drain applications. Perforated PVC pipe has been used mostly in foundations and leach bed drainage, and several miles were installed as shoulder drains in Illinois during the course of this project. PVC pipe meeting proposed specifications developed in this project (SGH PVC-TD, App. A2) can be evaluated for anticipated long-term performance with reasonable confidence, using procedures synthesized in the course of this project.

2. *Perforated corrugated PE tubing for underdrains*—Reportedly, hundreds of thousands of miles of this product have been used, mostly in agricultural land drainage applications, with an apparent high degree of success. Several states now permit its use in highway construction. Proposed specifications developed in this project (SGH PE-TD, App. A1) provide an improved level of confidence on long-term performance compared to present standards. Corrugation configuration and materials structural properties remain insufficiently characterized to permit rational estimates of short- and long-term structural performance of these products.

3. *ABS composite-wall pipe for storm drains*—The composite construction consists of a double plastic wall connected by integrally extruded webs to form a truss configuration, and the cavities formed by the walls and webs are filled with foamed cement. This pipe has received wide and successful use in municipal sanitary sewers. The configuration and construction of the wall, together with the lack of characterization of materials properties, preclude rational estimates of short- or long-term structural performance within the scope of this project.

4. *ABS pipe for underdrains*—This pipe has had lengthy but not very extensive application in sanitary sewer applications. It has been used in small diameter sanitary sewer service lines; however, performance in such secondary applications is difficult to establish. Technically, this system should be appropriate for transportation applications, although its short- and long-term performance can not be evaluated by rational methods because material properties are not suitably characterized.

### General Performance

1. *Chemical resistance*—Plastic pipe systems offered for subsurface use provide excellent resistance to natural

chemicals in soils and a variety of materials found in highway runoff including deicing salts—plastics are frequently used in corrosion resistant applications. Prolonged exposure to specific compounds such as oils, gasoline and solvents, and strong acids, which are not found in large concentrations in typical highway runoff, may degrade properties or cause stress cracking if accidental spills occur.

2. *Resistance to animals, insects, and Microorganisms*—Plastic pipe systems are, for the most part, resistant to animal, insect, and microbiological attack. Rodents may chew on corrugated tubing, and protection of this product by animal guards should be provided.

3. *Temperature and thermal effects*—The effects of temperature must be considered in the design of plastic pipe. The relatively large thermal coefficient of expansion of plastics must be accounted for in system design. High temperatures increase the flexibility of plastic pipe, making them more prone to deflection during installation when they are exposed to intense solar radiation. Corrugated tubing is particularly sensitive to this. Plastics may embrittle in cold weather and require special care during installation to prevent impact damage.

4. *Handling*—Overall, plastic pipe, which is light to moderate in weight, is easy to handle and is generally rugged. Plastic pipe need not be handled gingerly, as if fragile, but it should be treated with appropriate care to prevent breakage or other damage that may possibly affect long-term performance.

5. *Abrasion and wear*—Plastic pipe demonstrates good resistance to wear by abrasive slurries, and is frequently used in applications requiring this attribute, such as in the transport of mine tailings. When flow rates are high and capable of transporting large aggregates or when high velocity flow changes direction, special evaluation of abrasion resistance is needed.

6. *Resistance to sunlight*—Plastic pipe furnished for subsurface drainage may not be satisfactorily stabilized against deterioration and loss of properties resulting from exposure to sunlight, because present standards are either silent or inadequate on defining stabilization levels. This problem is serious because deterioration may occur during outdoor storage in the manufacturer's yard or in the field. This requires that acceptance tests be performed on receipt of materials at the job and that pipe be protected from sunlight if exposed more than a few weeks before installation. Obviously, the installed pipe should be protected from prolonged exposure to sunlight. Plastics used in pipe can be stabilized to provide high resistance to deterioration in sunlight, as demonstrated by PVC residential siding and PE cable covering, both of which are designed to withstand decades of exposure outdoors. However, more work is needed to determine suitable stabilization levels for plastic pipe during storage.

7. *Repair*—Plastic pipe can be repaired by cutting and patching, usually with solvent-bonded attachment of patches. Because criteria for quality of repairs are not available, the desired repair method is cutting and replacement with new section.

8. *Fire*—Plastic pipe burns. It should be protected from direct exposure to fires at its terminus.

### Installation

A plastic pipe installation is a structural system comprised of the pipe and embedment materials surrounding the pipe. The embedment structure is constructed in the field from soils or aggregates that are inherently variable and that are frequently installed under less than ideal conditions.

1. *Pipe support*—Because plastic pipe is flexible, pipe embedment must provide uniform support over the entire circumference and length of the pipe to prevent excessive deflection, stress, and strain in the pipe. Although all pipe should be carefully embedded, installation of plastic pipe will require considerable attention to details and procedures of installation in the transportation application.

2. *Materials selection*—To obtain maximum reliability of embedment quality, embedment materials should be selected to permit ready compaction to required densities over a wide range of moisture contents. Usually, well-graded crushed stone and other aggregates—or clean, coarse sands and gravels—normally used in transportation drainage applications provide these attributes. To preclude any migration of in-situ materials into voids in the embedment, however, the embedment gradation must be suitably designed. Otherwise, experience shows that the advantage of such materials may be negated by loss of support of the pipe via the migration mechanism. Embedment materials containing more fines than those defined can provide adequate pipe embedment; however, the reliability with which required density can be attained under field conditions should be verified.

3. *Materials density*—The stiffness of the support provided to the pipe by embedment material is strongly related to the density furnished in the embedment. Embedment should be compacted by positive means to minimize variations in density or stiffness, generally to 90 percent of maximum dry density (AASHTO T-99). When the installation is subject to traffic, a density of 95 percent of maximum dry density (AASHTO T-99) is appropriate to minimize cumulative deflections.

4. *Installation variability*—The maximum deflection, stress, or strain that occurs in an installation is frequently more a function of variations in the installation than it is a function of classical soil-structure interaction response due to earth loads. These variations, termed here installation deflections, can be minimized by proper design and workmanship and maximization of embedment density and pipe stiffness. Pipe stiffnesses greater than those considered here may ultimately prove desirable to minimize installation deflections.

### Structural Evaluation and Design of Plastic Pipe

1. *Evaluation of installed pipe*—Provided that plastics properties are suitably defined, stress-strain response of a plastic pipe, as installed, can be estimated and evaluated with reasonable confidence. Despite the complexities inherent in plastics behavior, such as nonlinear stress-strain and strength relationships, and the strong and nonlinear time dependence of these relationships, the in-ground behavior of plastic pipe can be estimated and evaluated with

a level of precision that is probably within the realm attainable for conventional buried pipe. This is true provided that (a) time dependent stress-strain and strength behavior of the plastic is suitably characterized; (b) strains in the pipe wall are maintained below a maximum value, termed the working strain limit; and (c) deflection levels are known or are within values specified to provide strains within the proposed limits.

2. *Predicting pipe-soil interaction behavior*—The average deflection of a plastic pipe installation can be estimated with fair accuracy providing soil stiffness and pipe properties are known and quality embedment materials (described earlier) surround the pipe. The traditional empirical "Iowa formula" used in the analysis of flexible conventional pipe is appropriate in this determination, as are more rigorous theoretical elastic methods such as proposed by Burns, provided that the effects of bedding are suitably accounted for. Maximum deflection, not average deflection, is of key importance in design. The magnitude of maximum deflection depends on the variability of the installation, which is comprised of several components. Variability depends on (a) density of the embedment material (lower compaction results in greater variation in density or soil stiffness), (b) stiffness of the pipe (lower pipe stiffness lowers resistance of the pipe to local, random pressures applied to the pipe during installation), (c) soil type (while not proven, materials that are difficult to compact should show more variability in density and hence stiffness), and (d) workmanship (as with any pipe system, the quality of workmanship can have major bearing on pipe performance; in the case of plastic pipe, which is very flexible compared to conventional flexible pipe of the same diameter, workmanship deficiencies can result in overdeflection and overstrain).

3. *Concentrated surface wheel loads*—Plastic pipe can be used at reasonable cover depths in installations that are subjected to heavy temporary construction traffic and in installations that receive occasional vehicle loads in service (e.g., typical shoulder underdrains). The conditions under which plastic pipe is suitable for use under sustained heavy traffic loads below permanent pavements can not be defined within the state of the art. Available plastic pipe may not provide sufficient stiffness to prevent significant cumulative displacements under sustained heavy cyclic loadings at shallow cover because of extended traffic. The use of very stiff and well-compacted embedment materials is indicated to minimize such displacement. Furthermore, an increase in pipe stiffness from that presently supplied in available systems may be required. Finally, the effects of fatigue during cyclic loads are not well defined for plastic pipe compounds. Until more information becomes available, the use of plastic pipe under long-term heavy traffic loadings at shallow cover remains experimental.

4. *Design/evaluation methods*—A procedure has been synthesized that can be used in the evaluation or design of a buried plastic pipe installation provided that the needed information on plastic used in pipe is available. The procedure considers stress and strain in the pipe wall and performance limits of pipe strength and buckling.

## RECOMMENDATIONS FOR RESEARCH

### Plastic Pipe Materials

1. *Resistance to sunlight*—Standards should be developed to define suitable levels of stabilization or other safeguards against deterioration of plastics under the levels of ultraviolet exposure expected during manufacturer's and job storage. In the interim, specified properties should be verified on materials received at the job site and protected thereafter from exposures lasting more than two weeks.

2. *Structural characterization of materials*—Engineering properties of plastic pipe compounds should be obtained to permit rational engineering analysis for specific installations. Without such analysis, there is no way to predict structural performance over the long lifetime of the installation with reasonable levels of confidence. Some present specifications are silent on values for short-term modulus of elasticity, for example, which is fundamental to any structural analysis and evaluation. Basic, minimum engineering properties required are short-term modulus of elasticity, time-dependent modulus of elasticity, or visoelastic modulus (*4*), short-term and long-term strength properties under sustained and cyclic strain, and combinations thereof. The influence of temperature and environment on these properties is required, and the further effects of notches (scratches, gouges, and perforations) should be determined. It has been recommended herein that "pressure rated" plastic compounds be used in buried drainage (nonpressure) pipe. Pressure rated compounds are characterized, using standard test and data analysis procedures, for their capacity to resist long-term stress. The plastic material used in buried transportation drainage pipe is more appropriately characterized for its capacity to resist sustained long-term strain, combined with cyclic strain when buried shallowly under traffic. The pressure rating requirement should be modified to reflect results of research into pipe performance under these loading conditions.

### Plastic Pipe Configuration

The configuration of the walls of plastic pipe should be characterized structurally. For smooth-wall pipe, section properties of the structural cross section and connections should be furnished by the manufacturer, as a minimum, and standardized as possible. For corrugated wall PE tubing, corrugation configurations and section properties should be provided by the manufacturer, as a minimum, and standardized as possible. For ABS composite-wall pipe, section properties, shear strength, interaction of plastic and foamed cement elements, and the influence of wall curvature and severe eccentricities of web-to-shell junctures on strength and local buckling resistance all need to be determined. Without such characterization, the several plastic pipe systems that appear to be promising candidates for the transportation drainage application are not subject to rational engineering evaluation for their adequacy in either short-term or long-term performance.

### Plastic Pipe Stiffness

Most plastic pipe systems are proportioned to provide a constant stiffness over the range of diameters furnished.

(The specified constant "dimension ratio" assures this.) This probably stems from soil-structure interaction theory, which predicts an equal percent of deflection for buried pipe of equal stiffness, independent of diameter, and provided that other features of the installation are the same. The results of this project indicate, however, that deflection of presently available plastic pipe is more a function of installation characteristics than of earth load. This suggests that plastic pipe should be proportioned to provide a consistent resistance to installation deflections (in terms of % deflection) rather than to earth load. This appears to be the criterion used in the proportioning of flexible corrugated metal pipe. In effect, this criterion, called the "handling criterion," results in a decreasing wall stiffness requirement for an increasing pipe diameter, or vice versa. This criterion could have major bearing on wall thickness (i.e. relatively thinner walls for larger diameter pipe) as larger diameters of plastic pipe become feasible.

#### Fittings

A review of specifications for fittings for both conventional and plastic pipe intended for burial reveals that specifications do not define needed structural characteristics. Fittings have not been addressed in detail because of the complexity of design and analysis for soil-structure interaction, which is well beyond the state of the art. Although admittedly complex, this whole subject needs to be addressed if plastic pipe offered for burial is to become an engineered system.

#### Pipe-Soil Interaction

1. *Installation deflections*—Although heretofore not widely recognized, deflections arising from or occurring as a result of characteristics of the installation exceed deflections resulting from any normal level of applied loads. Research should be directed toward the practical problem of determining realistic levels of deflection that occur in practical field installations.

2. *Deflection lag*—The deflection lag factor used in the Iowa deflection formula to account for time-dependent response of the soil reportedly can vary by a factor of sixfold depending on soil compaction level and soil type, and undoubtedly other factors that have not been identified herein. This variation in time-dependent response dominates the design problem and overwhelms any improved sophistication in classical soil-structure interaction analysis based on elastic theory. It needs significant further study and quantification. It is believed that this problem pertains to any flexible pipe, independent of material.

3. *Cumulative deflections.*—The extent to which cumulative deflections develop under traffic loads depends on the stiffness of the pipe and stability of the embedment materials under such loadings. Research is needed to determine the relationships between minimum depths of cover, burial depth, pipe stiffness, and embedment quality, under conditions of heavy repetitive traffic. An increase in available pipe stiffnesses from those considered may be required.

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# APPENDIX A

## PROPOSED SPECIFICATIONS

### APPENDIX I

SGH PE-TD - PROPOSED STANDARD SPECIFICATION FOR CLASS PS 50 CORRUGATED POLYETHYLENE (PE) TUBING SYSTEMS FOR SUBSURFACE DRAINAGE OF TRANSPORTATION FACILITIES

1. SCOPE

1.1 This specification covers the requirements and methods of test for corrugated polyethylene (PE) tubing, couplings, and fittings for use in subsurface drainage of transportation facilities.

1.1.1 Nominal sizes of 3 to 8 inches in 1-inch (75 to 200 mm in 25 mm) increments, in a stiffness class designated as PS 50 are included.

1.1.2 Materials, dimensions, pipe stiffness, elongation resistance, environmental stress-crack resistance, perforations, joining systems and form of markings are specified.

Note 1. The values stated in U. S. Customary units are to be regarded as the standard.

Note 2. Tubing and fittings should be installed in accordance with Proposed Recommended Practice SGH RP-TD.

2. APPLICABLE STANDARDS

2.1 **ASTM Standards:**

D 618 Conditioning Plastics and Electrical Insulation Materials for Testing

D 883 Definition of Terms Relating to Plastics



D 1248 Specification for Polyethylene Plastics Molding and Extrusion Materials

D 1598 Test for Time to Failure of Plastic Pipe under Constant Internal Pressure

D 1693 Test for Environmental Stress Cracking of Ethylene Plastics

D 2122 Determining Dimensions of Thermoplastic Pipe and Fittings

D 2412 Test for External Loading Properties of Plastic Pipe by Parallel Plate Loading

D 2837 Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials

F 412 Definitions of Terms Relating to Plastic Piping Systems

2.2 **Other Standards:**

SGH RP-TD Recommended Practice for Installation of Flexible Plastic Pipe Systems for Drainage of Transportation Facilities.

3. NOMENCLATURE

3.1 The terminology used in this standard is in accordance with the definitions given in ASTM D 883 and ASTM F 412 unless otherwise specified.

3.2 Crack: Any break or split that extends through the wall.

3.3 Crease: An irrecoverable indentation; generally associated with wall buckling.

4. USES

4.1 Corrugated polyethylene tubing is intended for subsurface drainage of transportation facilities.

4.2 Corrugated fittings complying with the requirements of this specification may be used with this tubing.

## 5. MATERIALS

5.1 Basic Materials — Pipe and fittings shall be made of virgin PE compounds which conform with the requirements of Grade P 23 Class C, Grade P 33 Class C, or Grade P 34 Class C as defined and described in ASTM D 1248. Compounds shall be tested in accordance with ASTM D 1598 and provide a minimum hydrostatic design basis (HDB) of 1000 psi (6894 kPa) for P23 materials and 1250 psi (8618 kPa) for P33 and P34 materials. Minimum HDB shall be evaluated in accordance with ASTM D 2837.

5.2 Reworked Material — Clean reworked material generated from the manufacturer's own production may be used by the manufacturer provided that the tubing or fittings produced meet all requirements of this specification.

## 6. REQUIREMENTS

6.1 **Workmanship** — The tubing and fittings shall be free of foreign inclusions and visible defects as defined herein. The ends of the tubing shall be cut squarely and cleanly so as not to adversely affect joining or connecting.

6.1.1 Visible Defects — Cracks, creases, unpigmented or nonuniformly pigmented tubing are not permissible.

### 6.2 Tubing Dimensions

6.2.1 Nominal Size — The nominal size for the tubing and fittings is based on the nominal inside diameter of the tubing. Nominal diameters shall be sized in one inch increments from 3 to 8 inches (76 to 203 mm) inclusive.



6.2.2 Inside Diameter Tolerances — The tolerance on the specified inside diameter shall be ± 3% when measured in accordance with 8.7.1.

6.2.3 Length — Tubing is an extruded product and may be sold in any length agreeable to the user. Lengths shall not be less than 99% of the stated quantity when measured in accordance with 8.7.2.

Note 3: Some transportation agencies report difficulty in obtaining straight runs after uncoiling coiled tubing which is 6 in. (152 mm) diameter or greater.

### 6.3 Fitting Dimensions

6.3.1 The maximum allowable gap between fitting and tubing shall not exceed 1/8 in. (3 mm) unless otherwise specified.

6.3.2 All fittings shall be within an overall length dimensional tolerance of ± 0.5 in. (±12.7 mm) of the manufacturer's specified dimensions.

6.4 **Perforations** — The perforations shall be cleanly cut so as not to restrict the inflow of water, and uniformly spaced along the length and circumference of the tubing. When measured in accordance with 8.7.3 circular perforations shall not exceed 3/16 inch (4.8 mm) in diameter, slots shall not be more than 1/8 inch (3.2 mm) wide, and the length of the individual slots shall not exceed 1-1/4 inches (32 mm) on 3 inch (76 mm) diameter tubing and 10% of the tubing nominal inside circumference on 4 to 8 inch (102 to 203 mm) diameter tubing, and the slots shall be centered in the valleys of the corrugations. Ends of slots shall be rounded. The water inlet area shall be a minimum of 1 square inch per lineal foot (2117 $mm^2/m$) of tubing.

6.5 **Pipe Stiffness** — The tubing shall have a minimum pipe stiffness (PS) of 50 lb/in./in. (345 kPa) at 5% deflection and 40 lb/in./in. (276 kPa) at 10% deflection when tested in accordance with 8.1. The tubing tested shall contain perforations, if specified.

6.6 **Elongation** – Three specimens of tubing, containing perforations if specified, shall be tested in accordance with 8.2, if tubing is supplied in lengths of 10 feet (3 m) or more.

6.6.1 The average elongation shall be 5% or less. For tubing having a higher elongation, the specimens shall meet the requirements of 6.6.2.

6.6.2 Tubing having an elongation greater than 5% shall be further tested in accordance with 8.3. Three specimens shall be tested; the average value of pipe stiffness (PS) shall be as required in 6.5.

6.7 **Environmental Stress Cracking** – There shall be no cracking of the tubing when tested in accordance with 8.4.

6.8 **High Temperature Strength** – There shall be no creasing in the tubing when tested in accordance with 8.5.

6.9 **Low Temperature Flexibility** – There shall be no cracking when tested in accordance with 8.6.

6.10 **Fitting Requirements:**

6.10.1 The fittings shall not reduce or impair the overall integrity or function of the tubing line.

6.10.2 Common fittings for corrugated tubing include in-line joint fittings, such as couplings and reducers, and branch or complementary assembly fittings such as tees, wyes, and end caps. These fittings are installed by various methods, such as snap-on, screw-on, and wrap around.

Note 4. Only fittings supplied or recommended by the tubing manufacturer should be used.



6.10.3 Fittings shall not reduce the inside diameter of the tubing being joined by more than 5% of the nominal inside diameter. Reducer fittings shall not reduce the cross-sectional area of the smaller size.

6.10.4 Tubing in in-line joint fittings shall not separate when tested in accordance with 8.8.1.

6.10.5 The fitting shall not crack or crease when tested in accordance with 8.8.2.

6.10.6 The design of the fittings shall be such that when connected with the tubing, the axis of the assembly will be level and true when tested in accordance with 8.8.3.

7. CONDITIONING

7.1 **Conditioning** – Condition the specimen prior to test at $70^{\circ}$ - $77^{\circ}$ F (23 $\pm$ $2^{\circ}$C), for not less than forty hours in accordance with Procedure A in ASTM D 618 for those tests where conditioning is required, and unless otherwise specified herein.

7.2 **Test Conditions** – Conduct the test in a laboratory temperature of $70^{\circ}$ - $77^{\circ}$F (23 $\pm$ $2^{\circ}$C), unless otherwise specified herein.

8. TEST METHODS

8.1 **Pipe Stiffness** – Test a minimum of three tubing specimens for pipe stiffness, (PS), as described in ASTM D 2412 except for the following: (1) The test specimens shall be 12 $\pm$ 1/8 in. (305 $\pm$ 3 mm) long. (2) Locate the first specimen in the loading machine with an imaginary line connecting the two seams formed by the corrugation mold (end view) parallel to the loading plates. The specimen must lie flat on the plate within 1/8 inch (3 mm) and may be straightened by hand bending at room temperature to accomplish this. Use the first location as a reference point for rotation and testing of the other two specimens. Test each specimen in one position only. (3) The deflection indicator shall be readable and accurate to $\pm$ 0.001 inch (0.02 mm).

Note 5: The parallel plates must exceed the length of the test specimen as specified above.

8.2 **Elongation** – Each specimen shall be 50 in. (1.27 m) long suspended with its longitudinal axis vertical. Loads shall consist of a tare weight of D lb or less, and an additional minimum test weight of 5 D lb (2.3 Dkg), where D is the nominal inside diameter of the specimen. Perform the test as follows: (1) Hang the tare weight from the lower end of the specimen, (2) mark a gage length of 30 in. $\pm$ 1/8 in. (0.76 m $\pm$ 3 mm) on the central portion of the specimen length, (3) apply the test weight gently, and remeasure the gage length to the nearest 1/8 in. (3 mm). Calculate the elongation, E, in percent, as the percentage change in the 30 in. (0.76 m) gage length.

8.3 **Pipe Stiffness While Elongated** – Remove a 30 in. (0.76 m) sample defined by the gage length, from the specimen used in 8.2, and test for pipe stiffness at 5% and 10% deflection as described in Method D 2412 except for the following conditions: (1) Elongate the test specimen as shown in Fig. 2 to the percent elongation (E) as measured in 8.3 and perform the test in this condition, (2) support the specimen on a rigid base plate 24 in. (610 mm) in length, (3) apply load through an upper plate 12 in. (305 mm) in length located at mid-length of the specimen.

8.4 **Environmental Stress Cracking** – Test sections of the tubing for environmental stress cracking in accordance with ASTM D 1693, except for the following modifications:

8.4.1 Three specimens shall be tested.



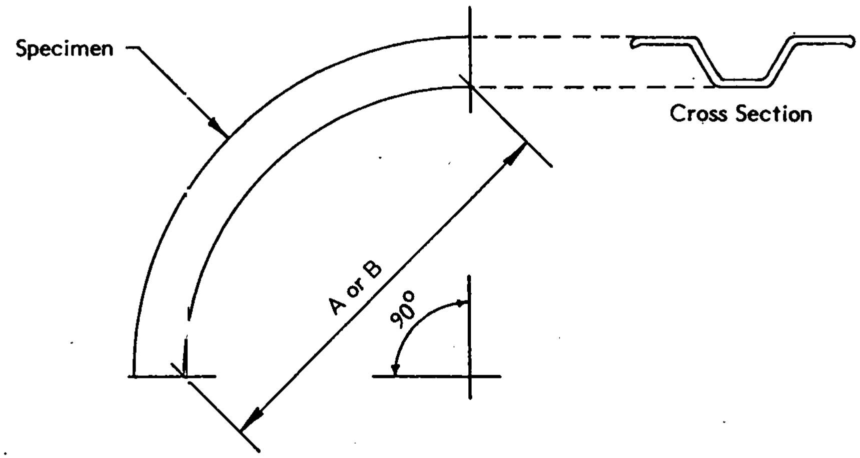



FIG. 1 SPECIMEN CONFIGURATION FOR TEST 8.4

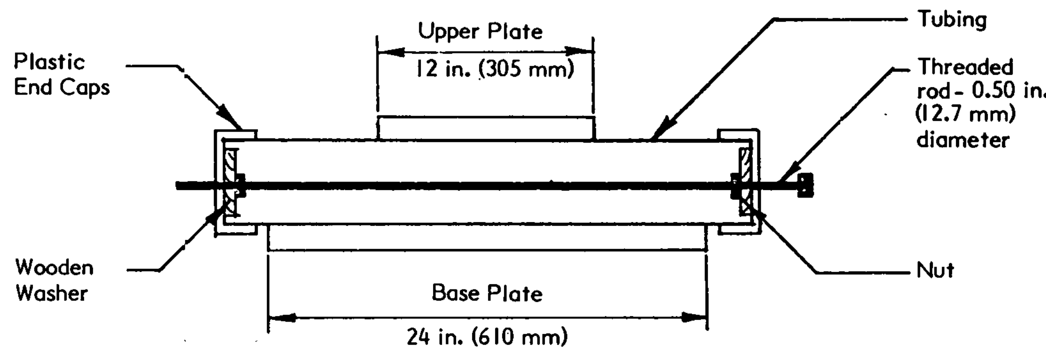



FIG. 2 TEST ARRANGEMENT FOR TEST 8.3

8.4.2 Each specimen shall consist of a $90^{o}$ arc length of tubing without perforations as shown in Figure 1.

8.4.3 Bend the specimens to shorten the inside chord length 20 $\pm$ 1 % and retain in this position using a suitable holding device. Determine the arc chord dimension (B) of the specimen under test as follows:

$$B = 0.8\ A$$

where A = the inside chord dimension before bending
B = the same dimension taken after bending (see Figure 1).

8.4.4 Place the bent specimen in a container of suitable size and cover completely with a preheated wetting agent at 122 $\pm$ 3.6°F (50 $\pm$ 2°C). Maintain this temperature for 24 hours, and then remove the sample and inspect immedately.

Note 6: The wetting agent used in this test is 100% "Igepal CO-630", a trade name for nonylphenoxy poly (ethyleneoxy) ethanaol.

8.5 **High Temperature Strength** – The tubing specimen shall be tested in accordance with ASTM D 2444. A Tup B, weighing 5.5 pounds (2.5 kg) shall be used and height of drop shall be 1.8 feet (0.55 m). The specimens shall be conditioned for 24 hours at a temperature of 120° $\pm$ 5°F (49 $\pm$ 2.8°C) and all tests shall be conducted within 60 seconds of removal from this atmosphere.

8.6 **Low Temperature Flexibility** – A minimum of three test specimens 5 ft (1.52 m) in length, shall be conditioned at a temperature of 25°F (-3.9°C) for a period of 24 hours. The test specimens shall then be bent over a 15 inch (381 mm) automobile wheel rim with the 180° bend being completed within 30 seconds of removal from the conditioning atmosphere. The specimens shall then be visually inspected for cracking.



8.7 **Tubing Dimensions**

8.7.1 **Inside Diameter** – Measure the inside diameter of the tubing with a tapered plug in accordance with ASTM D 2122.

8.7.2 **Length** – Measure tubing with any suitable device accurate to $\pm$ 1/4 inch in ten feet ($\pm$ 6.3 mm in 3 m) (0.2%). Make all measurements on the tubing while it is stress-free and rest on a flat surface in a straight line.

8.7.3 **Perforations** – Measure dimensions of perforations on a straight specimen with no external forces applied. Make linear measurements with instruments accurate to 0.01 in. (0.2 mm).

8.8 **Fittings**

8.8.1 **Joint Integrity** – Assemble in-line joint fittings to appropriate tubing in accordance with the manufacturer's recommendations. Use tubing samples at least 6 inches (150 mm) in length. Use the hanging weight test procedure described in 8.2, including both the tare weight and test weight. Determine whether the tubing separates from the fitting while under load. Test three fittings of each type.

8.8.2 **Strength** – Assemble each fitting to the appropriate tubing in accordance with the manufacturer's recommendations. Use tubing samples at least 6 inches (150 mm) in length. Load the connected tubing and fitting between parallel plates at the rate of 0.5 in. (12.7 mm)/minute until the vertical inside diameter is reduced by at least 20% of the nominal diameter of the fitting. Inspect for damage while at the specified deflection, and after load removal, and report the results of this inspection.

8.8.3 **Alignment** – Assure that the assembly or joint is correct and complete. If the tubing is bent, it should be hand-straightened prior to performing this test. Lay the assembly or joint on a flat surface and verify that it will accommodate straight-line flow.

## 9. INSPECTION AND RETEST

9.1 **Inspection** — Inspection of the material shall be made as agreed upon by the purchaser and the seller as part of the purchase contract.

9.2 **Retest and Rejection** — If any failure to conform to these specifications occurs, the tubing or fittings may be retested to establish conformity in accordance with agreement between the purchaser and seller. Individual results, not averages, constitute failure.

## 10. MARKING

10.1 All tubing shall be clearly marked at intervals of no more than 10 feet (3 m), and fittings shall be clearly marked, as follows:

10.1.1 Manufacturer's name or trademark.

10.1.2 Nominal size.

10.1.3 Material Desgination PE Gr P23, PE GR 33 or PE Gr 34.

10.1.4 The word "TRANSDRAIN".

10.1.5 The Class — PS 50.

10.1.6 The specification designation "XXXX".

10.1.7 Date of manufacture, and plant designation code.



## 11. QUALITY ASSURANCE

11.1 A manufacturer's certification that the product was manufactured, tested and supplied in accordance with this specification, together with a report of the test results, and the date each test was completed, shall be furnished upon request. Each certification so furnished shall be signed by a person authorized by the manufacturer.

APPENDIX 2

SGH PVC-TD - PROPOSED STANDARD SPECIFICATION FOR CLASS PS 50 POLYVINYL CHLORIDE (PVC) PIPING SYSTEMS FOR SUBSURFACE DRAINAGE OF TRANSPORTATION FACILITIES

## 1. SCOPE

1.1 This specification covers the requirements and methods of test for smooth-wall perforated and unperforated Polyvinyl Chloride (PVC) plastic pipe, couplings and fittings for use in subsurface drainage of transportation facilities.

1.1.1 Nominal sizes of 4 to 15 inches (102 to 381 mm), in a stiffness class designated as PS 50, are included.

1.1.2 Materials, dimensions, flattening, resistance, pipe stiffness, extrusion quality, joining systems, perforations, and form of marking are specified.

Note 1. The values stated in U. S. Customary units are to be regarded as the Standard.

Note 2. Pipe and fittings should be installed in accordance with Proposed Recommended Practice SGH-RP-TD.

## 2. APPLICABLE STANDARDS

### 2.1 ASTM Standards:

D 618 Conditioning Plastics and Electrical Insulating Materials for Testing.

D 883 Definitions of Terms Relating to Plastics.





D 1598 Standard Test Method for Time-To-Failure of Plastic Pipe Under Constant Internal Pressure.

D 1784 Specification for Poly (Vinyl Chloride) (PVC) Compounds and Chlorinated Poly (Vinyl Chloride) (PVC) Compounds.

D 2122 Determining Dimensions of Thermoplastic Pipe and Fittings.

D 2152 Test for Quality of Extruded Poly (Vinyl Chloride) (PVC) Pipe by Acetone Immersion.

D 2412 Test for External Loading Properties of Plastic Pipe by Parallel Plate Loading.

D 2444 Test for Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (Falling Weight).

D 2564 Solvent Cements for Poly (Vinyl Chloride) (PVC) Plastic Pipe and Fittings.

D 2837 Standard Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials.

D 2855 Recommended Practice for Making Solvent Cemented Joints with Poly (Vinyl Chloride) (PVC) Pipe and Fittings.

D 3212 Joints for Drain and Sewer Plastic Pipes Using Flexible Elastomeric Seals.

F 402 Handling Solvent Cements.

F 412 Terms Relating to Plastic Piping Systems.

### 2.2 Other Standards:

SGH RP-TD Proposed Recommended Practice for Installation of Flexible Plastic Pipe Systems for Subsurface Drainage of Transportation Facilities

## 3. NOMENCLATURE

3.1 **General** – The nomenclature used in this specification is in accordance with the definitions given in Nomenclature ASTM D 883 and Specification ASTM F 412, unless otherwise specified. The abbreviation for polyvinyl chloride is PVC.

## 4. MATERIALS

4.1 **Basic Materials** – Pipe and fittings shall be made of virgin PVC plastic having a cell classification of 12454-B as defined in ASTM D 1784. Compounds shall be tested in accordance with ASTM D 1598 and provide a minimum hydrostatic design basis (HDB) of 4000 psi (27.6 MPa) in water. Minimum HDB shall be evaluated in accordance with ASTM D 2837.

4.2 **Rework Materials** – Rework material from the manufacturer's own pipe or fittings production may be used by the same manufacturer, provided that the pipe or fabricated fittings produced meet all the requirements of this specification.

4.3 **Solvent Cement** – The solvent cement shall meet the requirements of Specification ASTM D 2564, "Standard Specification for Solvent Cement for Poly (Vinyl Chloride) (PVC) Plastic Pipe and Fittings."

## 5. JOINING SYSTEMS

5.1 **Elastomeric Gasket Joints** – All sizes of pipe may be supplied with gasket-type joints meeting the requirements of Specification ASTM D 3212.

5.2 **Solvent Cement Type Joints**

5.2.1 Perforated pipe may be connected with belled ends (Table 2), coupled with sleeve-type couplings (Table 5), or stop-type couplings (Specification ASTM D 3034, Table 9.)

5.2.2 Belled ends shall be centered to provide a visible shoulder around the entire circumference of the pipe.



5.2.3 When required, joints shall be solvent cemented with PVC cement as defined in ASTM D 2564, and shall be made in accordance with ASTM D 2855.

Note 3: Difficulty may be encountered in obtaining watertight joints when solvent cementing joints in pipe diameters greater than 6 in. (152 mm).

## 6. REQUIREMENTS

6.1 **Workmanship** – The pipe and fittings shall be homogeneous throughout, and free from visible cracks, flaws, foreign inclusions or other injurious defects. The pipe shall be as uniform as commercially practical in color, opacity, and other physical properties.

6.2 **Pipe Dimensions**

6.2.1 Diameter – The average outside diameter of the pipe shall be as specified in Table 1 when measured in accordance with Method ASTM D 2122.

6.2.2 Wall Thickness – The minimum wall thickness shall be as specified in Table 1 when measured in accordance with Method ASTM D 2122.

6.2.3 Length – Laying length shall be 20 feet (6 m) for diameters up to 8 inches (203 mm), and no less than 10 feet (3 m) for larger sizes; or as mutually agreed upon between purchaser and manufacturer. A tolerance of ± 1 in. (± 25 mm) on the nominal laying length shall be permitted.

6.2.4 Perforations – Perforated pipe shall be perforated in accordance with Table 6. The perforations shall be 3/16 to 3/8 in. (4.7 to 9.4 mm) in diameter, circular, and cleanly cut. The spigot end, and bell, of belled-end pipe shall be unperforated for a length equal to the depth of the socket and/or shoulder.

## TABLE I - PIPE DIMENSIONS

Outside Diameter

| Nominal Size (in.) | Average | Tolerance | Out-of-Roundness Minimum | Out-of-Roundness Maximum | Minimum Wall Thickness |
|---|---|---|---|---|---|
| | | MILLIMETRES (mm) | | | |
| 4 | 107.06 | ± 0.22 | 105.80 | 108.34 | 3.05 |
| 6 | 159.38 | ± 0.28 | 158.12 | 160.66 | 4.57 |
| 8 | 213.36 | ± 0.30 | 211.46 | 215.26 | 6.10 |
| 10 | 266.70 | ± 0.38 | 263.66 | 269.75 | 7.65 |
| 12 | 317.50 | ± 0.46 | 313.87 | 321.14 | 9.09 |
| 15 | 388.62 | ± 0.58 | 384.16 | 393.09 | 11.13 |
| | | INCHES (in.) | | | |
| 4 | 4.215 | ± 0.009 | 4.165 | 4.265 | 0.120 |
| 6 | 6.275 | ± 0.011 | 6.225 | 6.325 | 0.180 |
| 8 | 8.400 | ± 0.012 | 8.325 | 8.475 | 0.240 |
| 10 | 10.500 | ± 0.015 | 10.380 | 10.620 | 0.301 |
| 12 | 12.500 | ± 0.018 | 12.357 | 12.643 | 0.358 |
| 15 | 15.300 | ± 0.023 | 15.124 | 15.476 | 0.438 |



6.2.5 Integral Bell Dimensions – Integral bells for elastomeric seal joints shall meet dimensions recommended by the manufacturer. Socket-type bell dimensions shall comply with Table 2. The thickness of the wall shall be considered satisfactory if the bell was formed from pipe meeting the requirements of this specification.

**6.3 Fitting Dimensions**

6.3.1 Fitting Wall Thickness – The minimum wall thickness of sleeve-type couplings and molded fittings shall be no less than the respective minimum thicknesses listed for the equivalent pipe in Table I. The wall thickness of bends manufactured from pipe (Table 5) shall be considered satisfactory, providing the bend was formed from pipe meeting the requirements of this specification. For reducing fittings or those with smaller inlets, the minimum wall thickness of each inlet shall not be less than the minimum wall thickness for that size pipe.

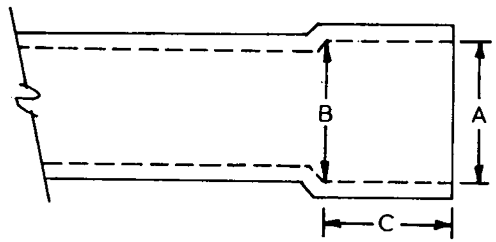
6.3.2 Laying Length – The laying length of fittings shall meet the requirements of Tables 4 and 5 of this Specification or Tables 3 to 11 of Specification ASTM D 3034.

**6.4 Minimum Pipe Stiffness** – The minimum pipe stiffness (PS) values shall be 50 lb/in./in. (345 kPa) when tested in accordance with 8.3. Three specimens shall be tested; all shall meet the requirements.

Note 4: It is recommended that any development of stiffer pipe classes be directed towards furnishing pipe stiffness (PS) of 100 lb/in./in. (490 kPa).

**6.5 Pipe Flattening** – There shall be no evidence of splitting, cracking, or breaking when pipe and couplings tested in accordance with 8.4 is examined without the use of magnification equipment.

TABLE 2 - PIPE SOCKET DIMENSIONS (BELLED ENDS FOR SOLVENT CEMENT TYPE ONLY)




| Nominal Size (in.) | Entrance (A) | | Socket Bottom (B) | | Min. Bell Depth (C) |
|---|---|---|---|---|---|
| | Diameter | Tolerance | Diameter | Tolerance | |
| | MILLIMETRES (mm) | | | | |
| 4 | 107.57 | ±0.22 | 106.93 | ±0.22 | 44.44 |
| 6 | 160.15 | ±0.28 | 159.26 | ±0.28 | 76.20 |
| 8 | 213.97 | ±0.30 | 213.06 | ±0.30 | 101.60 |
| 10 | 267.47 | ±0.38 | 286.32 | ±0.38 | 127.00 |
| 12 | 318.41 | ±0.46 | 317.04 | ±0.46 | 152.40 |
| 15 | 369.79 | ±0.58 | 388.04 | ±0.58 | 190.50 |
| | INCHES (in.) | | | | |
| 4 | 4.235 | ±.009 | 4.210 | ±.009 | 1.750 |
| 6 | 6.305 | ±.011 | 6.270 | ±.011 | 3.000 |
| 8 | 8.424 | ±.012 | 8.388 | ±.012 | 4.000 |
| 10 | 10.530 | ±0.015 | 10.485 | ±0.015 | 5.000 |
| 12 | 12.536 | ±0.018 | 12.482 | ±0.018 | 6.000 |
| 15 | 15.346 | ±0.023 | 15.277 | ±0.023 | 7.500 |



6.6 **Impact Strength** – The minimum drop weight impact strength for pipe and couplings shall meet the requirements of Table 3, when tested in accordance with 8.1.

6.7 **Joint Tightness** (Referee Test) – The joints of unperforated pipe shall not leak when tested in accordance with 8.2.

6.8 **Extrusion Quality** – The pipe and fittings shall not flake or disintegrate when tested in accordance with Method ASTM D 2152.

Note 5: Development of tests and requirements for fittings is in ASTM ballot. Requirements should be included when available.

## 7. CONDITIONING

7.1 **Referee Testing** – When conditioning is required for tests, the specimens shall be conditioned in accordance with Procedure A in Specification ASTM D 618 at 70 to 77°F (23 ± 2°C) and 50 ± 5% relative humidity for not less than 40 h prior to test. Tests shall be conducted under the same conditions of temperature and humidity, unless otherwise specified.

7.1.2 **Quality Control** – For quality control tests except impact, specimens shall be conditioned for a minimum of 3 h in air, or 1 h in liquid at 70 to 77°F (23 ± 2°C). They shall be tested at 70 to 77°F (23 ± 2°C) without regard to relative humidity.

7.1.3 **Impact Tests** – For the impact test described in 8.1, the specimen and the surrounding conditioning medium are to be in thermal equilibrium with one another at a temperature of 32 to 35°F (0 to 1.6°C).

## TABLE 3 - IMPACT STRENGTH AT 0°C (32°F)

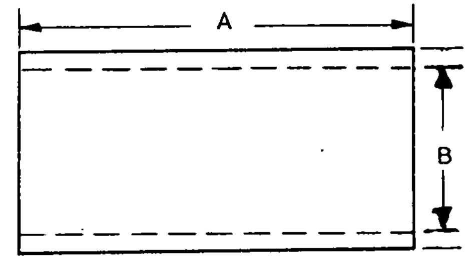
| Nominal Size (in.) | Joules | ft - lb |
|---|---|---|
| 4 | 88 | 65 |
| 6 | 115 | 85 |
| 8 | 129 | 95 |
| 10 | 129 | 95 |
| 12 | 129 | 95 |
| 15 | 129 | 95 |

Note: These values remain to be verified in larger sizes.

Note: 1 in. = 25.4 mm

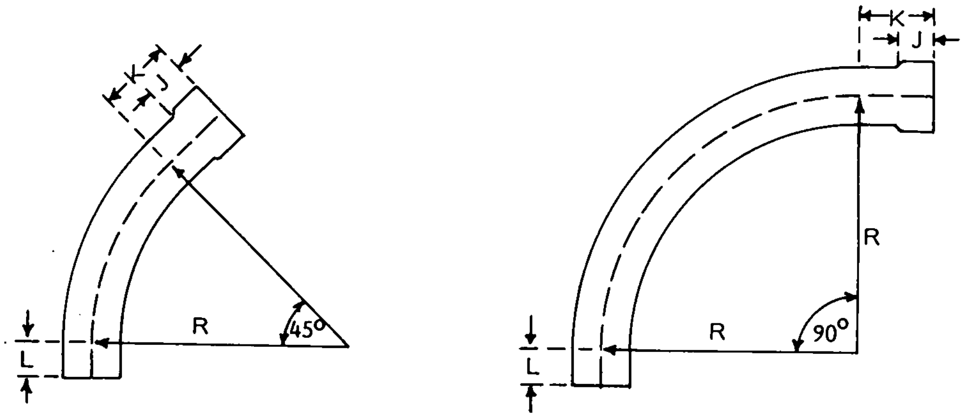


## TABLE 4 - SLEEVE COUPLING DIMENSIONS




| Nominal Size (in.) | Length (A) | | Inside Diameter (B) | |
|---|---|---|---|---|
| | Average | Tolerance | Average | Tolerance |
| | MILLIMETRES (mm) | | | |
| 4 | 88.8 | + 6.34 - 0 | 107.44 | ± 0.13 |
| 6 | 152.4 | + 6.34 - 0 | 159.79 | ± 0.13 |
| 8 | 203.2 | + 6.34 - 0 | 213.81 | ± 0.15 |
| 10 | 254.0 | + 6.34 - 0 | 267.21 | ± 0.18 |
| 12 | 304.8 | + 6.34 - 0 | 318.18 | ± 0.20 |
| 15 | 381.0 | + 6.34 - 0 | 389.51 | ± 0.23 |
| | INCHES (in.) | | | |
| 4 | 3.5 | + 0.25 - 0 | 4.230 | ± 0.005 |
| 6 | 6.0 | + 0.25 - 0 | 6.291 | ± 0.005 |
| 8 | 8.0 | + 0.25 - 0 | 8.418 | ± 0.006 |
| 10 | 10.0 | + 0.25 - 0 | 10.520 | ± 0.007 |
| 12 | 12.0 | + 0.25 - 0 | 12.527 | ± 0.008 |
| 15 | 15.0 | + 0.25 - 0 | 15.335 | ± 0.009 |

## TABLE 5 - LAYING LENGTHS OF BENDS MANUFACTURED FROM PIPE




| Nominal Size (in.) | Dimensions (min.) | | | |
|---|---|---|---|---|
| | Radius (R) | (J) | (K) | (L) |
| | MILLIMETRES (mm) | | | |
| 4 | 406.4, 609.6 or 914.4 | 44.44 | 88.90 | 50.80 |
| 6 | 609.6 or 914.4 | 76.20 | 152.40 | 88.90 |
| 8 | 609.6 or 914.4 | 101.60 | 203.20 | 127.00 |
| | INCHES (in.) | | | |
| 4 | 16, 24 or 36 | 1.75 | 3.50 | 2.00 |
| 6 | 24 or 36 | 3.00 | 6.00 | 3.50 |
| 8 | 24 or 36 | 4.00 | 8.00 | 5.00 |



## 8. TEST METHODS

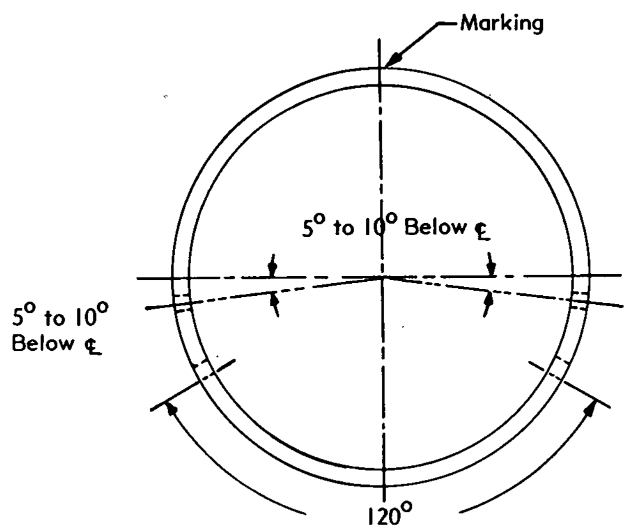
8.1 **Impact Resistance** – Five specimens, each nominally 6 in. (150 mm) long, shall be tested in accordance with Section 10 of Specification ASTM D 2444, using a 20 pound (10 kg) Tup A, and the Flat plate (holder B). When testing is performed at temperatures above 32°F (0°C) no more than 15 s shall elapse from the time of removal of the specimen from the conditioning medium until completion of that test. Perforated specimens must be positioned with the print marking, as shown in Table 6, uppermost; other specimens may be positioned with a random surface uppermost. All specimens must be located so that the contact point is centered. All five specimens shall pass. If one specimen fails, another five specimens shall be tested; nine out of ten specimens passing shall be acceptable.

8.2 **Joint Tightness of Unperforated Pipe** – A section of unperforated pipe shall be cemented to a bell or coupling, using the manufaturer's recommendations or, in their absence, the methods described in Specification ASTM D 2855. Unless otherwise specified, the assembly shall be allowed to stand for at least 6 h. It shall then be subjected to an internal pressure of 25 psi (172 KPa), using water as the test medium. The pressure shall be maintained for at least one hour. There shall be no leakage.

8.3 **Pipe Stiffness** – Determine the pipe stiffness (PS) at 5% deflection of the initial inside diameter, as described in Method ASTM D-2412. Test three specimens each 6 in. $\pm$ 1/16 in. (152 mm $\pm$ 1.6 mm) long. Unperforated pipe samples shall be placed so that the minimum wall thickness is uppermost (adjacent to the top bearing plate). Perforated pipe samples shall be placed with the marking, as shown in Table 6, uppermost.

8.4 **Pipe Flattening** – Flatten three specimens of pipe each 6 in. $\pm$ 1/16 in. (152 mm $\pm$1.6 mm) long, between parallel plates in a suitable press

TABLE 6 - PERFORATIONS




| Nominal Diameter (in.) | Minimum Rows Of Perforations | Hole Spacing | |
|---|---|---|---|
| | | MM | IN. |
| 4 | 2 | 82.55 ± 6.35 | 3-1/4 ± 1/4 |
| 6 | 4 | 82.55 ± 6.35 | 3-1/4 ± 1/4 |
| 8 | 4 | 82.55 ± 6.35 | 3-1/4 ± 1/4 |
| 10 | 4 | 102 | 4 |
| 12 | 6 | 152 | 6 |
| 15 | 6 | 152 | 6 |

Note: 1 in. = 25.4 mm



until the distance between the plates is twice the wall thickness plus 5% of the nominal diameter of the pipe. The rate of loading shall be uniform and such that the compression is completed within two to five minutes. Remove the load and examine the specimens.

8.5 **Dimensions** – Measurements shall be made in accordance with applicable sections of Method ASTM D 2122.

## 9. INSPECTION AND RETEST

9.1 **Inspection** – The material shall be inspected as agreed upon by the purchaser and the seller as part of the purchase contract.

9.2 **Retest and Rejection** – If the material fails to meet the requirements of Section 6 when tested in accordance with Section 8, the material may be retested to establish conformity in accordance with agreement between the purchaser and seller.

## 10. MARKING

10.1 All pipe shall be clearly marked at intervals of no more than 10 feet (3 m), with 3/8 in. (9 mm) or larger letters, and fittings shall be clearly marked, as follows:

10.1.1 Manufacturer's name or trademark.

10.1.2 Nominal size.

10.1.3 Material designation (PVC).

10.1.4 The word "TRANSDRAIN".

10.1.5 The Class — PS 50.

10.1.6 The specification designation "XXXX".

10.1.7 Date of manufacture, and plant designation.

10.2 In addition to the above, all bends made from pipe shall be marked to show the angle and radius of curvature.

10.3 The marking on perforated pipe shall be 180° from a point equidistant between the bottom row of holes as shown in Table 6.

10.4 When exposed, a "home" mark, located at spigot ends, indicates the proper position of the bell end, when the spigot end is fully inserted.

## 11. QUALITY ASSURANCE

11.1 A manufacturer's certification that the product was manufactured, tested, and supplied in accordance with this specification, together with a report of the test results, and the date each test was completed, shall be furnished upon request. Each certification so furnished shall be signed by a person authorized by the manufacturer.



# APPENDIX 3

## SGH RP-TD - PROPOSED RECOMMENDED PRACTICE FOR INSTALLATION OF FLEXIBLE PLASTIC PIPE SYSTEMS FOR DRAINAGE OF TRANSPORTATION FACILITIES

### 1. Scope

1.1 This recommended practice describes arrangements and installation procedures for both smooth-wall and corrugated-wall thermoplastic underdrain pipe for drainage of transportation facilities. Both perforated pipe, which serve as drainage collectors, and nonperforated pipe, which either drain the collector or serve as storm drains and culverts, are included. Installation requirements to achieve both flow for drainage collection and structural support of the pipe under vehicle loads and earth loads applied to the installation are provided.

### 2. Applicable Documents

| | |
|---|---|
| ASTM D 2487 | Classification of Soils for Engineering Purposes |
| AASHTO T 99 | The Moisture-Density Relations of Soils Using a 5.5 lb (2.5 kg) Rammer and a 12-in. (304 mm) Drop |
| SGH PE-TD | Proposed Standard Specification for Class PS 50 Corrugated Polyethylene (PE) Tubing Systems for Subsurface Drainage of Transportation Facilities |
| SGH PVC-TD | Proposed Standard Specification for Class PS 50 Poly Vinyl Chloride (PVC) Piping Systems for Subsurface Drainage of Transportation Facilities |

## 3. Terminology

3.1 Figure 1 illustrates the meaning and limits of the terms used in this document.

3.2 **Pipe stiffness** (PS) as defined in ASTM D 2412, is a measure of the ability of the pipe to resist diametral deflection.

3.3 **Elongation** is the extension of corrugated polyethylene tubing caused by tension applied along the cylindrical axis, as a percent increase of the laying length.

## 4. Significant Factors of Installation

4.1 Underdrains should be surrounded by a drainage envelope of granular material having a gradation which precludes infiltration of soil particles through the perforations in the pipe wall, and which is graded to preclude clogging of the envelope by excessive infiltration of fines from adjacent soils.

4.1.1 A filter fabric sleeve may be used as an alternate to the drainage envelope when the embedment material is not adequately graded for drainage purposes, but which conforms to the requirements recommended herein.

Note 1 The drainage envelope is commonly referred to as a "filter".

4.2 The structural performance of a thermoplastic pipe installation is governed by the system of embedment and pipe structure which is provided in the completed installation. The drainage envelope, or other embedment material which surrounds the pipe, functions as both a bedding and a side support for the pipe. This support is needed to sustain surface wheel loads and earth cover loads. The ability to resist



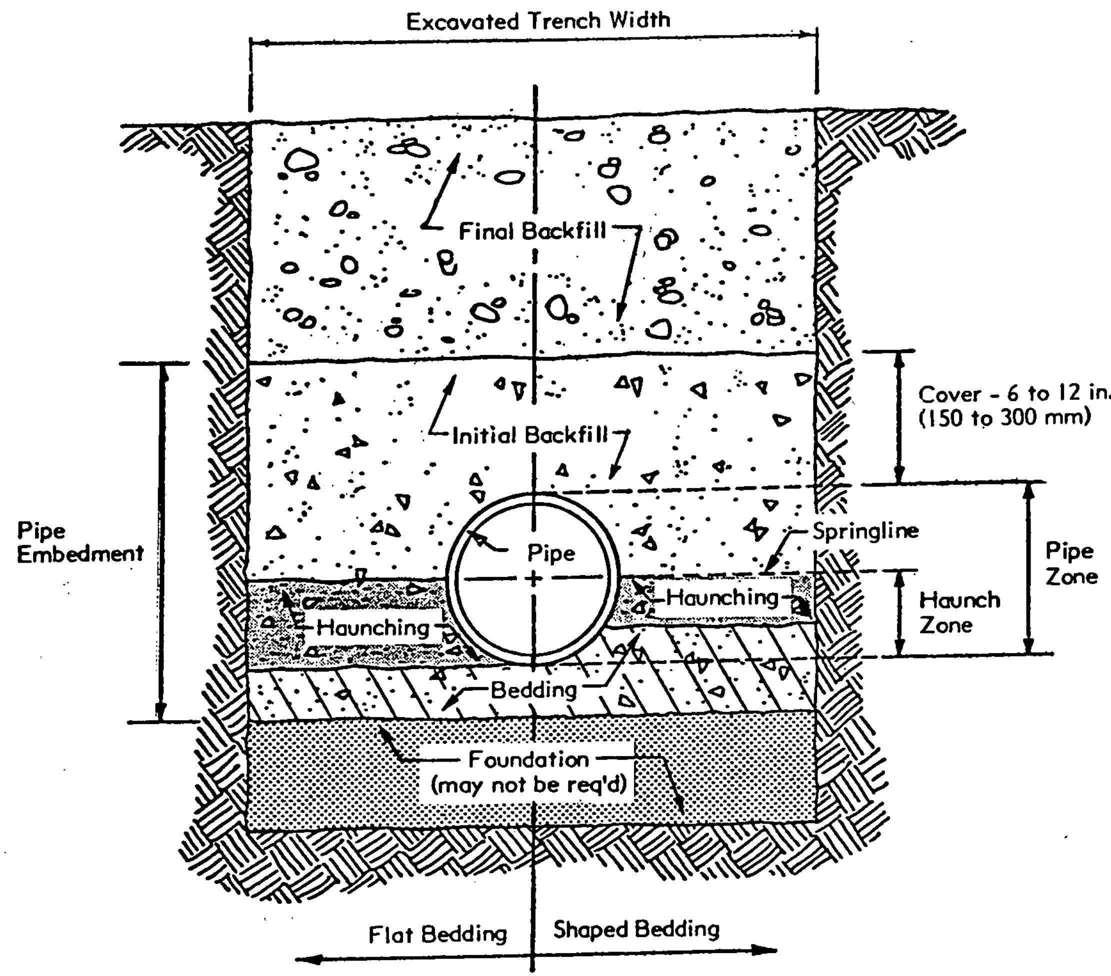



FIG. 1 TRENCH CROSS SECTION SHOWING TERMINOLOGY

these loads is almost totally dependent on the quality and density of the embedment materials which immediately surrounds the pipe.

4.2.1 The deflection of pipe induced during the process of installing the pipe decreases with increasing pipe stiffness. However, deviations from procedures recommended herein can result in major deflections, independent of practical pipe stiffness. Alternately, with proper care, pipe of high flexibility can be installed with negligible deflection.

## 5. General

5.1 Embed pipe in compacted granular materials as recommended herein. Embed perforated underdrain pipe or tubing in a compacted granular drainage envelope as recommended herein. Suitable filter fabric materials may be substituted for the drainage envelope in certain cases where gradation of embedment soil is compatible with characteristics of the filter fabric, and meets other requirements recommended herein.

5.2 Where the pipe system is to be placed in an embankment, first place and compact embedment in accordance with project specifications to a minimum height of 2 ft 6 in. (0.75 m) above design elevation at the top of the pipe, then excavate trenches and install pipe. The contractor should increase minimum cover height as required when especially heavy construction vehicles or high energy compaction equipment is expected to traffic the installation.

5.3 Provide suitable fittings supplied or recommended by the pipe manufacturer at all joints, changes in direction, changes in diameter, branch connections and ends of the line.

5.4 Connect pipe, except perforated pipe covered below, with solvent-cemented, gasketed or other positive watertight connecting joints.



5.5 Connections of perforated pipe and tubing need not be watertight. They may be "tacked" in place using solvent-cement, left "dry", or connected by sleeves or other suitable means, provided that the installed pipe remains properly coupled.

## 6. Embedment Materials

6.1 Embedment materials include processed, aggregate, and granular soils for general pipe embedment, and materials graded as recommended herein for the drainage envelope of perforated underdrains with or without external filter screen.

6.1.1 General Embedment Materials: Bedding, haunching and initial backfill materials for storm drains, culverts, and non-perforated underdrains.

6.1.1.1 For non-perforated pipe, use the following classes of materials, graded in accordance with 6.1.1.2 to 6.1.2.3, unless otherwise specified.

Class A Angular, 1/2-in.(13 mm) maximum size well graded crushed stone, coral, slag, cinders, and crushed shells.

Class B Clean, natural, or processed as required, coarse sands and gravels with maximum particle size of 1/2 inch (13 mm), including variously graded sands and gravels containing less than 12% fines, generally granular, and noncohesive when either wet or dry. Soil types GW, GP, SW and SP as classified in accordance with ASTM D 2487.

6.1.1.2 Gradation of embedment materials, particularly Class A materials, should be selected for compatibility with in-situ material or Class B materials used in the embedment. Embedment materials should be graded in accordance with Table 1, to provide suitable compatibility which minimizes migration of fines into voids in the coarser material.

## TABLE 1 - EMBEDMENT AND DRAIN ENVELOPE GRADATIONS

| Type of Pipe | Gradation | | |
|---|---|---|---|
| A. All Pipe and Tubing | $D_{15}$ drain envelope (only) | $\geqq$ | 5 $D_{15}$ surrounding soil |
| | | | Tubing: |
| | $D_{15}$ drain envelope or | $\leqq$ | 5 $D_{85}$ surrounding soil embedment |
| | $D_{50}$ drain envelope or | $\leqq$ | 25 $D_{50}$ surrounding soil embedment |
| B. Underdrain with Slots: | $D_{85}$ drain envelope | $\geqq$ | 1.4 times slot width |
| C. Underdrain with Holes: | $D_{85}$ drain envelope | $\geqq$ | 1.2 times hole diameter |

Note 2 "D" represents the sieve size and the subscript designates percent by weight passing that sieve size.

## TABLE 2 - COARSE SAND GRADATION FOR ONE-COURSE DRAIN ENVELOPE

| Sieve Size | 3/8 | No. 4 | No. 16 | No. 50 | No. 100 |
|---|---|---|---|---|---|
| Range in Allowable Percent Passing | 95-100 | 80-90 | 45-65 | 10-25 | 0-2 |



6.1.1.3 In medium to highly plastic clay soils without sand or silt partings, the $D_{15}$ size of the embedment material may be as great as 0.01 in. (0.4 mm), and the $D_{50}$ criteria given above may be disregarded if the embedment material envelope is well graded and has a ratio of $D_{60}$ to $D_{10}$ not greater than 20.

6.1.2 Drain Envelope Materials: For perforated underdrains use clean granular drainage envelope material with no more than 2% of particles finer than #100 sieve having gradation and particle sizes which conform to 6.1.1.2.

6.1.2.1 Where slot width is less than 0.10 inches (2.5 mm), or hole diameter is less than 0.14 inches (3.5 mm), gradation characteristics given below in Table 2 are acceptable for most applications.

6.1.2.2 Where a suitable external filter screen sleeve is used, a drainage envelope consisting of concrete sand, conforming to ASTM C33, except that not more than 2% may pass the #100 sieve or other clean granular well graded sand, as available from in-situ sources, is acceptable.

Note 3 The U. S. Army Corps of Engineers Guide Specificaion CE 805.02 describes filter screen materials; however, many new materials are presently available, which are not covered in this reference.

Note 4 Most of the presently available prefabricated filter sleeve material such as fiberglass, spun bonded nylon fabric, and plastic filter cloth act as protective filters. These filters must be specified to be compatible with the soil type that surrounds the underdrain since protective filters can clog and decrease inflow capacity of the system.

Note 5 Biodegradable organic filter materials such as jute are available, but are not recommended.

6.1.2.3 Where slot widths or hole diameters are greater than the limits given in Table 1, and where no filter screen sleeve is provided, a two-course filter envelope is required. Use an inner blanket consisting of Class A material for a minimum radial distance of 6 in. (150 mm) around the pipe, and concrete sand, ASTM C33, as an outer blanket extending for a minimum radial distance of 6 in. (150 mm) completely surrounding the inner blanket. Gradation of the Class A material should be designed in accordance with Table 1, to preclude any migration of the concrete sand.

## 7. Handling and Storage

7.1 Load, unload, store, and handle pipe in a manner which will insure satisfactory performance in the installation.

7.1.1 Broken Pipe: Repair broken pipe by removing and discarding broken end. Do not use or repair pipe with damaged bells.

7.1.2 Bowed Pipe: Discard bowed pipe which interferes with installing to specified line and grade.

7.1.3 Out-of-Round Pipe: Reject any pipe which is ovalled to an extent which will affect makeup or integrity of finished joints and connections. Ovalled pipe which meets the above criteria may be installed providing the finished installation meets specified deflection limits.

7.1.4 Gouged and Scratched Pipe: Deep gouges or cuts may impair performance and should be rejected. In case of dispute, gouged and scratched pipe may be accepted providing impact tests made on samples removed from a referee pipe, meet impact energy requirements called for in the pipe system specifications.



7.2 Storage in Sunlight: Protect pipe from solar radiation during storage for periods greater than a few weeks. Take particular care in regions which receive high levels of sunlight. Reject any discolored or chalked pipe. In case of dispute, such pipe may be accepted if it meets impact strength requirements called for in pipe system specifications.

## 8. Trench Excavation

8.1 Excavate trenches to the dimensions and grades shown in the plans, or as directed by the Engineer. Minimum width of trench is pipe diameter plus 2 feet (0.6 m). Trench width may be reduced provided that the contractor can demonstrate that materials and methods used result in an installation which satisfies the specified minimum density and maximum deflection limits.

8.2 Excavate, and dewater as needed, in such a manner that the undisturbed state of soils below and beyond the required excavation limits are preserved and that the bottom of the trench is maintained firm, and dry.

8.2.1 Unstable Trench Walls: Where unstable or running soil conditions are such that trench walls will not remain vertical, stabilize this condition prior to preparing bedding and laying pipe.

8.2.1.1 Sheeting and Bracing: If a sheeting and bracing support system is required, submit details to the Engineer. That portion of the sheeting or trench protection which extends below the top of the pipe, at least, should be designed to be left in place. If sheeting is not left in place, the width of the trench (and undisturbed embedment system) should be a minimum of five pipe diameters, to provide suitable lateral support for the pipe. It may be necessary to utilize chemical or cement grouting of the soil adjacent to the excavation to prevent lateral migration of the embedment and foundation material and the trench wall.

8.2.1.2 Portable Trench Boxes and Shields: Take care not to disturb embedment materials when advancing portable trench boxes or sliding shields. Unless special precautions are taken, width of trench (and embedment system) should be a minimum of five pipe diameters, or pipe diameter plus two feet, whichever is greater, to provide suitable undisturbed lateral support for the pipe. On approval of the Engineer, this minimum width can be reduced to pipe diameter plus two feet, providing Class A materials are used for embedment, and providing all voids between the trench box and shield and the undisturbed trench wall are filled with Class A material for the full height of the embedment and foundation immediately after the box is positioned. Furthermore, the trench box, when advanced, should be lifted vertically and placed vertically; not dragged.

8.2.2 Unstable Trench Bottom: Where an unstable trench bottom is encountered, it must be stabilized before laying pipe, or alternative foundation methods utilized. The Engineer may elect, depending upon the severity of the unstable soil, to require special foundations such as wood pile or sheeting capped by a concrete mat upon which bedding is provided, by wood sheeting with keyed-in plank foundation, or stabilization of the bottom material. In the latter case the Engineer may require that a sufficient depth of the unstable soil material be removed and replaced with a foundation and bedding of Class A material, except suitably graded, maximum aggregate size may exceed that given in 6.1.1.1 at the discretion of the Engineer, and acting as a mat into which the unstable soil will not migrate. The depth of the material used for foundation and bedding depends upon the severity of the trench bottom soil condition. Install such special foundation material in 4 to 6 in. (100 to 150 mm) layers and suitably compact to a minimum of 90 percent of maximum dry density (AASHTO T-99).

8.2.3 Rock Excavation: When the pipe is to be laid in a rockcut, provide 4 to 6 in. (100 to 150 mm) of bedding, consisting of Class A or Class B material. If running water is encountered in the rockcut, use the



procedures described in 8.2.4. Pipe underdrain located within the foundation or bedding may be necessary, depending upon the amount of water present.

8.2.4 Running Water: Water running in the trench must be removed in order to properly lay the pipe. The Engineer may elect to order removal of the water with trench-side pumps through Class A material suited for bedding. The depth of Class A material required depends upon the amount of water present. The trench wall should be stabilized to prevent erosion by running water. The Engineer may elect to utilize well points or underdrain to control excessive ground water from entering the trench. If Class A material is used as bedding and under drain, it must also be utilized to the springlines of the pipe.

8.2.5 Wide Trench: Take care during excavation to maintain the minimum practical trench width at a point level with the top of the pipe (see 8.1). If the trench width is greater than 6 pipe diameters, haunching and initial backfill should be compacted to a point at least 2.5 pipe diameters from either side of the pipe. Depending upon the severity of trench conditions, bedding, and foundation should be compacted at least to the same point or wider and, if required by the Engineer, to the trench wall. Where an unstable trench bottom is encountered, the entire trench bottom should be stabilized.

8.3 If the bottom of the trench contains stones in excess of 1/2 in. (13 mm) in diameter, stones should be removed or the trench should be over-excavated 4 in. (100 mm) and refilled to grade using suitable bedding material.

8.4 If a trench is excavated to a depth which is more than 6 in. (150 mm) below the required distance from pipe invert to trench bottom, apply to the Engineer for materials and compaction requirements for backfilling the excess excavation.

8.5 Foundation materials must provide stable support of the pipe. In general, foundation conditions which are suitable for pavement support are also suitable for the support of piping.

8.6 If unsuitable soil conditions are encountered at foundation level, the Engineer may direct that they be removed to a specified depth below pipe invert grade and replaced with suitable bedding material.

## 9. Bedding and Laying Pipe

9.1 Bed the pipe true to line and grade with uniform and continuous support from a firm base. Do not use blocking to bring the pipe to grade. Provide temporary holddowns, consisting of bent wire, mounds of embedment material, or other suitable means to maintain position of corrugated polyethylene tubing.

9.2 Use positive means to compact coarse sand drain envelope materials and Class A bedding materials to 90% of maximum dry density (AASHTO T 99) unless other densities are specified. Tamp or vibrate Class A and drain envelope materials. Do not use frozen material or materials with lumps or random stones in excess of 1 inch maximum size.

Note 6 A carefully prepared bedding groove is desirable since it provides good bedding. Grooved bedding is particularly suitable for corrugated polyethylene tubing installations since it is difficult to place and compact material in the haunch zone without changing line and grade.

9.3 If the pipe contains bell and spigot type joints, place bells "uphill", and excavate bell holes in bedding to allow for unobstructed assembly of the joint. Maintain the minimum size bell hole necessary to accomplish proper joint assembly. After the joint is made, fill the bell hole with compacted bedding or haunching material to provide uniform bedding support for the pipe throughout its entire length.



9.4 Care must be taken during the connection of tubing fittings to avoid creating a means of either obstructing flow or catching debris.

9.5 Use protective blocking across bell ends to prevent damage of pipe from crowbar or other devices used to set pipe at gasketed connections. Use only lubricants, as recommended by the pipe manufacturer, at gasketed connections.

## 10. Haunching and Initial Backfill

10.1 Hold pipe or tubing in place in the trench, as necessary, until secured by initial backfill. Place backfill materials in the trench using a chute or other means that minimizes impact, displacement and deflection of the pipe or tubing.

10.2 Place and compact embedment or envelope material to the springline in the haunch zone by tamping or other positive means. Install haunch layer in 6 in. (150 mm) thick maximum layers and compact to 90% of maximum dry density (AASHTO T 99) unless otherwise specified. Densify by tamping, vibration, flooding (drain envelope or Class B only, with approval of the Engineer) or a combination thereof. The materials used in the haunch layer must be the same as used for bedding. Work material beneath and around the pipe to preclude voids adjacent to the pipe in the haunch zone and compact firmly. Prevent movement of the pipe during placement of haunch material. If mechanical compaction equipment is used, avoid contact with the pipe and replace and re-lay any sections of pipe damaged during compaction.

10.3 Place and compact embedment in envelope material of the initial backfill layer(s) in 8 in(200 mm) maximum layers and compact to 90% of maximum dry density (AASHTO T 99) unless otherwise specified. Densify by methods given in 10.2. Do not compact zone above pipe until 6 in. (150 mm) or more of material is in place over the top of pipe.

10.4 For installations below shoulder pavements or heavy construction traffic, final backfill should be with material and compaction methods as specified for pavement base, sub-base or shoulder, including drainage courses as appropriate. For other installations, where trench consolidation is not critical, native materials may be used for final backfill and no special compaction, unless otherwise shown in the plans or specifications, is required.

## 11. Machine Installation

11.1 Machine methods of trenching, bedding, pipe laying and backfilling may be used provided they do not deform or elongate corrugated polyethylene tubing in excess of specified limits , and if they provide the compaction and deflection requirements of this recommended practice, and the alignment and grade tolerances shown on the plans or specifications.

11.1.1 When unstable or fluid soil conditions are encountered in the trench wall, protect the tubing from caving of the walls and floating until the tubing has been properly laid, embedded, and backfilled. In some cases an extended shield behind the shoe on the trencher may be used to protect the tubing under these conditions. The tubing should be laid immediately after the shoe has passed. The trencher shield must be long enough to provide sufficient time to surround the tubing with envelope material; and to achieve compaction of the embedment material to prevent caving and floating.

## 12. Special Precautions

12.1 Minimum Cover for Load Application: Provide at least 36 in. (0.9 m) of cover over the top of the pipe before the trench is wheel-loaded with H2O type vehicle (AASHTO Designation), and 48 in. (1.2 m) of cover before utilization of a hydrohammer during compaction. Submit documentation substantiating any reduction in these values to the Engineer for approval.



12.2 Use of Compaction Equipment: Any contact between compaction equipment and the pipe should be avoided to prevent damage to the pipe. Initial backfill located directly above the pipe should not be compacted until at least 6 in. (150 mm) of material is in place over the crown of the pipe.

12.3 When polyethylene tubing feels warm to the touch during hot weather installation, delay backfilling until the tubing temperature cools to the soil temperature.

12.4 Provide an animal guard at outlet pipes and at any other points where animals can enter the pipeline system (See Fig. 2).

12.5 Do not expose plastic outlet pipes to solar radiation.

12.6 Protect plastic outlet pipes from ground cover fires.

## 13. Deflection Check

13.1 When specified, check that deflection of the completed installation is within specified deflection control limits by pulling a go-no-go plug or suitable deflectometer through the line.

13.2 This check is to be carried out 30 days or more after completion of backfill, or just prior to installation of pavement above the pipe, whichever is sooner, or at any time during construction, at the discretion of the Engineer.

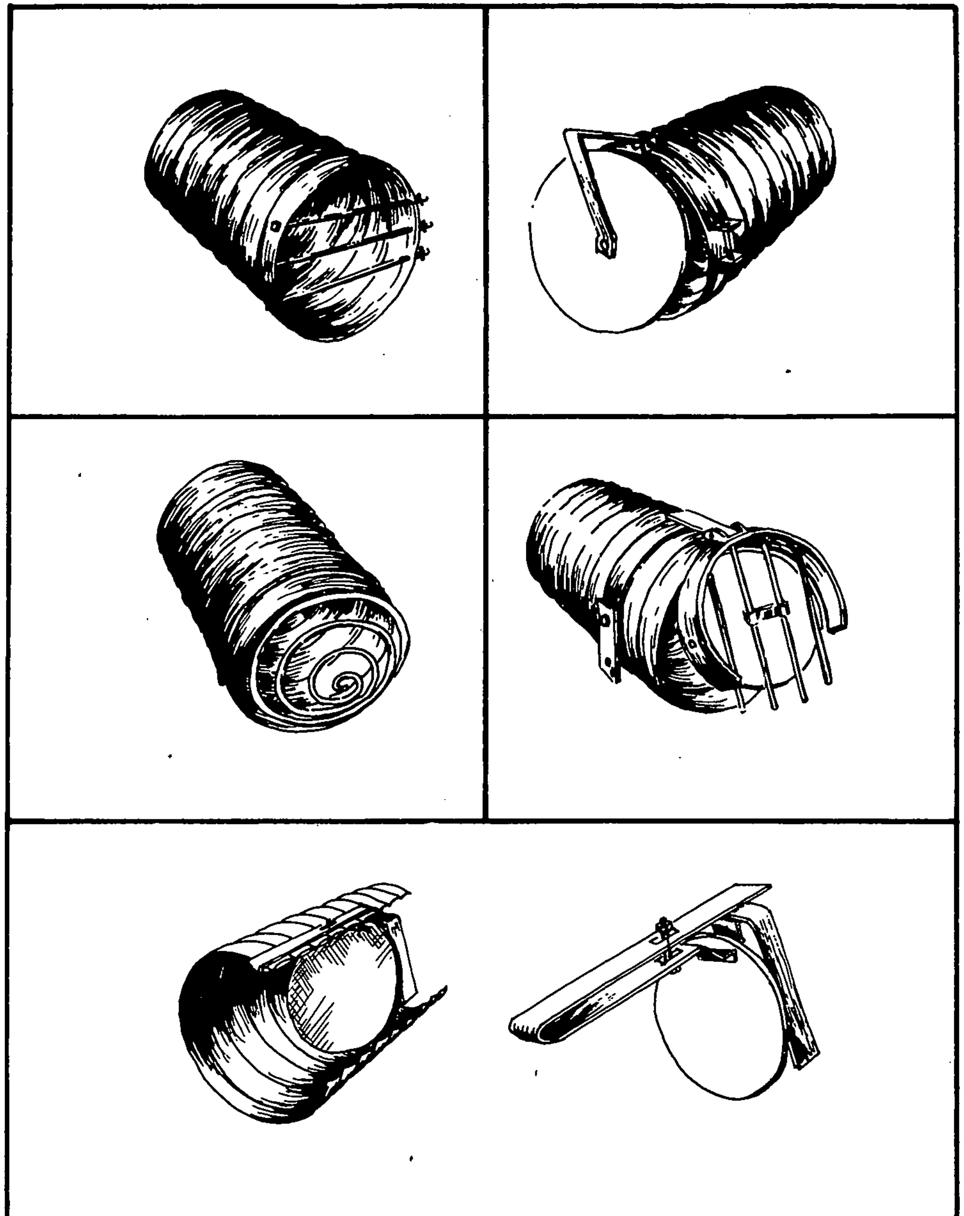


FIG. 2 - ANIMAL GUARDS



# APPENDIX B

## FIELD STUDIES

Field studies were undertaken in Phase II in cooperation with several state transportation agencies with the overall objectives as follows:

- Perform limited field studies to evaluate buried plastic pipe behavior and performance in several types of highway installations. These studies, conducted with major participation of the states of Maine and New Hampshire, provided opportunities to evaluate methods for predicting performance of plastic pipe, and to evaluate the tentative installation specifications prepared during Phase I.

- Observe and obtain information on past and ongoing State projects in which plastic pipe was used for highway drainage of transportation facilities. These projects consisted of full-scale test installations of several types of piping systems in Illinois, and ongoing corrugated plastic tubing shoulder underdrain installations in Georgia.

The States that cooperated in this effort provided valuable and frequently extensive assistance in the above investigations. The States of Illinois and Georgia provided history of the use of plastic pipe, plans and specifications, personnel for site visits to observe ongoing installations, and test data where appropriate. The States of Maine and New Hampshire provided major input into the detailed full-scale tests specifically designed for the project. They provided test sites, field coordination and engineering, installation personnel (either site contractor or State mechanics) and technical assistance in the field tests.

The field studies are briefly summarized below to provide a perspective on the scope and objectives of the field test program.

**New Hampshire:** The first and most extensive field studies were performed in New Hampshire. In the study designated NH-1, PVC pipe of two different wall thicknesses was installed as a culvert buried 5 ft (1.5 m) below a temporary interstate (I 95) bypass for 13 months. Several types of embedment material were used. The pipe was instrumented with strain gages and deflections were measured. Pipe were removed for testing after 14 months, when the bypass was removed from service.

In the project designated NH-2, 6 types of plastic pipe were installed in a trench which provided four feet of cover; the installation was immediately subjected to traffic by vehicles which were transporting earth to an adjacent embankment. Sand was used for pipe embedment. Later, a temporary embankment was constructed over the installation which provided a total of 20 ft (6 m) of cover over the pipe. Deflection measurements were made. Six months after installation, the temporary embankment was removed and sections of pipe were taken for testing. The site was re-designated NH-2.1 at this time.

In the project designated NH-2.1, the pipe that had been removed from NH-2 were replaced with three types of plastic pipe. Trench installation was similar to that of NH2, except that compaction of embedment material was minimal, and for some pipe embedment material was purposely omitted from the haunch zone. The installation was trafficked by construction vechicles. A permanent embankment was then constructed over the installation which provided 23 ft (7 m) of earth cover over the pipe. Two pipe lengths were instrumented with strain gages, and deflection measurements were made on all pipe. These pipe are still in place and available indefinitely for testing.

**Maine:** In the project designated ME-1, six types of plastic pipe were buried as culverts, in an unpaved maintenance turn-around between the northbound and the southbound lanes of I-95, which is trafficked by sand trucks and other maintenance vehicles. Depth of cover provided was 2 to 2-1/2 ft (0.6 to 0.75 m). Two pipes were instrumented with strain gages and deflections were measured.

**Georgia:** In Georgia, observations were made of ongoing construction projects in which corrugated PE tubing was being installed as shoulder underdrains.



**Illinois:** In Illinois, observations were made of ongoing installation of corrugated PE tubing shoulder underdrains. Installation was by a modified conventional trencher. Also observed was a modified version of a combined trencher-installer normally used in agricultural drainage installations.

The details of these cooperative projects and the findings obtained therefrom are described in detail below.

## B.1 New Hampshire I (NH-1)

### Objective

The first field study initiated in New Hampshire (NH-1) was undertaken to evaluate performance of PVC pipe furnished in two stiffnesses, when buried 5 ft (1.5 m) below the pavement of a temporary Interstate bypass, in three different embedment materials.

### Site

The site for the NH-1 installation was a temporary two-lane bypass which was constructed to divert traffic around a toll-booth construction site on Interstate 95, in Hampton, New Hampshire. The pipe was installed as a culvert to drain ponded water which was trapped on the north side of the bypass.

### Materials

About 100 ft (30 m) of each of the following 12-in. (305 mm) diameter pipe were used in the test:

- PVC sewer pipe, ASTM D 3033-DR 41, made from a PVC compound designated 12454-B. Joints were bell and spigot, with an elastomeric O-ring gasket. The pipe was obtained from available stock in a distributor's yard.

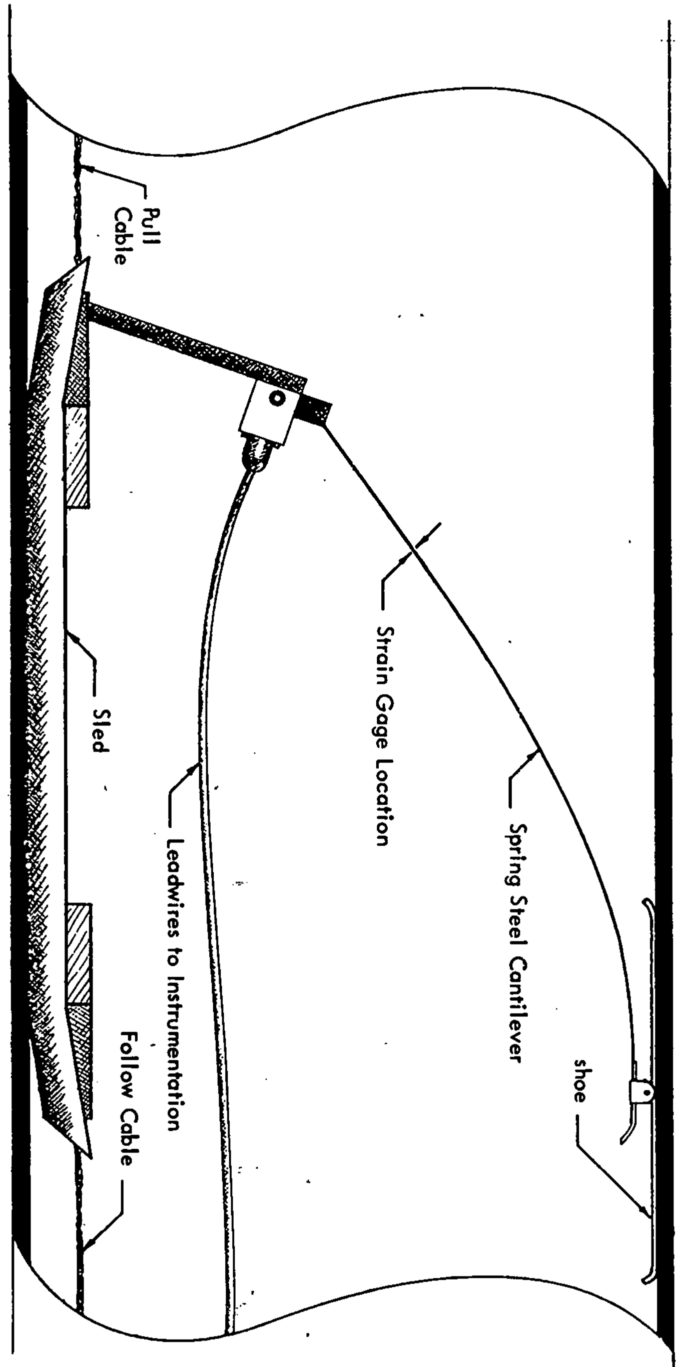



FIG. B-1 SCHEMATIC OF CANTILEVER/STRAIN GAGE DEFLECTOMETER



- PVC sewer pipe, ASTM D 3034-DR 35, made from a PVC compound designated 13364-C. Joints were bell and spigot, with an integral elastomeric seal captivated in the bell end. Pipe were obtained from a contractor's stockpile which had been scheduled for a local sewer pipe installation.

Three types of materials were used to embed the pipe. The materials conform to the following classifications, in accordance with ASTM D 2321, and the Unified Soil Classification System (USCS) where appropriate.

**Class I:** Crusher run crushed stone, with 3/8 in. (9.5 mm) maximum size and 6% finer than a No. 200 sieve. This material contained slightly more fines than the 5% maximum specified; however, it was accepted to expedite the installation which was delaying construction of the highway.

**Class II:** Medium to fine sand with a little coarse sand (SP).

**Class III:** Part of the Class III material used was a medium to fine sand with a little gravel and a little silt (SM). This was the in-situ material. The remainder of the Class III material was an imported gravelly coarse to fine sand with a little silt (GM-SM).

**Instrumentation**

Two devices were used to measure deflections (changes in diameter) of the installed pipe. The first device, which was on loan from industry. This deflectometer was used in early deflection measurements; however, it provided erratic results. This malfunction was later traced by the owners to defective waterproofing of the circuitry.

A second deflectometer used in the tests utilized a strain gaged flexible cantilever mechanism, as shown in Figure B-1). This device, termed here the **Cantilever/Strain Gage Deflectometer**, consists of a sled on which a thin spring-steel cantilever beam is mounted. A shoe is fastened to the tip of the cantilever, which in turn contacts the underside of the crown of the pipe. Strain gages are mounted near the base of the cantilever; the magnitude of strain is proportional to deflection. A standard portable single-channel strain-gage readout device is used to measure strain. The Cantilever/Strain Gage deflectometer was used in all tests, after the deflectometer previously described was abandoned.

A trial installation of strain gages was made at the locations shown in Figure B-2, to test waterproofing, instrumentation, and temperature compensation techniques. Results were erratic, and thus lead to refinements which were used to provide a successful long-term installation in the NH 2.1 tests which will be described.

**Installation Details**

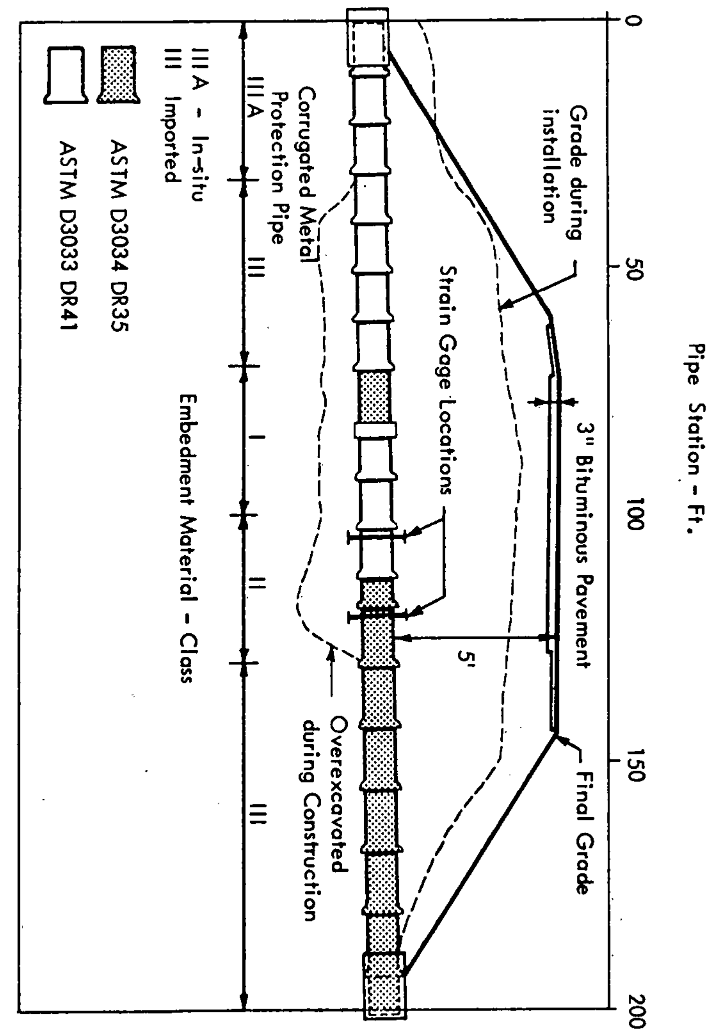
The pipe was installed on 22 and 23 September 1975. Installation was performed by the site contractor and monitored by project and State personnel. The pipe was removed in November 1976, when the bypass was taken out of service.

The two types of pipe were used in alternate sections such that each type of pipe was exposed to approximately the same service and embedment conditions (Fig. B-2). Short sections of corrugated metal pipe were provided at the ends of the pipe for fire and weather protection. In some cases the existing trench bottom was judged unsuitable for the test, and the trench bottom was over excavated from the design profile. The over-excavated areas were replaced with Class III material. Trench width was typically 4.5 to 6.5 ft (1.4 to 2 m); the design width was 4.0 ft (1.2 m), which was selected to accomodate the 18 in. (460 mm) width of the vibratory plate compactor.

All pipe were bedded in a groove which conformed to the lower 120° arch of the pipe. The groove was shaped by a hand-held semi-circular template, cut to the desired radius. Either Class I, II, or III materials were used as embedment (Fig. B-2 and B-3).








Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. B-2 CROSS SECTION OF NH-1 TEST INSTALLATION

Embedment material was tamped under the pipe haunches using the end of a D-handled shovel. The remainder of the embedment material was placed in 6 inch lifts. The Class II material was compaced to a density of 93 to 95% of maximum dry density (AASHTO T-99). The Class III material was compacted to a density of 85 to 91% of maximum dry density (AASHTO T-99). Samples of each embedment material were removed for laboratory characterization and confined compression tests.

In the case of the Class I crushed stone embedment system, a filter layer of Class II material was placed around the stone envelope. The purpose of this layer was to minimize migration of fines from the in-situ material, a Class III material.

The trench was then backfilled with in-situ Class III material, placed by backhoe. It was compacted randomly by pressure applied by the flat end of the backhoe bucket.

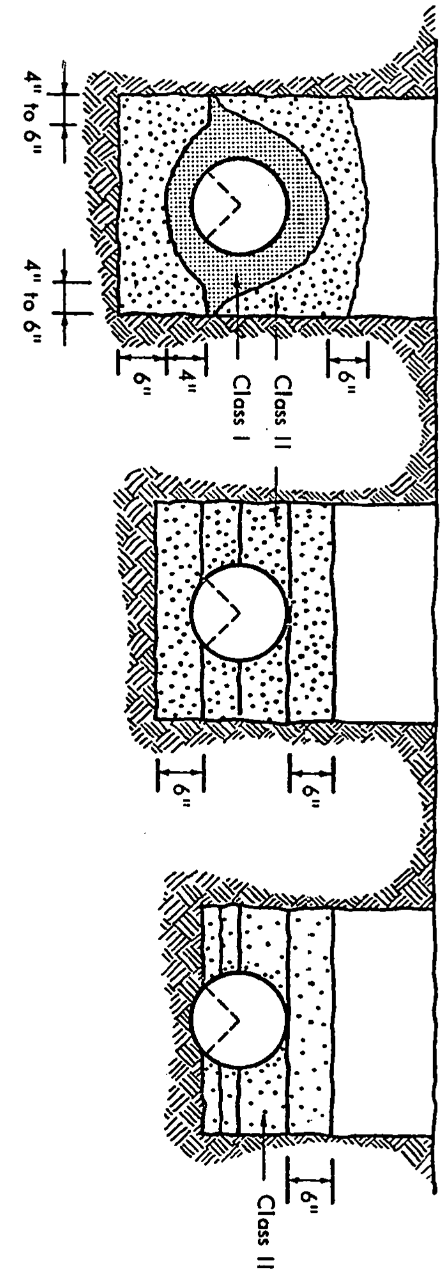
A vibrating-drum compactor (Raygo "Rascal" Dynamic 400) was used for final compaction of the subgrade, including the trench, prior to constructing the pavement. During one experiment, when the pipe had 3 ft (0.9 m) of cover over the crown, the compactor was inadvertently left running in a stationary position for several minutes. The compactor indented the sub-base by about 6 to 12 in. (150 to 300 mm) across the top of the trench. The drum of the compactor was located above the DR 41 pipe in Class II embedment.

Samples of pipe were taken prior to installation, and samples were also removed after dig-up of the installation. They were tested for conformance to the ASTM standard applicable to the pipe.

**Measurements of Pipe Deflections**

Deflection measurements were made soon after the pipe was installed using the Pantograph/Potentiometer Deflectometer. This device provided erratic and irreproducable results. Also, the pipe was installed with a very low slope to meet field conditions, and the pipe began filling with silt immediately after installation.






a. Class I (Two Course Envelope)

b. Class II

c. Class III

Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. B-3 DETAILS OF NH-1 TRENCH INSTALLATIONS

This condition of silting in the pipe and the high water table at each end did not permit further deflection measurements until just prior to removal in November 1976, 14 months after installation. At this time, an improvised hoe was used to clean each length of pipe, just prior to removal, since the silt deposits could not be removed by either fire hoses or water jet sewer cleaning equipment. The Cantilever/Strain Gage deflectometer was used to measure deflections at one foot (305 mm) intervals along the length of the pipe, prior to removal.

**Results**

Overall, the NH-1 installation provided a valuable dry-run for subsequent tests, and an opportunity to dig up pipe for subsequent evaluation after 14 months of burial under heavy interstate traffic. The data obtained was somewhat limited because of the practical field problems of early silting and the malfunction of the deflectometer used for early measurements.

The deflection results obtained just prior to removal of the pipe are summarized in Table B-1. The mean deflection, the standard deviation, and the "maximum" deflection are given in the table. The maximum deflection is estimated from the mean and the standard deviation assuming a normal distribution. It is actually the 99-percentile deflection below which 99% of the deflection measurements are expected to fall.

- The maximum deflection varied from 1.3% to 5.7% except for one pipe length which will be discussed below. This holds for pipe having two different pipe stiffnesses, embedded in either Class I, II, or III materials, whether or not the pipe was under the pavement or the embankment.

- One section of ASTM D 3033-DR 41 pipe delfected significantly at the bell end. The first four deflection readings taken at one foot (300 mm) intervals from the bell end ranged from 6.4 to 26.2%. The probable reason for these high deflections was the excessive vibratory laods experienced during experiments with the Raygo compactor. The compactor was near the highly deflected region when the vibrating drum indented the subgrade 6 to 12 in. (150 to 300 mm).





## TABLE B-1 - SUMMARY OF DEFLECTIONS AT END OF TEST PERIOD AT NH-1

| Pipe | Soil Type (ASTM D 2321) | Deflections (%) | | |
|---|---|---|---|---|
| | | Mean | Standard deviation | Maximum** |
| ASTM D 3033 DR 41 Measured Pipe Stiffness 44 lb/in./in. | Class I | 2.9 | 1.20 | 5.7 |
| | Class II | 6.6 | 7.28 | 23.5 |
| | Class II* | 2.4* | 0.82* | 4.3* |
| | Class III | 1.9 | 1.03 | 4.3 |
| ASTM D 3034 DR 35 Measured Pipe Stiffness 75 lb/in./in. | Class I | 2.0 | 0.30 | 2.7 |
| | Class II | 0.5 | 0.58 | 1.9 |
| | Class III | 0.3 | 0.42 | 1.3 |

* Same condition as previous line but omitting 4 highly deflected points below compactor.

** Maximum deflection is the 99-percentile deflection (mean + 2.33 x standard deviation).

Note: 1 lb/in./in. = 1 psi = 6.9 kPa

- The stiff DR 35 pipe deflected roughly one-half as much as the less stiff DR 41 pipe.

- Both types of pipe deflected more when placed in Class I embedment material than when placed in Class II or Class III soils, although the differences are not great.

- The smallest deflections were found in pipe bedded in Class III soil; however, this pipe was buried under the shoulders away from the traffic lanes of the roadway.

Table B-2 compares laboratory test results on samples removed from pipe as received, to results obtained on samples removed after 14 months of the NH-1 field tests. Following are significant results:

- Dimensions and flattening requirements were within specification.

- Pipe stiffness was significantly higher than specified. This has been consistently noted in other tests made during this project.

- While all control samples passed the impact test requirement, a number of the samples removed after field tests failed.

The significance of these results will be assessed in Appendix D.

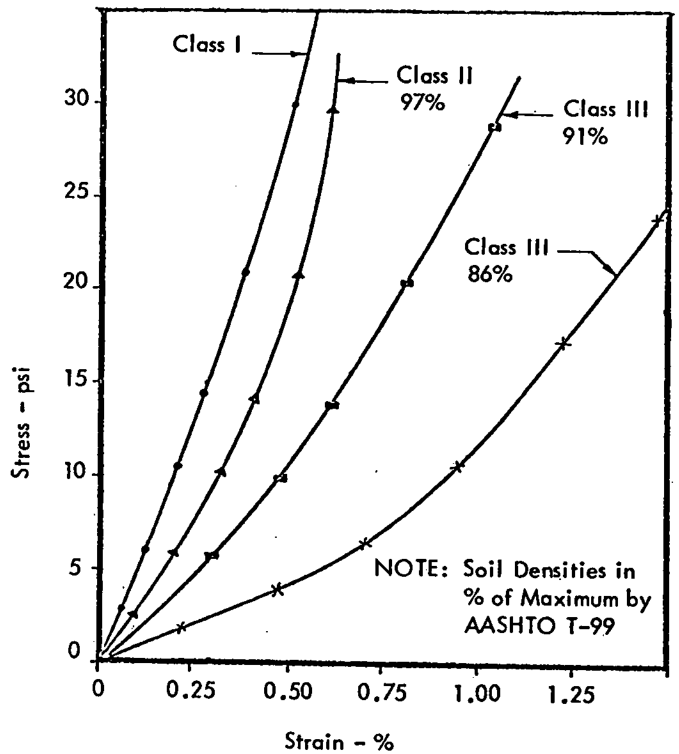
Figure B-4 presents the stress strain curves from the confined compression tests on each type of embedment material. The tests were conducted on samples which were compacted to approximately the same density as was obtained in the field.



**TABLE B-2 - RESULTS OF LABORATORY TESTS ON NH-I PIPE**

| Pipe | Sample | O.D. (in.) | t (in.) | Pipe Stiffness (lb.In./in.) | Flattening | Impact (ft - lb) |
|---|---|---|---|---|---|---|
| PVC ASTM D 3033 DR 41 | Specification | 12.24 ± 0.018 | 0.299 | 28 min. | no failures @ 60% deflection | 220/Tup A V-Block Holder |
| | Control | 12.25 | 0.349 | 51 | all passed | all passed |
| | After Field Test | 12.24 | 0.352 | 52 | all passed | 4 of 6 failed |
| PVC ASTM D 3034 DR 35 | Specification | 12.5 ± 0.018 | 0.36 | 46 min. | no failures @ 60% deflection | 220/Tup A V-Block Holder |
| | Control | 12.50 | 0.385 | 75 | all passed | all passed |
| | After Field Test | 12.48 | 0.381 | 66 | all passed | 5 of 6 failed |

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$




Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$

FIG. B-4 STRESS STRAIN CURVES FROM CONFINED COMPRESSION TESTS ON NH-1 EMBEDMENT MATERIALS





## B.2 New Hampshire 2 (NH-2)

### Objective

The second field study initiated in New Hampshire (NH-2) was undertaken to evaluate installation procedures, pipe-soil interaction, and pipe performance when subjected to substantial earth loads.

### Site

The site for the NH-2 installation was a temporary embankment which was constructed to preload underlying soils prior to installation of a new bridge abutment and approach ramp. The pipe was buried in a 3 ft (0.9 m) thick sand blanket which had been installed to speed the drainage of vertical sand drains drilled into the substrata. The finished embankment was 25 ft (7.5 m) high, with approximately 20 ft (6.0 m) of cover over the pipes. The pipes were not intended to provide any site drainage and were subjected only to incidental moisture.

### Material

Five types of plastic pipe were evaluated in the NH-2 field tests. Two of these were the 12 in. (305 mm) diameter ASTM D 3033 - DR 41, and ASTM D 3034 -DR 35 PVC pipe which were used in the NH-1 test program and described in Section B.1. The other pipe are described below:

- ABS Composite Pipe, 15 in. (381 mm) diameter, ASTM D 2680. Pipe was supplied in 12.5 ft (3.75 m) lengths. Joints were solvent-cemented bell and spigot type. Pipe was obtained from a local distributor's stock.

- Corrugated PE tubing, 8 in. (203 mm) diameter, ASTM F 405, perforated with slots and wrapped with a filter fabric sleeve. Tubing sections were provided in 20 ft (6 m) lengths. Joints were snap-on split couplings, fastened by plastic tape. This tubing was specially manufactured for the project.

- Smooth-wall PE pipe, 16 in. (405 mm) diameter, DR 32, no ASTM specification available. Pipe was supplied in 30 ft (9 m) lengths. Joints were made by fusion welding using special mobile equipment. Pipe was obtained from the manufacturer's stock.

Class III soils (ASTM D 2321) were used for the pipe embedment. An in-situ fine sand, which had been installed as the drainge blanket for the embankment, was used for embedding most of the installation. In two locations, a different (but similar) fine sand was imported from a local supplier.

**Special Instrumentation**

The Pantograph/Potentiometer Deflectometer used in NH-1 studies, and described earlier in Section B.1 was used in early tests for deflection. Later deflection measurements were obtained using the Cantilever/Strain Gage Deflectometer, also described in Section B.1.

A hose settlement gage was installed in the trench near one pipe line to monitor settlements of the embankment.

**Installation Details**

The pipe were installed between 30 October and 10 November 1975. The embankment was completed in December of that year. Installation was by State labor, who did not have experience in pipe installation; the installation was monitored full-time by both project and State engineering personnel.

The installation was scheduled to accommodate ongoing embankment construction, which extended several hundred feet to the east of the site. One half of the 140-ft (42 m) width of the site was kept open to construction traffic at all times. Hence, about 70 ft (21 m) of trench was excavated at one time, then the pipe was installed and the trench was backfilled. Immediately after backfilling, the site was used as a haul road for vehicles constructing the embankment. Because of the alternating installation procedure, all pipe were subjected to this very heavy construction traffic.



Details of the installation are summarized in Figure B-5. Each trench provided approximately 4 ft (1.2 m) of earth cover over the crown of all pipe. Trench width was varied for each pipe, to provide sufficient clearance between the pipe and the trench wall to accommodate the 18-in. (450 mm) wide vibratory compactor.

Pipe were arranged in the trenches as follows:

- The two types of PVC pipe each occupied one-half of the length of one trench. They were connected by a specially fabrciated sleeve with O-ring gaskets which were selected to accommodate the outside diameter of each type of pipe.

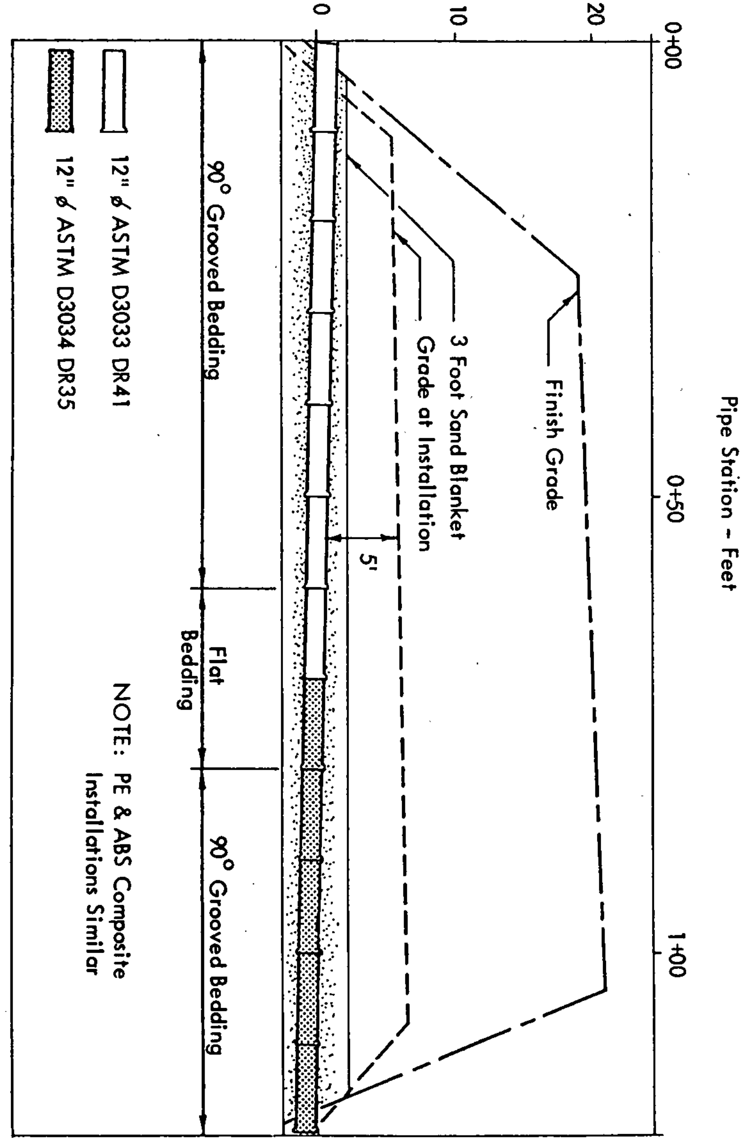
- The ABS composite pipe was installed over the full length of one trench.

- Corrugated PE tubing and smooth-wall PE pipe each occupied one-half of the length of one trench. They were connected by a vertical wood baffle arrangement which capped the end of the larger smooth-wall pipe, and which contained a hole for the insertion of the smaller tubing.

All pipe were connected to permit passage of the deflectometer from one end of the trench to the other.

A portion of each type of pipe was placed on flat bedding; the remainder was placed in a $90^{o}$ bedding groove which was shaped with a hand-held template, conforming to the outside diameter of the pipe. In each case, embedment material was then placed and tamped under the pipe haunches. Difficulty was encountered in compacting haunching under the corrugated tubing because of weight and flexibility.

The material used to embed the pipe was the in-situ sand blanket. In two cases the pipe elevation was above the top of the blanket. When this condition arose, imported Class III embedment materials were used. Embedment materials were placed and compacted in 6 in. (150 mm) lifts up to 6 in. (150 mm) above the




Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. B-5 INSTALLATION DETAILS OF PVC PIPE AT NH-2



crown. Measured density varied between 92 and 95% of maximum dry density (AASHTO T-99). The installation cross-section was the same as for the Class III material installed at NH-1 (Fig. B-3). The remainder of the backfill was dumped. Samples of embedment material were removed for laboratory characterization and confined compression tests.

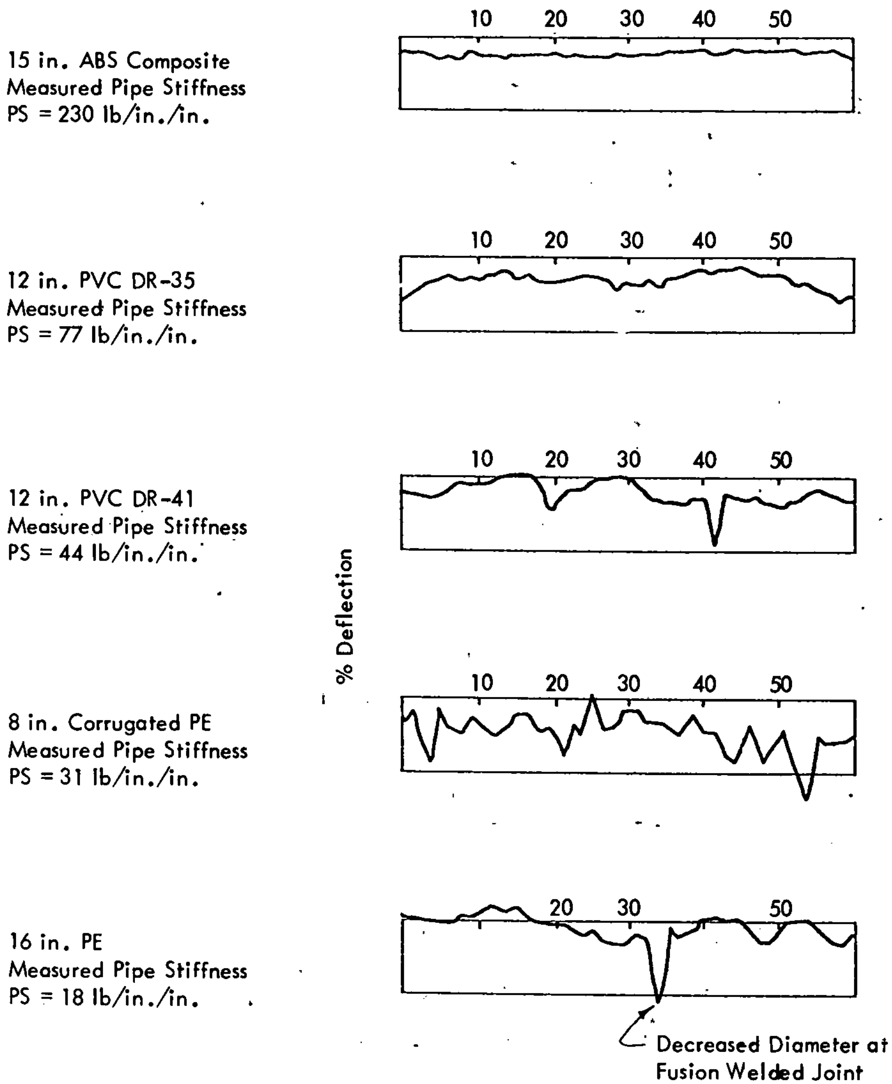
Early deflection measurements were made using the Pantograph/Potentiometer Deflectometer, and the erratic behavior noted in NH-1 persisted despite an on-site review of the problem by the inventor. The Cantilever/Strain Gage Deflectometer was used for deflection measurements in later tests with good reproducibility.

The hose settlement gage was read prior to backfill, and 4 months after the embankment was in place.

The temporary embankment over the pipe was removed between 30 March and 5 April 1976. At this time portions of each pipe type, which had been located under the maximum cover, were removed for laboratory testing. After these pipe samples were removed, the installation was redesignated NH-2.1. The removed pipe were replaced with new pipe, and the permanent embankment was installed. This provided a final earth over of 23 ft (6.9 m) above the pipe. The NH-2.1 test program will be discussed in Section B.3.

**Results and Discussion**

Typical deflection profiles of the NH-2 pipe obtained prior to removal of the temporary embankment are shown in Figure B-6. The plots are arranged in order of decreasing pipe stiffness. Comparison of the plots indicates a trend of increasing deflection and increasing variation in deflection with decreasing stiffness. Furthermore, the corrugated PE tubing shows a pronounced increase in variation in deflection. It appears that the lack of longitudinal stiffness caused by the corrugation patterns makes the pipe more sensitive to installation variations than smooth-wall pipe having either greater or lesser stiffness.




Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 lb = 2.2 kg; 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. B-6 DEFLECTION PROFILES OF NH-2 TEST PIPE WITH 20 FT OF COVER



A summary of deflection data obtained prior to removal of the temporary embankment is presented in Table B-3. Following are significant results:

- The 99-percentile deflection varied from 1.3 to 5.5% for all pipe tested.
- The mean, standard deviation, and maximum deflection all increased with decreasing pipe stiffness except for the smooth-wall PE pipe, which had the lowest pipe stiffness.
- Although no early deflection data are available for confirmation, the low deflection of the smooth-wall PE pipe, which was the most flexible and which had the greatest diameter, may have been the result of initial ovalling in a vertical direction during placement and compaction of the embedment material.

Analysis of the above data indicates that there was no significant difference between pipe which were installed in a flat bedding and then haunched, and pipe which were installed in a grooved bedding and then haunched.

The hose settlement gage measurements showed that the settlement of the center of the embankment relative to its sides was negligible during the period of test.

Table B-4 summarizes the results of laboratory tests of samples removed from pipe as received, and after the 6 month test duration of NH-2. Following are significant results:

- Dimensions, flattening, and impact requirements were all within specified limits.
- Pipe stiffness of both types of PVC pipe were significantly higher than specified because wall thickness and modulus of elasticity were higher than specified.

## TABLE B-3 - SUMMARY OF PIPE DEFLECTIONS AT NH-2

| Pipe | Diam. (in.) | Measured Pipe Stiffness lb/in./in. | Deflections (%) Mean | Standard Deviation | Maximum* |
|---|---|---|---|---|---|
| ABS Composite | 15 | 230 | 0.8 | 0.2 | 1.3 |
| PVC DR 35 | 12 | 77 | 1.3 | 0.4 | 2.2 |
| PVC DR 41 | 12 | 44 | 1.7 | 0.6 | 3.1 |
| Corrugated PE | 8 | 31 | 2.9 | 1.1 | 5.5 |
| Smooth Wall PE | 16 | 18 | 0.8 | 0.6 | 2.2 |

* Maximum deflection is the 99-percentile deflection (mean + 2.33 x standard deviation).

Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 lb = 2.2 kg; 1 in. = 25.4 mm; 1 ft = 0.3048 m

## TABLE B-4 - RESULTS OF LABORATORY TESTS ON NH-2 PIPE

| Type | Sample | OD (in.) | t (in.) | Pipe Stiffness (lb/in./in.) | Flattening | Impact (ft - lb) |
|---|---|---|---|---|---|---|
| ABS Composite ASTM D 2680 | Specification | 17.62 ± 0.09 | None | 200 min. | No failures @ 7-1/2% Deflection | None |
| | Control | 17.63 | 1.41 | 242 | all passed | - |
| | After field test | 17.63 | 1.41 | 198 | all passed | - |
| PVC ASTM D 3034 DR 35 | Specification | 12.5 ± 0.018 | 0.360 min. | 46 min. | No failures @ 60% deflection | 220/Tup A V-Block Holder |
| | Control | 12.50 | 0.385 | 75 | all passed | all passed |
| | After field test | 12.50 | 0.387 | 78 | all passed | all passed |
| PVC ASTM D 3033 DR 41 | Specification | 12.24 ± 0.018 | 0.299 min. | 28 min. | No failures @ 60% deflection | 220/Tup A V-Block Holder |
| | Control | 12.25 | 0.349 | 51 | all passed | all passed |
| | After field test | 12.25 | 0.324 | 40 | all passed | all passed |
| Corrugated PE ASTM F 405 | Specification | ID 8.0 ± 0.24 | None | 30 min. | None | None |
| | Control | 8.13 | - | 32 | - | - |
| | After field test | 8.15 | - | 35 | - | - |
| Smooth Wall PE DR 32 | No Specification | | | | | |
| | Control | 15.97 | 0.539 | 18 | - | - |
| | After field test | 16.10 | 0.544 | 18 | - | - |

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$

- Pipe stiffness of the control ABS Composite pipe was 20% greater than the specified minimum; that of the pipe removed after field test was 1% below minimum.

These test results will be evaluated further in Appendix D.

The stress-strain curve for the embedment material is the same as that for the Class III soil in Figure B-4.

## B.3 New Hampshire 2.1 (NH-2.1)

### Objective

The NH-2.1 field test was undertaken to evaluate the time-dependent pipe-soil interaction behavior of plastic pipe under wheel loads applied at shallow burial, and under deep burial conditions. The study was also designed to determine the effects of omitting embedment material from the haunch zone, and the use of dumped embedment having a low density backfill. The NH-2.1 installation was partly new, and partly a continuation of the NH-2 study.

### Site

The NH-2 site, described in Section B.2, was used for the NH2.1 test program. The installation was designated starting at the time the central sections were removed from the NH-2 pipe. At this time, the embankment which had been installed during NH-2 had been removed to provide access for construction of a reinforced concrete bridge abutment at the west end of the installation.

### Material

While five types of pipe were removed from the NH-2 test, only three types of pipe were used as replacement, as follows:



- ABS Composite Pipe. Two lengths of new pipe were used to replace the two lengths which had been removed.

- Corrugated PE Tubing. Approximately 24 ft (7.3 m) of tubing was installed to replace the smooth-wall PE and corrugated PE sections which had been removed.

- PVC. Two lengths of DR 41 pipe were used to replace once length each of DR 35 and DR 41 pipe which had been removed.

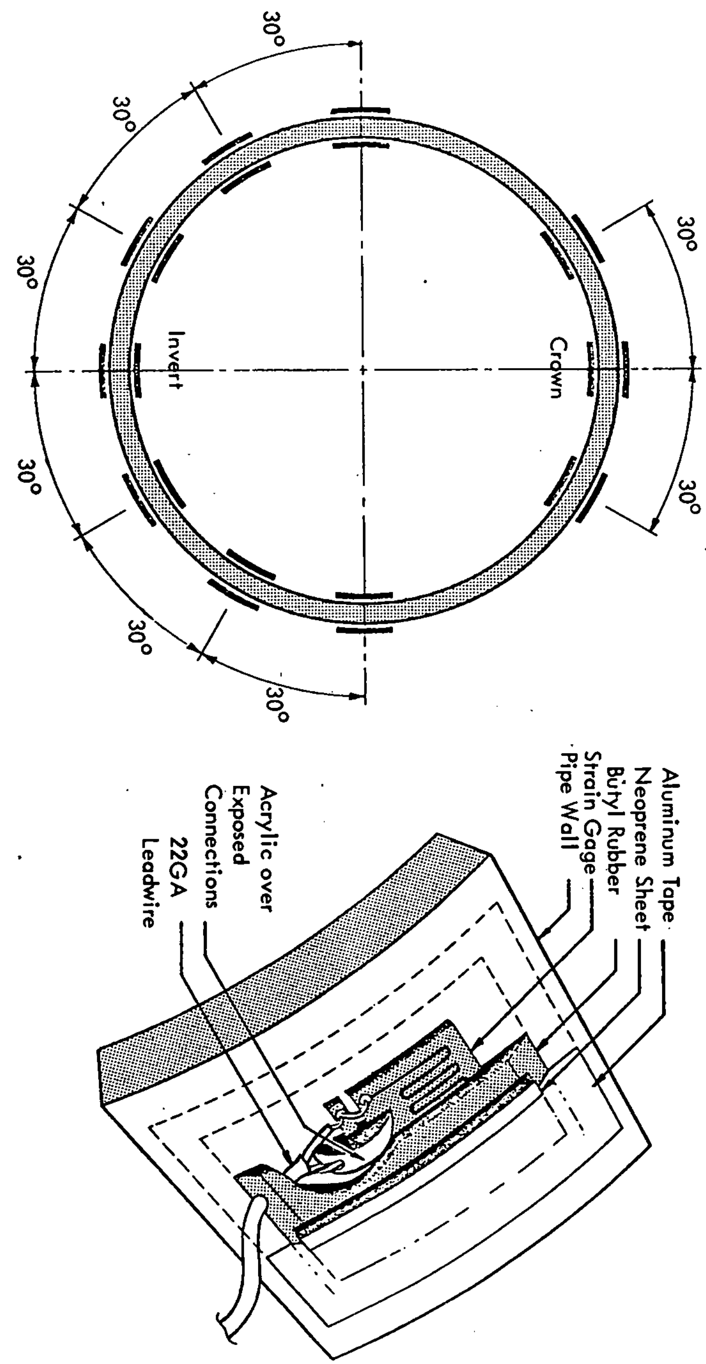
These replacement pipe were similar to the pipe of the same type described previously in Sections B.1 and B.2.

### Instrumentation

The PVC pipe installed as part of NH-2.1 was instrumented with three "rings" of electrical resistance foil strain gages. Ring 1 contained 10 gage pairs (one gage inside, opposite one gage outside), located as shown in Figure B-7. Rings 2 and 3 each had 4 gage pairs, mounted at the crown, invert, and springlines. All gages were oriented to measure circumferential strain. Rings 1 and 2 were installed in the test sections where haunching material was omitted from the pipe embedment. Ring 3 was placed in an area in which haunching material was placed and compacted under the pipe.

Temperature compensation was provided by dummy gages, mounted on narrow rings of pipe. The rings were surrounded loosely by low density plastic foam, and placed in waterproof boxes made from acrylic plastic sheet. The boxes were surrounded by foam, and placed in the backfill about 3 ft (0.9 m) from the pipe springline.

Two temperature sensors (bondable resistance thermometers) were installed to monitor the pipe and soil temperatures. One sensor was installed inside the PVC pipe near Ring 1, the other was installed with a ring of dummy gages.




a. Ring 1 Strain Gage Locations

b. Typical Gage Installation Details
Showing Waterproofing

FIG. B-7 STRAIN GAGE LAYOUT AND INSTALLATION DETAILS AT NH-2.1





Details of a gage installation are shown in Figure B-7. All gages were mounted in close conformance with recommendations of the gage manufacturer. An epoxy adhesive was used to attach the gages. Extreme care was taken to apply the same pressure and temperature to all gages during the curing process. Prior laboratory investigations showed that acceptable temperature compensation could only be obtained provided that gages be applied at the same pressure and temperature during curing. Furthermore, suitable compensation required that dummy gages be mounted on full rings of pipe and located on the same surface (inside or outside) and with the same orientation (circumferential) as the active gages.

Waterproofing was also applied in accordance with recommendations of the manufacturer, as shown in Figure B-7b. All leads from strain gages and sensors were terminated in a weathertight box, some 70 ft (21 m) from the installation. Each gage was read individually by connecting appropriate leads to a standard portable strain gage readout device. A switching box was purposely not used, to minimize any possible long-term shifts in calibration.

The Cantilever/Strain Gage Deflectometer was used for all deflection measurements.

## Installation Details

The NH-2.1 installation was generally similar to the NH-2 installation described earlier. The new pipe were installed in the period 27 to 30 April 1976. After installation, the top of the trench was trafficked by construction vehicles which were involved in the construction of the bridge abutment immediately adjacent to the installation. On completion of the abutment, the embankment was again brougnt to final grade and paved. This is now a permanent installation with approximately 23 ft (6.9 m) of cover over the pipe.

All new pipe were installed entirely on flat bedding, which was the in-situ soil at the bottom of the trench. Embedment material was placed and hand tamped under the pipe haunches for one-half of each pipe length. This step was purposely omited for the other half-length of each pipe.

The NH-2.1 pipes were all embedded in a Class III material which was nearly identical to the Class III imported material used for the NH-2 test. The backfill material was placed (dumped) to the crown of the pipe and lightly compacted with shovels and random foot traffic. An average density of 80% (AASHTO T-99) was achieved except on the instrumented PVC pipe where heavy foot traffic during installation resulted in an average density of 89% near the crown. At the time of installation the trench provided nominally 4 ft (1.2 m) of cover over the crown of all pipe.

Strain gage readings and pipe deflections were measured during the installation, as follows:

1. Pipe in place, no embedment material.

2. Pipe backfilled to crown with embedment material.

3. Trench backfilled.

After the initial installation, the strains and pipe deflections were measured after a period of construction traffic, and then at convenient intervals before and after the full embankment was completed. The most recent deflection readings were taken on 23 August 1977. The last set of strain readings was taken on 21 October 1978. Deflections and strains were also measured during wheel load tests performed on 28 June 1976. A truck carrying a gross load of 55,000 pounds (25,000 kg) with 44,000 pounds (20,000 kg) on the tandem rear axle was located such that a pair of wheels carrying 10,800 pounds (5,000 kg) was located over the gaged locations. Deflection and strain readings were taken with the wheel located directly over each ring of gages.

**Results**

Table B-5 summarizes the deflection data obtained and Figure B-8 is a graphical summary of these results. Deflections increased significantly during each stage of construction. The most significant increases were caused by the backfilling of



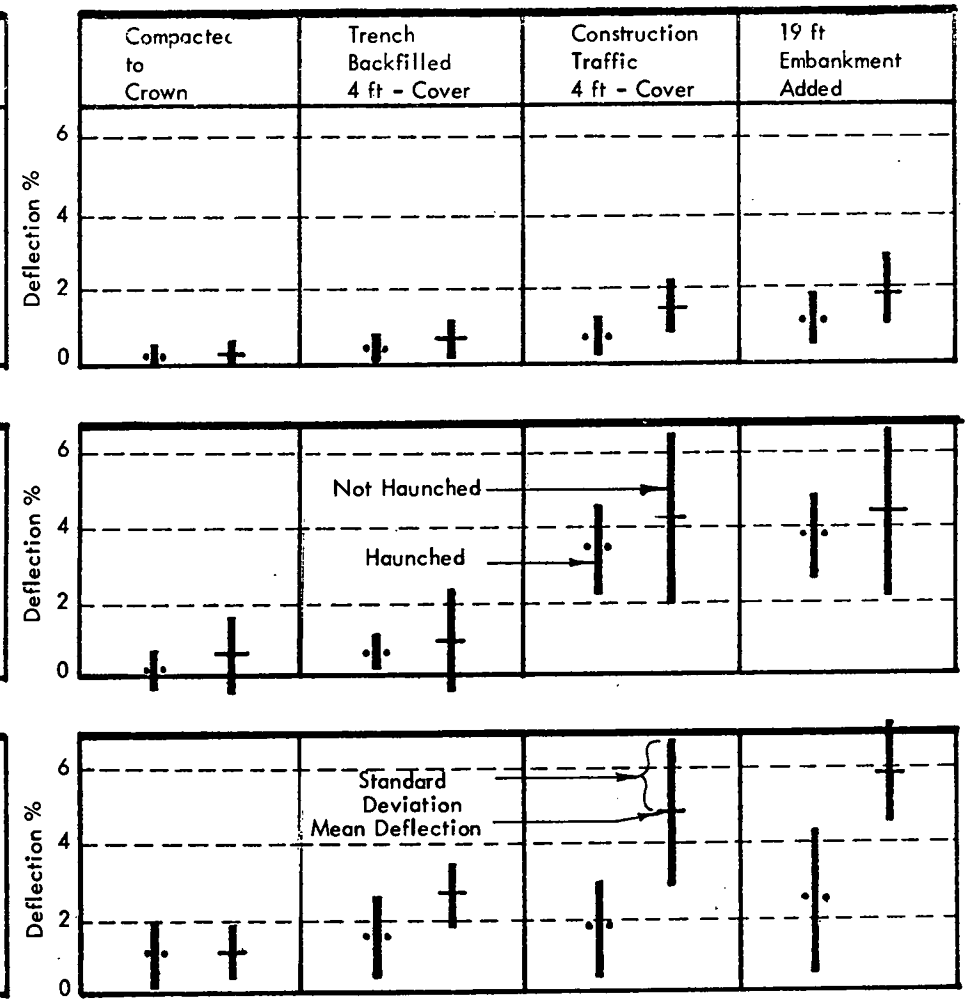


TABLE B-5 - SUMMARY OF DEFLECTIONS AT NH-2.1

| | | Deflections - % | | | | | |
|---|---|---|---|---|---|---|---|
| | | Haunched | | | Not Haunched | | |
| Pipe | Construction Stage | Mean | Standard Deviation | Maximum* | Mean | Standard Deviation | Maximum* |
| ABS Composite | Fill to Crown | .11 | .04 | .20 | .16 | .04 | .25 |
| | Trench Backfilled | .35 | .20 | .82 | .64 | .27 | .27 |
| | After Construction Traffic | .58 | .41 | 1.53 | 1.46 | .16 | .298 |
| | Full Embankment | .96 | .43 | 1.96 | 1.75 | .71 | 3.40 |
| PVC DR 41 | Fill to Crown | .08 | .17 | .48 | .42 | .82 | 2.33 |
| | Trench Backfilled | .69 | .28 | 1.34 | .89 | 1.16 | 3.59 |
| | After Construction Traffic | 3.27 | .98 | 5.55 | 4.37 | 2.41 | 9.98 |
| | Full Embankment | 3.44 | .98 | 5.72 | 4.45 | 4.41 | 10.10 |
| Corrugated PE | Fill to Crown | .94 | .84 | 2.89 | .96 | .61 | 2.38 |
| | Trench Backfilled | 1.43 | .95 | 3.64 | 2.57 | .87 | 4.59 |
| | After Construction Traffic | 1.43 | 1.18 | 4.17 | 4.60 | 1.76 | 8.69 |
| | Full Embankment | 2.24 | 1.87 | 6.59 | 5.68 | 1.41 | 8.96 |

* Maximum deflection is the 99-percentile deflection (mean + 2.33 x standard deviation).

| Pipe | Pipe Stiffness lbs/in./in. |
|---|---|
| 15 in. ABS Composite | 252 |
| 12 in. PVC DR 41 | 38 |
| 8 in. PE Corrugated | 32 |




Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 lb = 2.2 kg; 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. B-8 DEVELOPMENT OF DEFLECTIONS DURING CONSTRUCTION - NH2.1

the trench to a cover height of 4 ft (1.2m), and by construction vehicles which trafficked the site shortly after installation. A significant result is that the addition of the full embankment, which represents an addition of 19 ft (5.7 m) of earth load, caused less change in deflections than did any of the earlier events. Subsequent measurements taken up to 15 months after adding the embankment have shown all deflections to be essentially constant since the embankment was added. The sections of pipe for which haunching was omitted showed significantly higher mean deflections and standard deviations than observed for the pipe which were haunched.

Trends in the strain gage data for the PVC pipe was consistent with those observed for deflections discussed above. Figure B-9 shows the increase in ring compression and ring bending strains at the invert of Ring I, which was located where haunch material was omitted. The trends are similar to those shown by deflections, the major increases occurred during the construction stages. The following results are particularly significant:

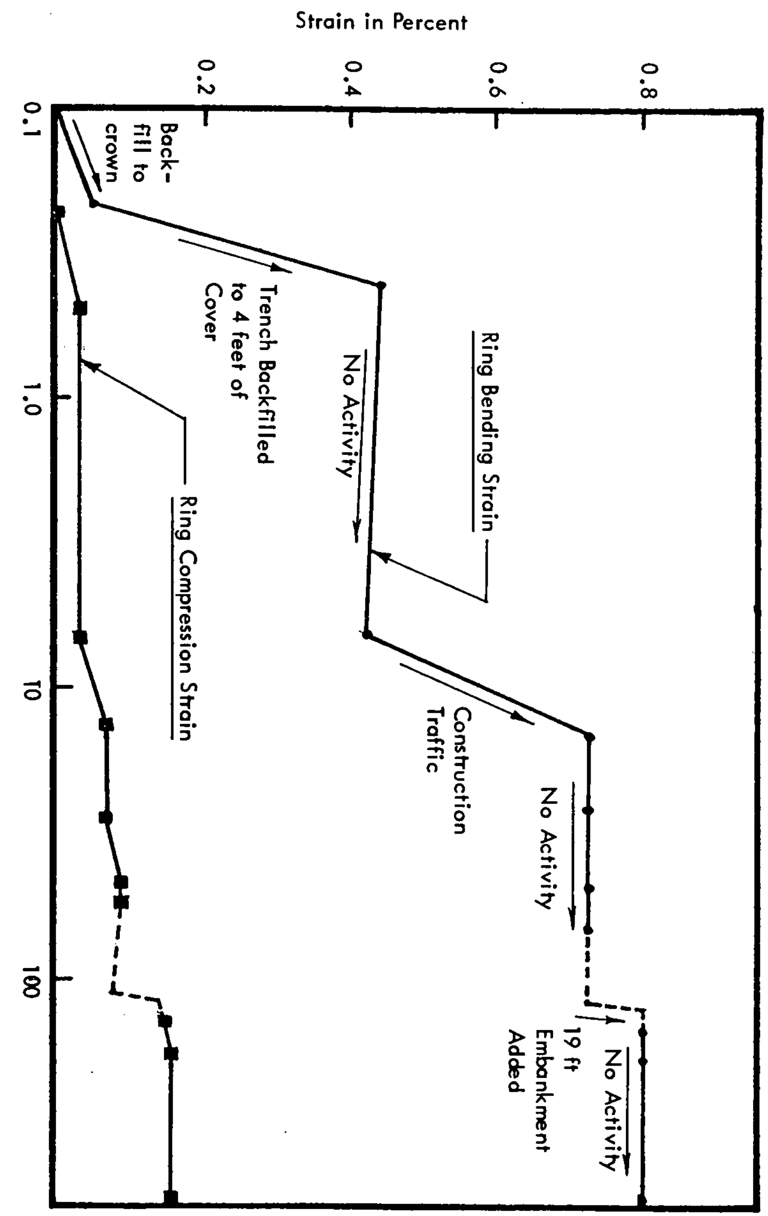
- The bending strains are essentially stable between construction stages. This indicates that a state of constant bending strain exists when load is stabilized.

- The ring compression strains are small relative to bending strains. The compression strains increase with time after each construction event; they continue to increase slightly even after construction was complete. The increasing compression strain indicates that the pipe is in a state of compressive creep. This will be discussed in more detail later.

Figure B-10 shows the distribution of ring bending and ring compression strains around the circumference soon after the completion of the embankment. The following are significant findings:

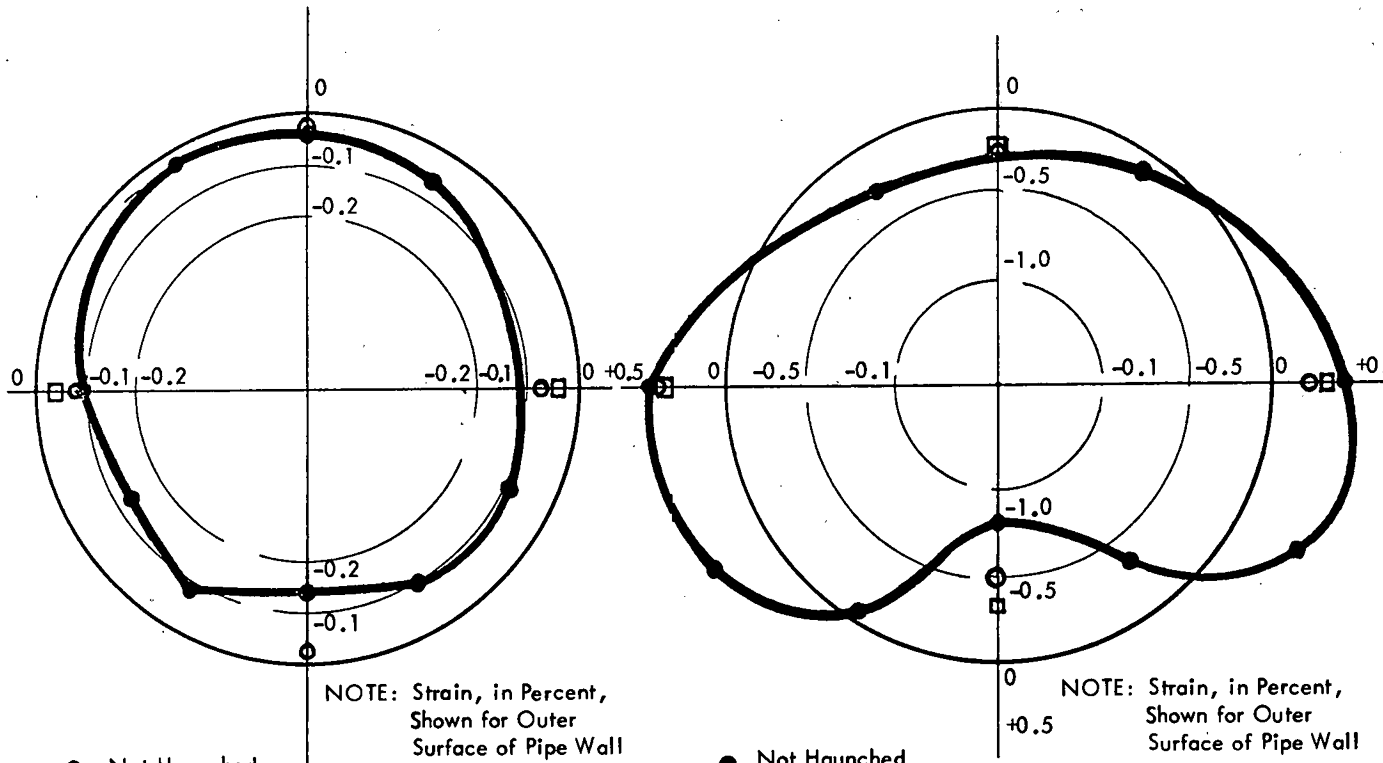
- The distribution of bending strains is rational; the outer surface at crown and invert is in flexural compression, and the outer surfaces at springlines are in flexural tension. The distribution is reasonably symmetrical about a






Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. B-9 DEVELOPMENT OF STRAINS AT NH2.1 - UNHAUNCED PVC PIPE




● Not Haunched
○ Not Haunched
□ Haunched
– Initial Compaction ~ 80% +
– Class III Embedment

a. Ring Compression Strain

● Not Haunched
○ Not Haunched
□ Haunched
– Initial Compaction ~ 80% +
– Class III Embedment

b. Ring Bending Strain

Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. B-10 STRAINS IN PVC PIPE UNDER 23 FT OF COVER AT NH 2.1

vertical axis; this symmetry is expected, and provides a check of validity of the data.

- The largest bending strains occur at the invert, as expected. The peak strains were least for the haunched pipe and greatest for the pipe in which haunching was omitted. The largest bending strain of 0.8%, which occurred in the unhaunched section, is twice that measured for haunched pipe.

- Ring compression strains act around the full circumference of the pipe, and they are more or less uniform. They are much smaller than bending strains.

Deflections from the live load test were too small to measure. This test was performed after the period of construction traffic which had already produced large deflection decreases. Peak bending stresses occurred at the springlines during the live load tests, but were very low, approximately 45 psi (310 kPa). Thrust stresses were also low, approximately 25 psi (170 kPa). These stresses were calculated from measured strains and the short-term modulus of elasticity of the plastic, as determined in short-term ring bending tests.

Temperature measurements showed that the temperature inside the pipe and in the earth, 3 ft (0.9 m) from the pipe, were nearly the same. During the first summer, prior to embankment construction, the ground temperature in the trench was stable at about 65°F (18°C). After completion of the embankment, temperature decreased to 55°F (13°C) and has remained stable.

Results of laboratory tests made on control samples of pipe used at NH-2.1 are shown in Table B-6. All samples met specifications. These results will be evaluated further in Appendix D.

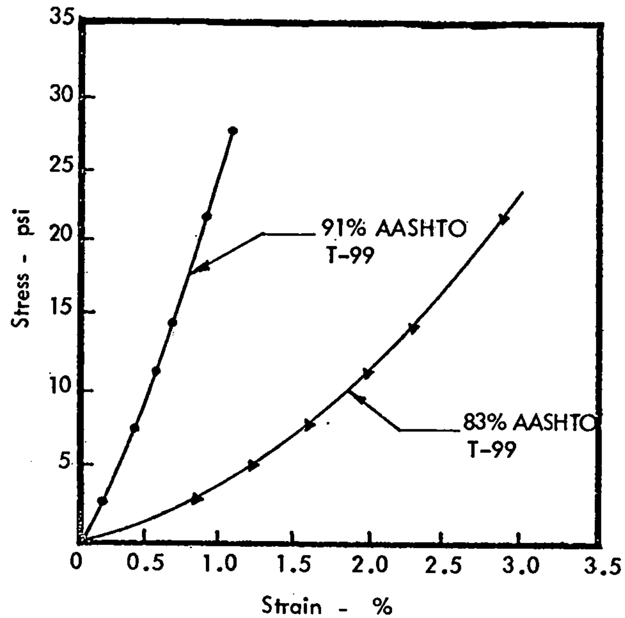
Figure B-11 shows the stress-strain curve for the embedment material at 80% of maximum dry density (AASHTO T-99). For comparison, the curve for the same material at 90% of maximum density is reproduced from Figure B-4.



**TABLE B-6 - RESULTS OF LABORATORY TESTS ON NH-2.1 PIPE**

| Type | Sample | OD (in.) | t (in.) | Pipe Stiffness (lb/in./in.) | Flattening | Impact (ft - lb) |
|---|---|---|---|---|---|---|
| PVC ASTM D 3033 DR 41 | Specification | 12.24 ±0.018 | 0.299 min. | 28 min. | No failures @ 60% deflection | 220/Tup A V-Block Holder |
| | Control | 12.24 | 0.313 | 38 | all passed | all passed |
| ABS Composite ASTM D 2680 | Specification | 17.62 ±0.07 | None | 200 min. | No failures @ 7.5% deflection | None |
| | Control | 17.64 | 1.41 | 242 | all passed | - |
| Corrugated PE ASTM F 405 | Specification | ID 8.0 ±0.24 | None | 30 min. | None | None |
| | Control | 8.13 | - | 32 | - | - |

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$




Note: I psi = 6.9 kPa

FIG. B-11 CONFINED COMPRESSION STRESS STRAIN CURVES ON EMBEDMENT SAND AT NH-2 AND 2.1





## B.4 Maine - I (ME-I)

### Objective

The ME-I field test was undertaken to evaluate the behavior and performance of several types of plastic pipe systems when subjected to traffic under shallow burial conditions.

### Site

The ME-I site was an unpaved cross-over road which connects the northbound and southbound lanes of Interstate I-95 in Old Town, Maine. A state road maintenance facility was located near the site, hence the cross-over was used frequently by state vehicles, including those hauling sand to the stock pile at the facility. In winter, the site was trafficked frequently by road sanding and plowing equipment.

### Materials

Six different types of pipe were evaluated in the ME-I installation. Five were the same as used in NH-2, and described in Sections B.I and B.2. The other pipe was a smooth-wall ABS pipe, described below:

- Smooth-wall ABS sewer pipe, 6 in. (152 mm) diameter, ASTM D 2751 - DR 35. Pipe were supplied in 12.5 ft (3.8 m) lengths. Joints were slip-fit, bell and spigot type, intended for solvent-bonded connections. The pipe was obtained from available stock of a local distributor.

Circular perforations were field drilled into two pieces of the smooth-wall ABS sewer pipe, and two pieces of DR 35 PVC sewer pipe. The perforation pattern used is similar to that required by AASHTO for conventional underdrain pipe, and is shown in Figure B-12.

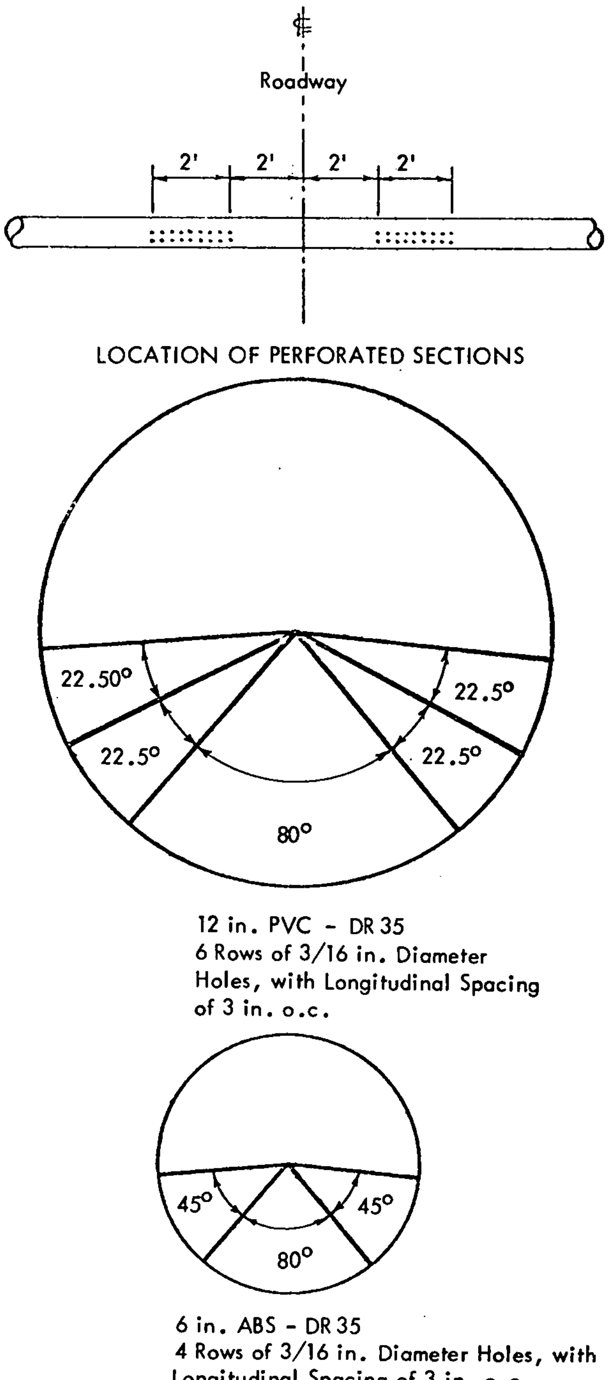



FIG. B-12 PERFORATED PIPE SECTIONS FOR ME-1 STUDY

Note: 1 psi = 6.9 kPa
1 in. = 25.4 mm
1 ft = 0.3048 m



**Instrumentation**

One section of the DR 41 PVC pipe was instrumented with strain gages. The gages were installed by Maine personnel.

Deflection measurements at the time of installation were made using the Pantograph/Potentiometer Deflectometer, which had been repaired after the NH-2 installation. All later measurements were made with the Cantilever/Strain Gage Deflectometer.

**Installation Details**

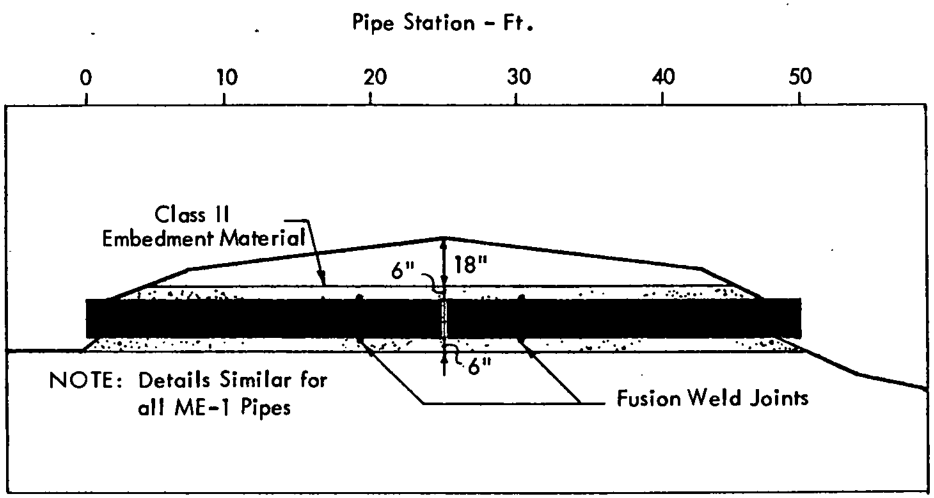
The pipe were installed during the period 18 November to 2 December 1975, and removed in May 1977. During this time the installation was subjected to frost penetration of 4 to 5 ft (1.2 to 1.5 m), and traffic by maintenance vehicles having gross weights up to 6,000 lbs.

Trenches were cut across the cross-over roadway, a distance of approximately 50 ft (15 m). Trenches were excavated 3 ft (0.9 m) wider than the outer diameter of each type of pipe to accomodate the available 18 in. (456 mm) wide vibratory plate compactor used to compact the embedment materials. Trench depth was selected to provide an earth cover of about 2 ft (0.6 m) above the crown of each type of pipe. Details are shown in Figure B-13.

The in-situ embankment was primarily a Class II (ASTM D 2321) coarse sand material, except that it contained some cobbles. An imported Class II sand was used for pipe embedment.

Six inches of the imported Class II bedding material was placed on the trench bottom and compacted. One half of each pipe run, was laid on the flat bedding so prepared. The other half was installed in a bedding groove which was cut by template to conform to the lower 90° arc of the pipe.

The 50-ft (15 m) long smooth-wall PE pipe was installed in one piece. The two fusion-welded joints, which had been made previously at NH-2 using the special




Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. B-13 ME-1 INSTALLATION DETAILS FOR SMOOTH WALL PE PIPE



joining equipment, were spaced about 7 ft (2.1 m) apart, and placed to coincide with the wheel paths. Other pipe were connected as appropriate. The smooth-wall ABS joints, which are intended to be solvent cemented in the sewer application, were left dry since a watertight cemented joint is not required for underdrain applications.

Embedment material was placed under pipe haunches for the full length of the pipe, and compacted by tamping. Embedment material was then placed in 6 in. (150 mm) lifts to a total depth of 6 in. (150 mm) above the crown of each pipe. Each lift was compacted to 90 to 94% of maximum dry density (AASHTO T-99). The remainder of the backfill was dumped, and left to be compacted by service traffic.

Deflection was measured during installation, but the data was discarded due to problems with the Pantograph/Potentiometer Deflectometer. Deflections were measured on two subsequent occasions during which the wheel loading tests, described below, were performed. The Cantilever/Strain Gage Deflectometer was used in these tests, and it gave consistent results.

Load tests were conducted on 3 December 1975, 18 May 1976 and 17 May 1977. The installation had been subjected to traffic prior to the tests. A State maintenance vehicle was used for these tests. The measured gross vehicle weight was 55,000 lb (25,000 kg) and the tandem rear axle weighed 42,000 lbs (19,000 kg). The pipe were removed immediately after completion of the 1977 load tests.

**Results**

The deflection data obtained 6 months and 18 months after installation are summarized in Table B-7. Following are significant findings:

- Deflection of all pipe, except the very stiff ABS Composite pipe increased over the 1 year duration between tests. This may be caused by continued traffic over the unpaved installation, frost effects, or both. Analysis of the gradation of the embedment soil indicates that the material is not highly frost susceptible.

## TABLE B-7 - SUMMARY OF DEFLECTION DATA AT ME-I

| Pipe | Date of Test | Measured Pipe Stiffness | Embedment % Max. Dry Density AASHTO T-99 | Deflection - % Mean | Standard Deviation | Maximum* |
|---|---|---|---|---|---|---|
| ABS Composite | May 1976<br>May 1977 | 250 | 90 | 1.7<br>1.5 | 0.3<br>0.2 | 2.4<br>2.0 |
| PVC DR-35 | May 1976<br>May 1977 | 76 | 92 | 1.6<br>2.5 | 0.6<br>0.7 | 3.0<br>4.1 |
| ABS Smooth Wall | May 1976<br>May 1977 | 55 | 91 | 3.1<br>5.1 | 0.7<br>0.6 | 4.7<br>6.5 |
| PVC DR-41 | May 1976<br>May 1977 | 45 | 94 | 0.8<br>1.4 | 0.4<br>0.7 | 1.7<br>3.0 |
| PE Corrugated | May 1976<br>May 1977 | 30 | 91 | 4.7<br>8.5 | 1.4<br>1.3 | 8.0<br>11.5 |
| PE Smooth Wall | May 1976<br>May 1977 | 18 | 93 | 4.4<br>6.9 | 0.6<br>0.9 | 5.8<br>9.0 |

* Maximum deflection is the 99-percentile deflection (mean + 2.33 x standard deviation).

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$



- The magnitude of deflection varied inversely with pipe stiffness except for the PVC DR 41 pipe and the smooth-wall PE pipe. However, the embedment density obtained around the PVC DR-4 pipe was somewhat higher (94% of AASHTO T-99) than that obtained around other pipe (90 to 92% of AASHTO T-99). The PE pipe may have ovalled vertically during installation.

Analysis of the data shows that differences in deflection resulting from the grooved flat bedding were negligible. However, all pipe were "haunched" by tamping embedment material below pipe haunches prior to placing embedment. This shows that proper hand haunching can negate any significant excessive bending which would otherwise develop when a pipe is supported on flat bedding.

Wheel load tests, which involved a single application of load to the surface of each trench, produced deflections which were too small to measure (less than 1%). The following results were obtained during wheel load tests on the PVC DR 41 pipe installation which was instrumented with strain gages:

- During the December 1975 load tests, the peak bending stress was 250 psi (1,700 kPa), and occurred at the crown. The average ring compression stress at the springline was 60 psi (410 kPa). Peak combined stress was 200 psi (1,360 kPa) in tension and 300 psi (2,040 kPa) compression at the crown.

- During the 18 May 1978 load test, the peak bending stress was 115 psi (780 kPa), and the springline axial strains were 45 psi (300 kPa).

- The gages became inoperable prior to the 1977 load tests.

Test results for conformance of samples to applicable specifications are summarized in Table B-8. Significant findings are as follows:

- All samples met specification dimensional requirements except that the outside diameter of the ABS perforated pipe was slightly low.

TABLE B-8 - RESULTS OF LABORATORY TESTS ON ME-1 PIPE

| Pipe | Sample | OD (in.) | t (in.) | Stiffness Factor (lb/in./in.) | Flattening | Impact (ft - lb) |
|---|---|---|---|---|---|---|
| PVC ASTM D 3033 DR 41 | Specification | 12.24 ± 0.018 | .299 min. | 28 min. | No failures @ 60% deflection | 220 ft-lb Tup A V-Block Holder |
| | After Field Test | 12.23 | .330 | 42 | all passed | 3 of 6 failed |
| PVC ASTM D 3034 DR 35 | Specification | 12.5 ±0.018 | .360 min. | 46 min. | No failures @ 60% deflection | 220 ft-lb Tup A V-Block Holder |
| | After Field Test | 12.48 | .998 | 76 | 1 of 6 split @ springline | all passed |
| | After Field Test | 12.48 | .395 | 82 | 2 of 2 cracked at perforations | all passed |
| ABS Composite D 2680 | Specification | 17.62 ±0.017 | None | 200 min. | No failures @ 7.5% deflection | None |
| | Control | 17.63 | 1.41 | 242 | all passed | – |
| | After Field Test | 17.60 | 1.41 | 242 | all failed | |
| Corr. PE ASTM F 405 | Specification | I.D. 8.0 ± 0.24 | None | 30 25 | None | None |
| | Control | 8.13 | – | 32 | – | - |
| | After Field Test | 8.12 | – | 30 | | |
| Smooth ABS ASTM D 2751 | Specification | 6.275 ± 0.011 | 0.180 min. | 45 min. | No failure @ 40% deflection | 90 ft-lb Tup B flat holder |
| | Control | 6.305 | 0.196 | 55 | 2 of 3 failed | all failed |
| | Control/Perf. | 6.280 | 0.198 | 59 | all passed | 3 of 5 failed |
| | After Field Test | 6.282 | 0.193 | 51 | all passed | all failed |
| | After Field Test/Perf. | 6.230 | 0.200 | 60 | all passed | not tested |
| Smooth PE | No Specification | | | | | |
| | Control | 15.97 | 0.539 | 18 | – | - |
| | ME-1 | 15.96 | 0.537 | 16 | – | - |

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$

- Wall thickness of all pipe was significiantly greater than required by specification.

- All control samples passed stiffness, flattening and impact tests, except the ABS smooth-wall pipe, which failed flattening and impact requirements. (It had been observed in the field that this pipe was brittle; prior to installation, one length split longitudinally when a man stood on the spigot end.)

- In one instance, the control ABS smooth-wall pipe failed the flattening test, whereas the samples removed from the field test passed.

- Most pipe removed from the field failed either the flattening test or the impact test, or both.

These test results will be evaluated in Appendix D.

Soil stress strain curves for the embedment material are contained in Figure B-14.

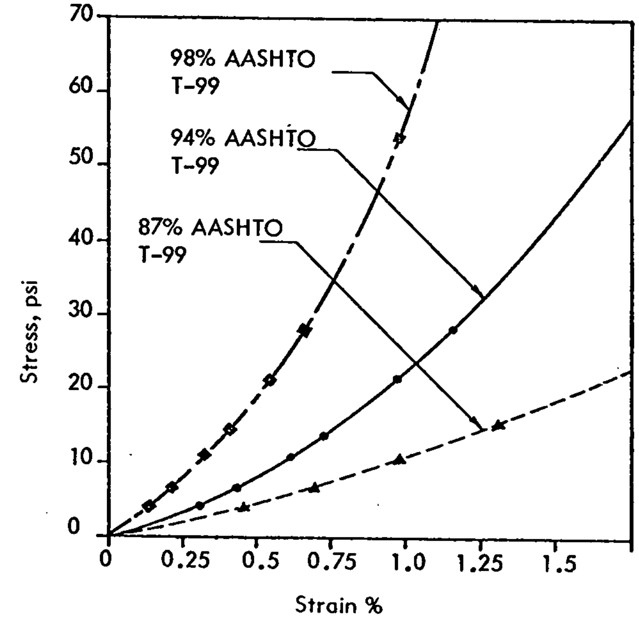
## B.5 Georgia Installation

The State of Georgia allows the use of perforated corrugated PE tubing as an alternate to conventional underdrains in highway construction. Project personnel visited the Research and Materials Division of the Georgia Department of Highways to discuss details of design and installation, and also to observe field installations. The following summarizes the results of this visit.

### General

Georgia has used perforated corrugated PE tubing extensively as shoulder drains in the rehabilitation of paving which has experienced problems related to drainage. The State has also been using this tubing as shoulder and lateral drains in new construction. As of November 1976, specifications for perforated PVC underdrain were in the development stage.






Note: 1 psi = 6.9 kPa

FIG. B-14 CONFINED COMPRESSION STRESS STRAIN CURVES ON EMBEDMENT SAND AT ME-1

Initially, Georgia attempted to evaluate corrugated tubing using laboratory "sand-box" tests, however, experimental difficulties were encountered. A full-scale wheel load test was then performed to evaluate the tubing. Briefly, the test is as follows:

- Six inch diameter tubing having a stiffness of 45 lb/in./in. was installed in a 5-ft (1.5 m) wide trench, which was 3 ft-3 in. (970 mm) deep.

- A 3 in. (75 mm) bedding of 3/8 in. (10 mm) to No. 8 crushed stone was placed in the trench. Then the tubing was embedded in a 6 in. (150 mm) layer of this stone and compacted.

- The remainder of the trench was filled with stone with no compaction, and covered by a 6 in. (150 mm) layer of compacted soil.

- Pipe deflection was measured prior to backfill, and during and after the application of wheel loads to the top of the trench. Axle load was approximately 19,700 lbs (88 kN) which applied a load of 9,800 lbs (44 kN) to a dual tired wheel.

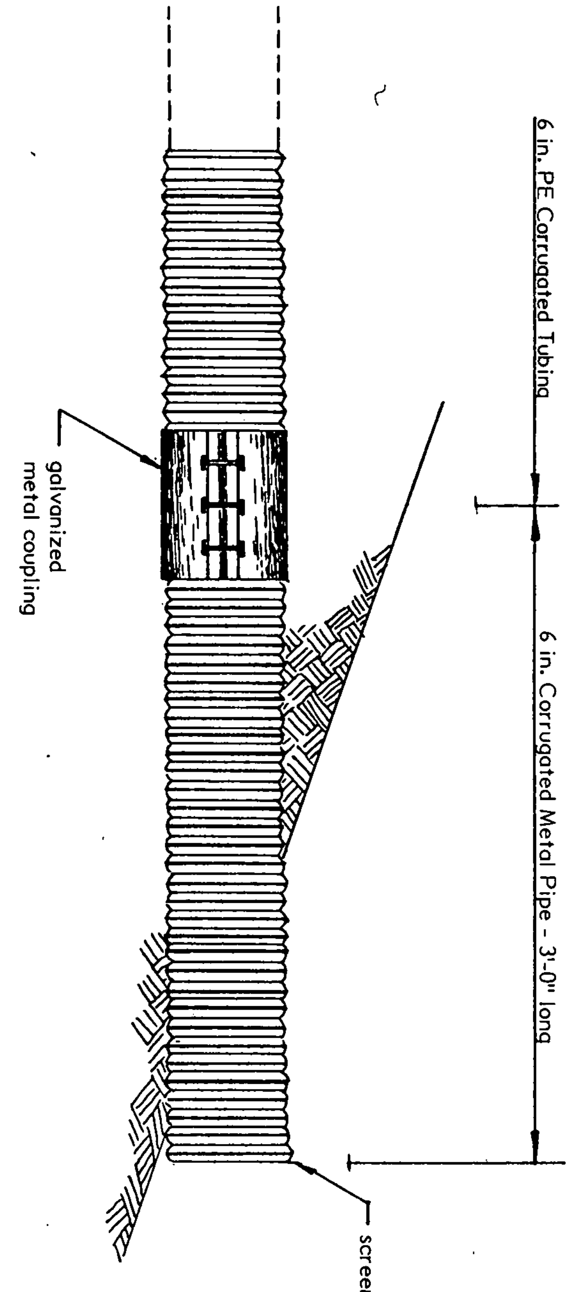
The tests showed that the backfilling process caused a deflection of about 1%. Application of the wheel load resulted in an increase of deflection to about 7%. Removal of the load left a residual deflection of 6%. Subsequent loading and unloading resulted in total deflections of 7% and 6%, respectively.

Georgia allows the use of coiled tubing in diameters less than 6 in. (152 mm), but requires straight sections which are 10 ft (3 m) or greater in length for 6 in. (152 mm) and larger sizes. Problems have been encountered with dilation of perforation slots, and cracks propagating from such slots in 6 in. (152 mm) diameter coiled pipe in cold weather. These problems have not been encountered in coiled pipe having diameters less than 6 in. (152 mm).

The corrugated PE tubing is terminated at outlets with a 3-ft (0.9 m) length of corrugated metal pipe (Fig. B-15), as a protection against fire and other damage.








Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. B-15 CORRUGATED METAL OUTLET FOR GEORGIA UNDERDRAIN

A screen is placed over the exit end of the metal pipe to prevent entry by rodents.

The screen is galvanized hardware cloth, having a 1/2 in. (12.7 mm) or 1/3 in. (8.5 mm) square mesh size.

**Pavement Rehabilitation**

Corrugated PE tubing has been used as underdrains in maintenance of existing highways since 1975. Existing reinforced concrete pavements have experienced "pumping" of the subgrade, which experiments show is the result of water penetration through the cold joint between the continuously reinforced concrete pavement and the bituminous shoulder. In the remedial repairs, the shoulder pavement and a portion of the stabilized base are removed, and a trench is installed approximately 2 ft (0.6 m) outside the edge of the concrete pavement (Fig. B-16a). This avoids damaging the stabilized base in the critical area immediately adjacent to the primary pavement. Crushed stone is used in the trench and below the new bituminous concrete shoulder pavement to drain the cold joint.

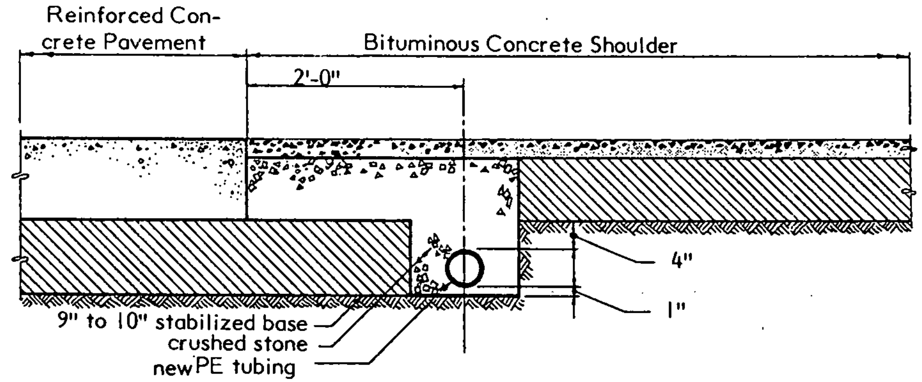
The corrugated PE tubing used on rehabilitation projects is supplied to the job in coiled lengths of 100 ft (30 m) or more. It is buried 18 in. (450 mm) deep, and outlets are provided every 100 to 300 ft (30 to 90 m), depending on terrain.

**New Construction**

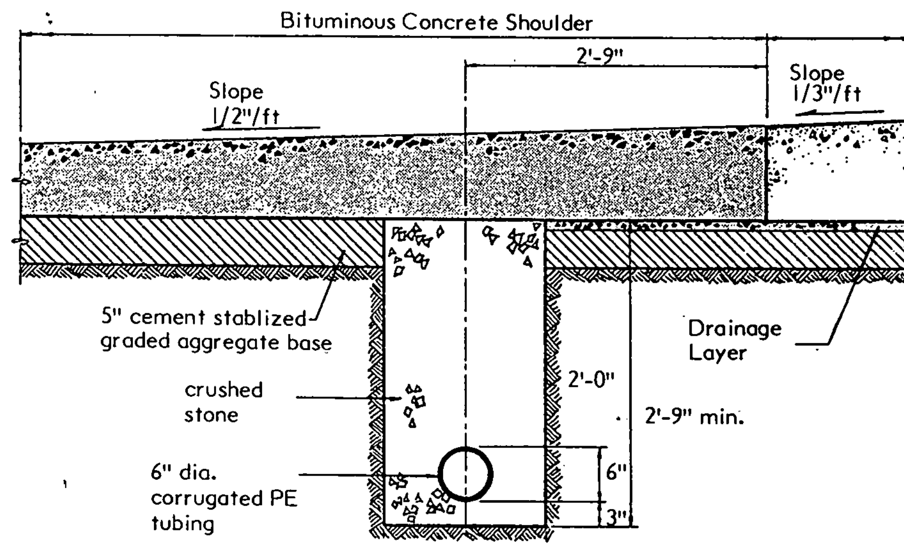
Georgia is also using corrugated polyethylene tubing for shoulder drains and for lateral drains in cuts where the water table is high. The drainage trench is installed adjacent to the stabilized base which extends 2 ft (600 mm) beyond the edge of the reinforced concrete pavement (Fig. B-16b).

Six inch (150 mm) diameter perforated corrugated tubing is used in new construction. Tubing is supplied in 20 ft (6 m) lengths.






a. Rehabilitation of Existing I-95 Pavement, Georgia




b. Underdrain Installation in New Construction

**FIG. B-16 GEORGIA INSTALLATION OF CORRUGATED PE TUBING**

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$

## B.6 Illinois Field Studies

Illinois Department of Transportation (ILL-DOT) has been actively studying potential cost and performance benefits to be derived from buried plastic pipe. They have been monitoring behavior of storm drains made from Reinforced Plastic Mortar (RPM) pipe and ABS composite sewer pipe for several years, and performing evaluation tests on a variety of plastic pipe for underdrain and storm drain applications. Illinois information has been used extensively on this project.

Illinois installations which have been active during the program are described below:

### ILL-DOT-1

The ILL-DOT-1 trial installation consisted of some 20 miles (32 km) of 4 in. (100 mm) corrugated polyethylene tubing for shoulder underdrains along the Springfield West Bypass, Route 4. The tubing is perforated with circumferential slots, and wrapped with a factory applied non-woven plastic filter sleeve to restrict infiltration of fines from the drainage envelope. The drainage trench is located below the bituminous concrete shoulder pavement, about 18 in. (450 mm) away from the edge of the concrete pavement; its purpose is to drain expected water penetration through the "cold" joint between the reinforced concrete pavement, and the paved bituminous concrete shoulder.

Pertinent details of the ILL-DOT-1 installation are as follows:

**Tubing**

- Nominal diameter: 4 in. (100 mm) i.d.; 4-3/4 in. (120 mm) o.d.
- Length: 250 ft (75 m) coils
- Specification: ASTM F 405 except minimum stiffness 50 psi (340 kPa) @ 5% deflection.





**Trench**

- Bedding: 180° semi-circular groove, 6 in. (152 mm) diameter
- Width: 8 in. (202 mm) typical
- Cover over crown: 14 in. (356 mm) during construction; 22 in. (556 mm) below surface of paved shoulder.

**Embedment/Drainage Envelope Material**

- Type: Illinois Type FA-1 or FA-2 (concrete or "torpedo" sand)
- Compaction: 85 to 90% density (AASHTO T-99)

**Trencher**

- Small chain - type with crumber modified to provide a 180° semi-circular bedding groove, having a 3 in. (76 mm) radius.

**Installation**

An installation rate of about one mile per day was achieved. During subsequent shoulder paving operations the top of the trench was trafficked continuously by heavy construction equipment including pavers and trucks hauling bituminous concrete for the shoulders.

Several manholes were provided along the installation to obtain access for measurements of in-situ pipe deflection using the ILL-DOT deflectometer, which is similar to the Cantilever/Strain Gage Deflectometer used in project field tests, and described in Section B.1. Associated apparatus and instrumentation provide a continuous plot of deflection (or diametral variations) along the length of the pipe.

## Results

Approximately 62% of the tubing length deflected less than 5%, 15% of the tubing length deflected 5 to 10% and 23% of the tubing length deflected over 10%. Subsequent investigation indicated that the largest deflections had occurred at locations where removal of boulders resulted in a wide and deep trench. Furthermore, some high deflections were traced to inadequate compaction of the trench. Compactors which were used were wider than the trench, and hence desired compaction of the backfill was not achieved. Finally, the radius of the bedding groove was large compared to the pipe radius, and large deflections were required to permit the pipe to conform to the groove.

In a second project similar to ILL-DOT-1, the trencher was further modified by welding several circular cutting teeth to the digging chain. This was done to improve the shape of the bedding groove. Deflections measured after installation and paving were similar to those observed after ILL-DOT-1 except that the maximum deflection was 23%.

## ILL-DOT-2

The ILL-DOT-2 trial installation was undertaken to increase both the reliability and the speed of installation of corrugated tubing from that achieved in ILL-DOT-1. To do this, a modified version of an automated trencher-installer was ultilized. The basic machine was developed in Europe to install agricultural drainage pipe systems, in a continuous operation.

The installation was generally similar to that of ILL-DOT-1. Pertinent details of the ILL-DOT-2 installation are as follows:

### Tubing

- Nominal Diameter: 4 in. (100 mm) i.d.; 4-3/4 in. (120 mm) o.d.



- Specifications: ASTM F 405 except that three tubing stiffnesses were examined. Pipe stiffnesses were 35 and 50 lb/in./in. (240 and 350 kPa) at 5% deflection and 50 lb/in./in. (350 kPa) at 10% deflection.

### Trench

- Bedding: $180^{\circ}$ semi-circular groove, either 5 or 5.5 in. (127 or 140 mm) diameter.

- Width: 10 in. (254 mm) to accommodate dimensions of available equipment.

- Cover over crown: 16 in. (406 mm) during construction; 22 in. (560 mm) below surface of paved shoulder.

### Embedment/Drainage Envelope Material

- Type: Illinois Type FA-1 or FA-2 (concrete or "Torpedo" sand)

- Compaction: 85 to 90% density (AASHTO T-99)

### Trencher

Installation was by a modified automated agricultural trencher-installer (Fig. B-17). This automated installation machine has been used extensively in agricultural drainage installations due to its speed and automation. The features of this machine as used in the agricultural application are noted below:

- Locomotion is provided by a tractor located on the front end.

- A chain-type trencher is mounted on a "floating" boom. The depth of the trench can either be controlled automatically by a laser control mechanism or the trench can be made a fixed depth below grade.

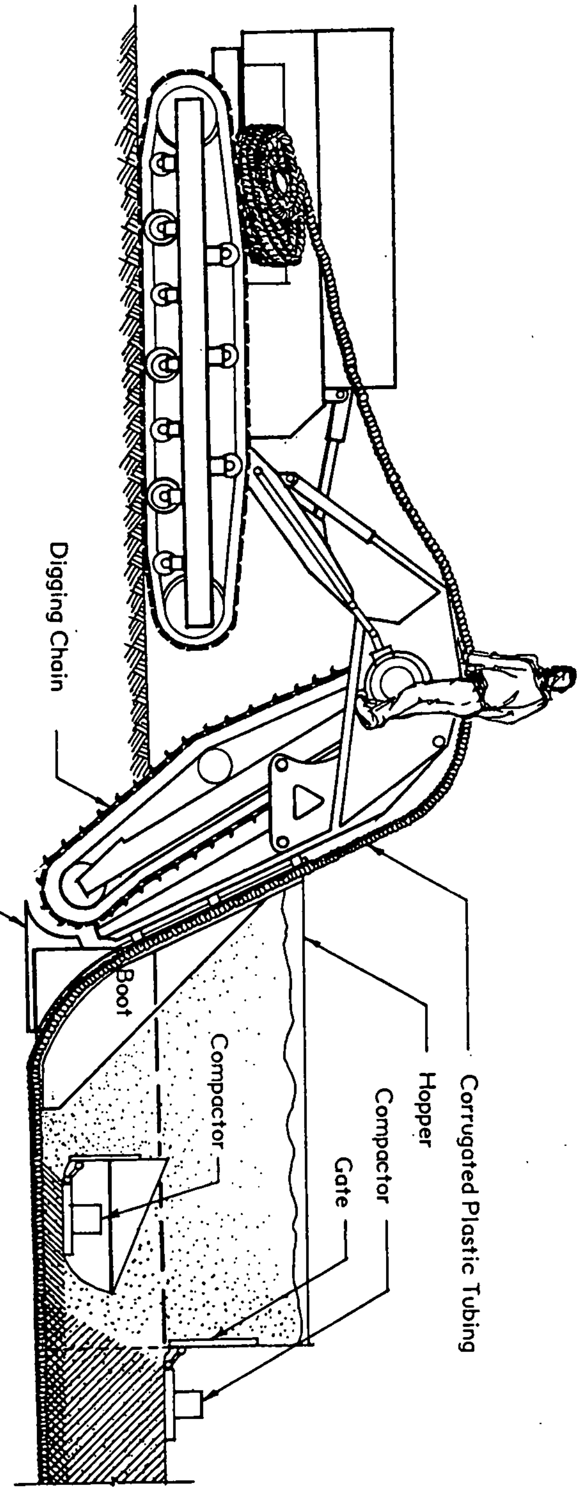



FIG. B-17 AUTOMATED EQUIPMENT FOR INSTALLING PE TUBING IN ILLINOIS





- Either spiral worm screws or conveyor belts mounted below the trencher chain deflect the excavated material falling from the scoops to each side of the trench.

- A large "boot", which acts as a shield, fits into the trench and provides continuous support to the trench walls and excludes crumbs while tubing is introduced through and below the boot. A depressor mechanism located at the bottom of the boot holds the tubing in place, while outriggers at the far end of the boot reclaim a portion of the spoil material previously excavated to cover the tubing with a few inches of backfill. (This first few inches of cover is termed "blinding" in the agricultural industry.) Backfilling is completed by a small bulldozer.

This machine, with the aid of a few men, can install two or more miles (3.2 or more km) of agricultural tubing in one day.

If a select blinding and/or backfill material is to be placed, compartments or bins are added to the boot and filled with appropriate select materials. The select material from the first bin flows around the tubing and forms the drainage envelope. Material from the second bin provides the backfill.

In the Illinois experiment, the trenching mechanism was specially modified for the highway installation to provide either a 5 or 5-1/2 in. (125 or 140 mm) diameter, 180° semi-circular bedding groove in the trench bottom. The machine was further modified to compact the select envelope and backfill material (concrete sand) automatically as the installation proceeded. Two compactors, which were about as wide as the trench, were attached to the hopper. The first compactor, which is located inside the hopper, compacts material for a depth of 5 in. (125 mm) over the crown of the tubing. The second compactor is mounted on the trailing end of the hopper, and compacts material at the level of the top of the trench.

### Evaluation of the Installation

Illinois has evaluated the installation by checking installed density of the envelope material, and by measuring deflection of the tubing before and after the shoulder paving is installed. Typically, the density of the backfill was found to be 90 to 95% of maximum dry density (AASHTO T-99).

The results of the deflection measurements which were made on several runs of tubing are summarized in Table B-9. The results cover three tubing stiffnesses and two bedding groove diameters. The deflection data provided by Illinois included the average deflection over the length of the measured run, and the standard deviation of the data. The results shown in Table B-9 indicate the following:

- The bedding groove diameter had the most influence on deflection. The larger bedding groove resulted in high deflections before paving, and significant increases in these deflections after paving.

- Tubing stiffness had small influence on deflections for the close fitting bedding groves.

- Tubing stiffness had significant influence on deflection of tubing with the larger bedding groove.

As a result of this study, Illinois now requires a bedding groove which is no more than 1/4 in. (6.5 mm) greater than the outside diameter of the tubing, in an attempt to restrict maximum deflection. They have retained a requirement of 50 psi (350 kPa) at 5% until more experience is obtained with tubing having other stiffnesses.

## ILLINOIS STUDY OF PVC UNDERDRAINS

Illinois has installed over 16,000 ft (4.8 km) of perforated smooth-wall PVC underdrains in experimental projects. The piping systems used conformed partly



### TABLE B-9 - EFFECTS OF BEDDING GROOVE AND PIPE STIFFNESS ON DEFLECTION OF MACHINE INSTALLED TUBING

| Pipe Stiffness (lb/in./in.) | Measured Before/After Paving | Deflection (%) 5 in. Dia. Groove Average | 5 in. Dia. Groove Maximum* | 5-1/2 in. Dia. Groove Average | 5-1/2 in. Dia. Groove Maximum* |
|---|---|---|---|---|---|
| 35 @ 5% | Before | 3.8 | 5.8 | – | – |
| | After | 4.4 | 6.1 | – | – |
| 50 @ 5% | Before | 5.7 | 7.7 | 7.8 | 11.9 |
| | After | 4.5 | 6.6 | 10.7 | 14.4 |
| 50 @ 10% | Before | – | – | – | – |
| | After | – | – | 5.8 | 8.2 |

* Maximum deflection is the 99-percentile deflection (average + 2.33 x standard deviation)

Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 lb = 2.2 kg; 1 in. = 25.4 mm; 1 ft = 0.3048 m to interim recommendations made during the Project 4-11. Pertinent details of the installation are as follows:

**Pipe**

All pipe conformed to ASTM D 3034, except the pipe material was restricted to cell classification 12454 (ASTM D 1784), having an HDB of 4,000 psi (27.6MPa) ASTM D 2837), and the pipe were perforated in a manner similar to AASHTO configurations for conventional underdrains. Holes were 3/16 in. (4.8 mm) in diameter. Pipe were 4 or 6 in. (102 or 152 mm) in diameter, and the stiffness range provided was 36 to 84 lb/in./in. (250 to 580 kPa). (Table B-10).

Test lengths of each pipe type ranged from 180 to 300 ft (54 to 90 m). The heavier wall, higher stiffness 4 in. (102 mm) diameter tubing, was a part of a full-scale installation totaling some 16,000 ft (4.8 km) of pipe.

**Trench** (See Fig. B-18)

- Bedding: Flat with 1 in. (25 mm) sand layer below pipe
- Width: 11 in. (280 mm) for a 4 in. (102 mm) pipe; 18 in. (456 mm) for a 6 in. (152 mm) pipe
- Cover over crown:

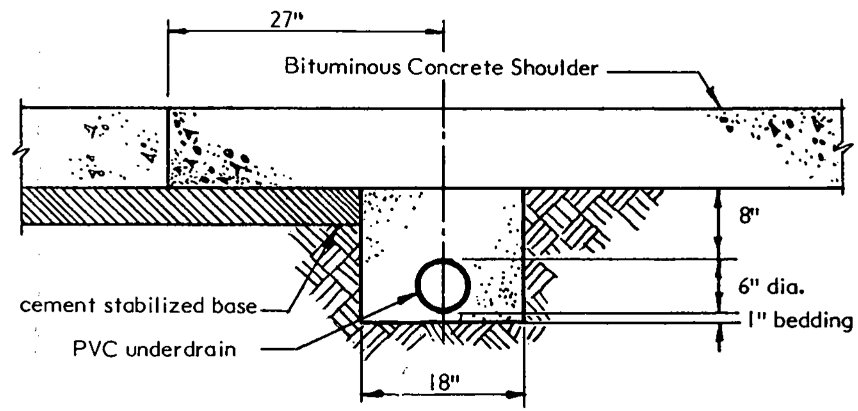
  4 in. (102 mm) pipe - 16 in. (406 mm) during construction; 24 in. (610 mm) after paving shoulder

  6 in. (152 mm) pipe - 8 in. (203 mm) during construction; 16 in. after paving shoulder

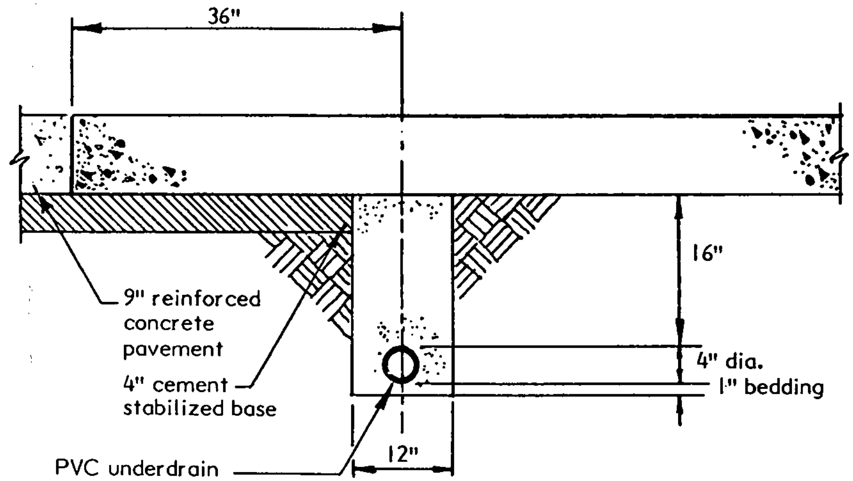
**Installation:**

The 1 in. sand bedding was dumped and levelled. The pipe was placed on the bedding, and the remainder of the backfill was dumped by chute to the surface of






a. Interstate I-72 Installation of 6" PVC Underdrain




b. Illinois Route 2 Installation of 4" PVC Underdrain

**FIG. B-18 ILLINOIS TRIAL INSTALLATIONS OF PVC UNDERDRAIN**

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$

TABLE B-10 - ILLINOIS TEST RESULTS ON PVC UNDERDRAIN INSTALLATION

| Diameter (in.) | Stiffness (lb/in./in.) | Wall Thickness (in.) | Deflection (%) | |
|---|---|---|---|---|
| | | | Average | Maximum * |
| 4 | 36 | 0.098 | 5.7 | 7.6 |
| | 39 | 0.099 | 2.6 | 4.1 |
| | 78 | 0.131 | 2.0 | 3.9 |
| | 84 | 0.131 | 3.7 | 5.4 |
| 6 | 47 | 0.168 | 2.1 | 3.4 |
| | 67 | 0.192 | 1.7 | 2.8 |

* Maximum deflection is the 99-percentile deflection (average + 2.33 x standard deviation).

Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 lb = 2.2 kg; 1 in. = 25.4 mm; 1 ft = 0.3048 m



the trench, then the backfill was compacted using a vibratory compactor which was attached to the chute.

**Evaluation of the Installation:**

Illinois personnel measured deflection of the pipe, using their deflectometer described earlier. The results are shown in Table B-10. The results indicate that the pipe having the lowest stiffness deflected significantly more than the other pipe tested. This is true for both pipe sizes tested.

Recent tests indicate that the pipe is now showing lower deflections, indicating a slight rerounding from the installed condition.



# APPENDIX C

## EXPLORATORY STUDIES ON STRAIN LIMITS

As will be explained in Appendix D, a working strain concept is adopted as a structural design criterion for plastic materials used in pipe. However, this concept is primarily based upon research on the behavior of plastics under constant tension stress (creep), while buried non-pressurized pipe are primarily subject to constant bending strain (relaxation). For this reason, the approach is considered conservative, but appropriately so, in view of the lack of data available.

**Objective**

The limited laboratory exploration of the strain limit concept was conducted to determine whether a there is a limiting constant bending strain, that when imposed for long periods, will damage or rupture pipe materials. In addition, experimental work on the strain limit of PVC pipe, which was performed by others during the course of the project, was reviewed and is summarized herein.

**Materials**

The following pipe were tested:

- 6 in. diameter DR-35 PVC pipe, ASTM D 3034, having a cell classification of 12454-C as defined in ASTM D 1784
- 6 in. diameter, DR-35, ABS pipe, ASTM D 2751, material class not marked on pipe

**Procedure**

Portions of each pipe were abraded with coarse sand paper, to simulate scratches made by wear or mild abuse. Then, specimens were placed in a fixture which imposed fixed levels of constant deflection (and hence strain), on the sample. Some samples were left in air, others were placed in water. The samples were monitored visually at convenient time intervals.

In the early experiment, samples of the PVC pipe were deflected to produce maximum strains of 1.5% and 2.1%. Since no failures became evident, a second experiment was undertaken in which the samples of the ABS pipe were deflected to produce a maximum strain of 4%. ABS materials are usually considered more sensitive to fracture under constant strain ("stress-cracking") than PVC, and the high maximum strain level was selected to accelerate failure.

**Results**

No failures have been observed in either the ABS material which has been under test for 15,000 hours (1.7 years) or the PVC material which has been on test for 19,000 hours (2.2 years). After 6,800 hours (40 weeks), the abraded portion of the ABS sample which was immersed in water, displayed "stress-whitening". For this pipe, stress whitening appears as a lighter shade of the original gray color of the material. The whitening appears to originate on the tension surface at the tips of the notches created by the abrasion by sandpaper. The whitening is a sign of crazing or first damage.

As yet, these crazes have not progressed into visible cracks. It is not possible to determine if crazing has occurred in the PVC, since the material as supplied is white, and stress whitening cannot be detected by readily available means.

**Other Studies**

Instigated in part by the present project, studies were performed by others on filled and unfilled PVC in an attempt to find a limiting strain for these materials (C.1). Samples were both notched and unnotched, and tests were made in air only, but at temperatures between 0°F and 70°F.



Some tests were performed on rings of pipe in much the same manner as the tests performed during this project as just described. No failures were observed when samples of notched and unnotched pipe were held at deflections of up to 35% to 40% for filled material, and up to 50% for unfilled material. No failures were observed after a period of several hundred to over 1,000 hours (actual test period not reported).

In a second series of tests, samples removed from pipe made from filled material were straightened as required at high temperatures and then fabricated into tension samples. Some samples were notched to a nominal depth of 0.024 in. (0.6 mm). These samples were strained at 70°F (21°C) to levels of 1% to 95%, depending on the temperature to which the samples were to be exposed subsequently. Samples were then exposed to temperatures of either 70°F (21°C) or 0°F (-18°C). Maximum duration of tests was not noted. Significant results were as summarized in Table C-1.

Crazing and cracking was noted during tests at strain levels above 10%.

**Discussion**

Overall, the above exploratory test programs demonstrate that for the specific compounds tested at room temperature, some in air and some in water, very high levels of deflection and strain can be sustained for long periods. No trend of failure strain (or deflection) vs time under load could be established since almost all samples did not fail, despite the high levels of imposed strain.

Crazing and cracking was noted in both types of materials tested (PVC and ABS). As will be discussed in the next section, the presence of such damage may accelerate rupture should an agressive environment come in contact with the pipe. This indicates a need for further similar tests in which exposure to possible aggressive environments is simulated, to confirm that high strain limits can be used with confidence.

**Table C-1**
**Results of Stress Relaxation Tests on PVC Pipe (filled compound) (C.1)**

| Notch Condition | Temperature of Relaxation Test | Direction of Sample | Target Strain Level | Result |
|---|---|---|---|---|
| No notch | 70°F (21°C) | Axial<br>Circumferential | 50% to 95%<br>5% to 50% | No failures in 5 samples. 1 of 7 samples failed on initial loading at 38% strain. 6 of 7 samples showed no failures. |
| | 0°F (-18°C) | Circumferential | 5 to 50% | 4 of 11 samples failed on initial loading at 70°F (21°C) at strains between 33% and 50%. 1 of 11 samples strained to 50% failed within one day after loading, during relaxation. 6 samples did not fail when strained up to 46%. |
| Notch | 70° (21°C) | Axial | 1 to 5% | 2 of 5 samples failed at 2% to 5% strain during initial load at 70°F. 2 more failed at strains of 1.5% within a day. The sample strained to 1% did not fail. |



The 70°F (21°C) tests by others, on filled PVC tension samples notched to a depth of 0.024 in. (0.6 mm) demonstrate the importance in establishing a limiting strength in terms of stress or strain. Samples failed at between 2% and 5% strain during loading at 70°F (21°C). Samples strained to 1.5% failed within a day when this strain was maintained. Since scratches of a depth of 0.024 in. (0.6 mm) cannot realistically be prevented in the field, and the effects of other notches remains unknown, this leaves serious questions as to the desirability of using filled PVC materials for drainage applications.

It is not clear why the notched tension samples made from filled PVC compounds failed at such low strains at 70°F (18°C) whereas the notched ring specimens made from a similar compound sustained large deflections and strains for long periods even at low temperatures. Possible reasons for this anomaly include:

- Notch depth. The notch was smaller for the tension samples than for the ring specimens.
- Size effects. The tension samples were removed from 15 in. (381 mm) diameter pipe; the ring samples were removed from 4 in. (102 mm) pipe.
- Materials. Although both pipe are identified as "filled PVC" the materials in the two pipe may not be identical.
- Process. The variables introduced in extruding pipe of such different sizes may result in different properties in the end products.
- Orientation. Tension samples were stressed in the axial direction, whereas ring samples were stressed in the circumferential direction.
- Stress Distribution. The distribution of stress across the tension sample is significantly different from that in bending.

Much more work is needed to find the reason for the low strains at failure in the tension tests on notched samples.



**Conclusions**

The project tests and tests by others did not produce a procedure which could be used to determine a limiting value of strain under conditions of relaxation. Further tests under various aggressive environments, temperatures, and conditions of notching are required to further explore and define long-term strength during relaxation.

Tests by others on filled materials indicate that strength limits in terms of stress or strain must be introduced to minimize chances for failure should the pipe be scratched or gouged. The low ultimate strain values of 1.5% for these materials under these conditions of test indicates that a small margin of safety is available under realistic field conditions.

**REFERENCES**

C.1 Jensen, B.M. "Investigations of Strain Limits Proposed for Use in Designing PVC Pipe Subjected to External Soil Pressure", Master of Science Thesis, Utah State University, Logan, Utah, 1977.

# APPENDIX D

## BACKGROUND FOR PERFORMANCE CRITERIA

### D.1 Introduction

This Appendix provides background for the development of performance criteria for plastic pipe used in subsurface transportation drainage installations. Structural adequacy is a key criterion, since pipe used in such installations may experience heavy loadings due to earth fill or vehicles traversing the surface of the installation. Other criteria which are frequently much more difficult to quantify include chemical and abrasion resistance, burning behavior and the like. These and other criteria are formulated and evaluated below.

**Plastic Pipe Materials**

The term plastics covers a myriad of materials, having different compositions and structures which display an extremely broad range of properties. Furthermore, virtually all plastics have been used in the manufacture of pipe and tubing.

The three generic plastic materials considered in detail in this study, Acrylonitrile-Butadiene-Styrene (ABS), Polyethylene (PE) and Polyvinyl Chloride (PVC) are those used in pipe for subsurface drainage-related applications. All three are thermoplastic in that they are plastics which repeatedly soften when heated and harden when cooled (D.1).

**Composition of Pipe Materials**

The chemical compositions of ABS, PE, and PVC are very different, just as in metals, zinc differs from iron. As important, but frequently not recognized by those unfamiliar with plastics, composition of a generic plastic can be modified in a number of ways to provide broadly different properties. This is similar to metal alloys in which an iron is combined with other elements to produce, for example, steels or cast iron. Like metals, the variations introduced in plastics compounds always result in tradeoffs in terms of properties, economics, manufacturing ease





and the like. While such versatility in formulation offers obvious advantages, it proves difficult to evaluate the effects of variations in formulations on overall long-term performance of plastics products. Thus far, the capabilities of industry to produce such variations, far exceeds the state of the art in characterizing them for design purposes.

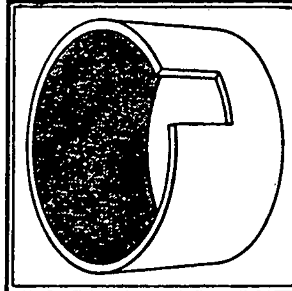
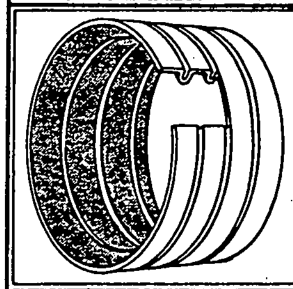
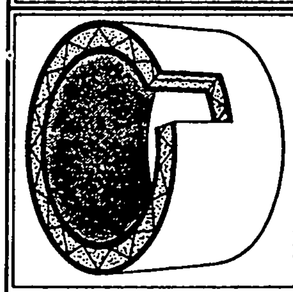
**ASTM Specifications**

ASTM Specifications contain requirements for structural properties of both compounds used in pipe and the pipe itself. A review of these specifications shows that they do not provide positive assurance that buried pipe products can meet even the most basic design criteria set forth herein. Furthermore, products meeting a given specification can possess significantly different and unknown structural properties. Finally, a product meeting the standard at the time of manufacture may be changed greatly by exposure to sunlight by the time it is installed.

As noted in Table D-1, specifications vary broadly in the number of plastic compounds which they allow within a generic material. Current ASTM specifications for ABS composite pipe permit the use of only one category of ABS compound; however, ASTM specifications for smooth-wall ABS allow three categories of ABS compounds, all having significantly different characteristics. ASTM specifications for PVC pipe allow the use of either filled or unfilled compounds having significantly different structural characteristics. Specifications for corrugated polyethylene tubing permit the use of four categories of compounds which essentially cover the entire spectrum of available polyethylenes. In perspective, only specifications for PVC pipe provide the fundamental structural engineering property of modulus of elasticity.

**Wall Construction**

Several types of plastic pipe systems are considered here as candidates for transportation drainage applications. The basic wall construction of these systems are categorized as follows (See Figure D-1):

| Wall Construction | Material | Diameter Range (in.) |
|---|---|---|
|  a. Smooth Wall | ABS | 8-15 |
| | PVC<br>PE | 4-15 |
|  b. Corrugated Wall | PE | 3-8 |
|  c. Composite Wall | ABS | 8-15 |

Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

**FIG. D-1 PLASTIC PIPE AND TUBING FOR DRAINAGE OF TRANSPORTATION FACILITIES**



**Smooth-Wall:** Smooth-Wall pipe are extruded in a cylindrical tube, with material distributed throughout the wall thickness.

**Composite-Wall:** Composite-wall pipe are extruded in one piece to form a wall having a circular truss-like configuration. Two concentric tubes comprise the inner and outer walls, which form the chords of the truss. Continuous webs are an integral part of the extrusion; they connect the inner and outer walls to form the diagonals of the truss. The cavity which is created between webs and walls is filled with Portland cement based materials. (Foamed cement is presently used.)

**Corrugated-Wall:** Corrugated wall pipe, called tubing, is an extruded product, which is forced into molds after extrusion, but while still hot, to form a corrugated wall section.

## D.2 Structural Criteria

Even though the number of piping systems considered herein is limited, the matrix of structural properties which can be generated from the variables of wall constructions, general material types, and different specific compounds within generic categories is indeed very large. Detailed technical evaluation of all available options under all possible conditions is clearly not possible.

The primarily good experience record of candidate systems selected for this study speaks for their general acceptability. The essence of this study, however, is to determine, within the state of the art, whether or not a plastic pipe stays whole when buried and subjected to earth and vehicle loads, over a significant life span. Criteria are needed to estimate structural adequacy for the next several decades, when most systems as they are today have had a decade or less of substantial use. Since stiffness and strength of plastics, which are a primary determinate of performance, are time-dependent, even field test programs as conducted during this project, present significant limitations in terms of testing times. Furthermore, since the structural characteristics of standardized pipe are far from standard, as noted in the previous section, past experience with a standard pipe provides no assurance that a new pipe made to the same standard will perform as well.

No failures were observed in field tests, and while this is encouraging, the primary focus of the evaluation rests with estimating the potential for failure in the very long-term, with knowledge of the stresses, strains and deflections imposed in the field. The criteria on which performance is established is based on state-of-the-art methods, broad assumptions, and rules of thumb.

**Structural Properties**

Strength and stiffness properties of plastics depend upon duration of applied stress and strain. Knowledge of these basic properties is needed to perform an engineering evaluation of buried plastic pipe. The structural properties provided in present specifications, shown in Table D-1, are all short-term properties obtained in tests lasting a few minutes. It is important to note that any of the material grades or classes, and related properties listed for a given specification, may be used in the manufacture of the pipe system.

The information given in Table D-1 is insufficient to define either stress-strain or strength behavior of the pipe materials. For example, the elastic modulus is not known for three systems. Strength requirements are slightly more definitive, yet in corrugated PE tubing, minimum strength requirements vary by a factor of almost 2. The specifications are silent on requirements for long-term stress-strain or strength behavior.

With the state of the art as it is, any structural evaluation must necessarily be highly approximate. The approach taken here is to apply very simplified rules of thumb which have been developed or proposed elsewhere for evaluating plastics to estimate potential structural performance of plastic pipe.

Criteria for structural evaluation are developed below. Terminology used, and methods developed are primarily based on information given in (D.2, D.3), with some simplifications and additions.





**TABLE D-1 - REQUIRED SHORT-TERM PROPERTIES OF STANDARD BURIED PLASTIC PIPE MATERIALS**

| Pipe Material | ABS | | ABS | PE | | PVC | |
|---|---|---|---|---|---|---|---|
| Wall | Smooth | | Composite | Corrugated | | Smooth | |
| ASTM Specification | D 2751 | | D 2680 | F 405 | | D 3033 & D 3034 | |
| Material Grade or Class | 3-2-2 | 1-3-3 & 2-2-3 | 2-2-3 | P14 P23 | P33 P34 | 13364 | 12454 |
| Tensile Strength minimum (psi) | 4000 | 5000 | 5000 | 1800 | 3200 | 6000 | 7000 |
| Elastic Modulus minimum (psi) | none | none | none | none | none | 500,000 | 400,000 |

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$

**Short-Term Stiffness:** The short-term stiffness of plastics, as defined by the initial tangent to the stress-strain curve obtained at conventional testing rates, is essentially independent of strain rate. This modulus, $E_o$, can be used to estimate stress-strain behavior under short-term loads (Fig. D-2). This modulus is temperature-dependent, and, ideally, different values should be used for different temperatures. Since the effects of temperature are generally not available, properties obtained at room temperature are used in most design methods, and will be used herein, recognizing that this approach is not vigorous.

**Long Term Stiffness:** The effective stiffness of plastics, which are **viscoelastic**, decreases with duration of stress or strain (Fig. D-3). Strain continues to increase during constant stress **(creep)**, and stress decreases during constant strain **(relaxation)**. The **viscoelastic modulus** which is the effective modulus, as defined by the ratio of stress to strain at a given time, obviously decreases with time of loading.

Analysis of the behavior of several generic thermoplastics, which have been subject to tests lasting up to 16 years, indicates that the viscoelastic modulus for long durations, say 10 years, is nominally one-half of the short-term apparent modulus. This is true for tests at room temperature. Other sources indicate that long-term stiffness may decrease by a factor closer to 3 or 4. Thus, a rule of thumb is assumed to hold at temperatures of interest in the buried pipe application, which is that long-term viscoelastic modulus, $E_{10}$ is 1/2 to 1/4 of the short-term modulus, $E_o$.

**Short-Term Strength:** Short-term strength is assumed to be the tensile yield strength of the material as determined in short-term tests. Yield strength in compression is typically the same as or higher than the tensile strength (they are assumed the same herein). Short-term maximum strength (modulus of rupture) of thermoplastics in flexure is typically 1.5 to 2 times the yield strength in tension. This is in part the result of plastification of the bending cross section, and hence it is an apparent stress; actual maximum stress is that which occurs at the yield point.



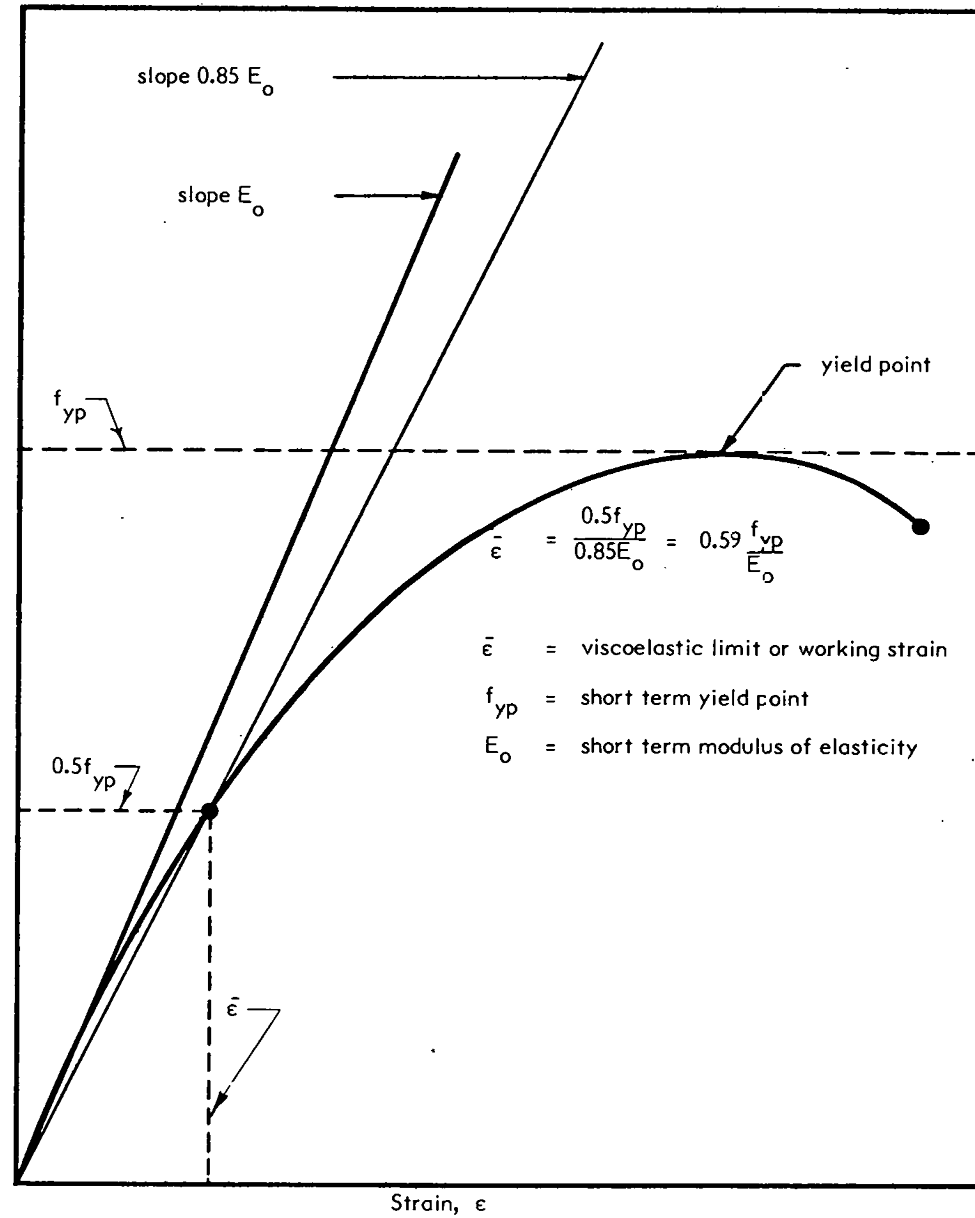
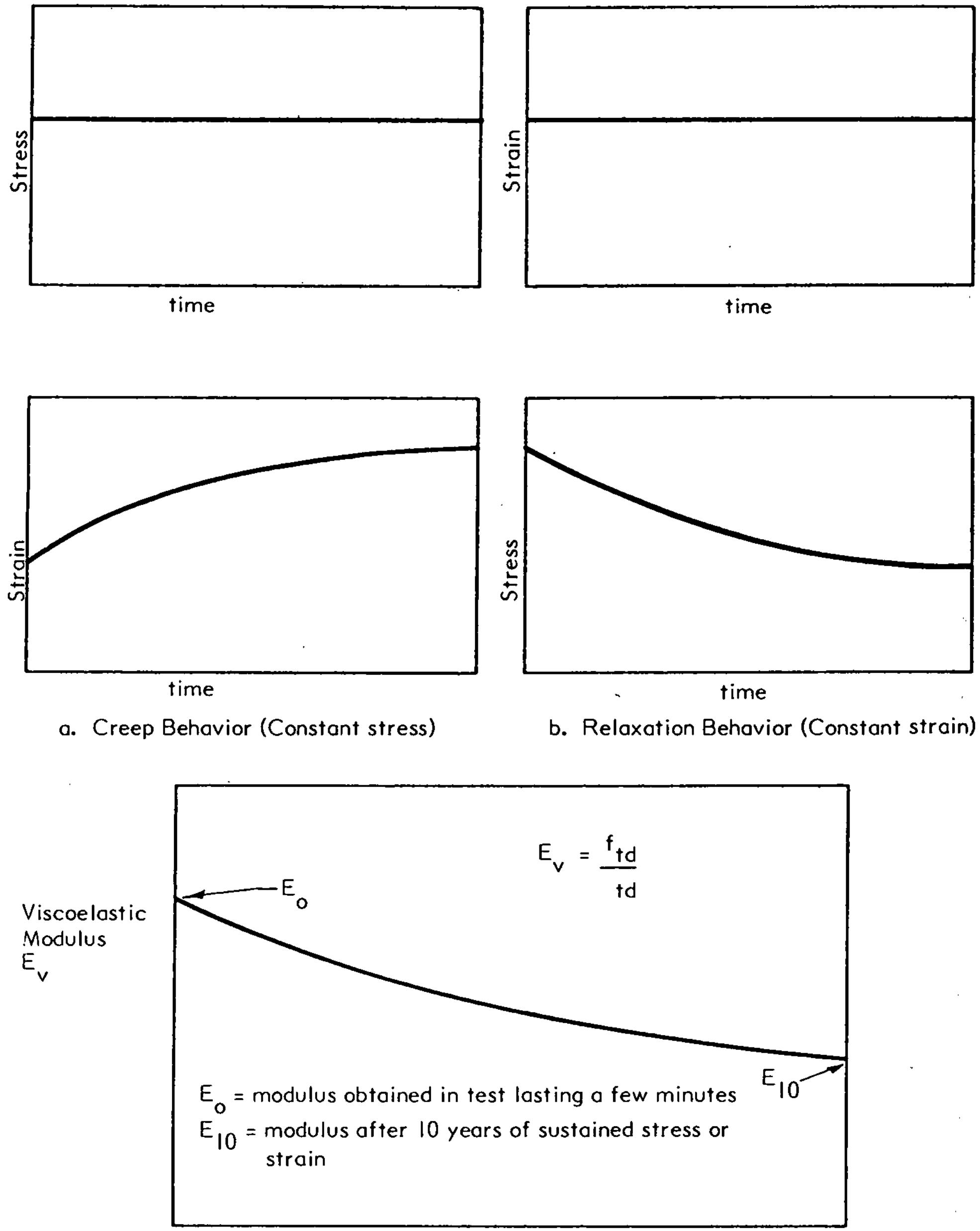



FIG. D-2 SHORT-TERM STRESS-STRAIN RELATIONS FOR PLASTICS




a. Creep Behavior (Constant stress)

b. Relaxation Behavior (Constant strain)

c. Time-Dependent Viscoelastic Modulus

FIG. D-3 VISCOELASTIC STRESS - STRAIN BEHAVIOR OF PLASTICS



**Long-Term Strength:** Strength under long-term stress or strain is as much a function of environment and chemical exposures as it is an intrinsic time-dependent strength of the material. For certain compounds used in plastic pressure pipe tested in water, extrapolated long-term (11.4 years) strength under sustained stress (creep) is about 1/3 to 2/3 the short-term (1 hour) strength. This depends strongly on the generic type of plastic and the specific type of plastic compound. Some of these "pressure-rated" compounds are used in the manufacture of buried plastic pipe but ASTM specifications do not specifically require their use.

**Long-Term Strain:** As shown in project field tests, a buried (non-pressure) pipe which is properly installed is subjected principally to sustained flexural strain. Criteria for establishing design limits for maximum permissible long-term strain are not well defined, and they are presently the subject of both research and controversy.

A very simple strength criterion has recently been proposed for buried plastic pipe subjected to sustained strain (D.4). That is, the maximum initial stress permitted is taken as one-half the yield strength, as determined in short-term tensile tests. This criterion presumes that pipe materials stressed at this level initially, can sustain the nearly constant strain expected in the buried installation for the indefinite future.

It proves convenient to restate the above criterion in terms of strain rather than stress, since strain in the buried condition is assumed invariant, whereas stress changes with time due to relaxation. Since the stress-strain curve for plastics is nonlinear, the strain at one-half the yield-point stress is greater than that which would be predicted by elastic methods (Fig. D-2). For purposes of the study, the **working strain** is taken as the actual strain at one-half the yield point stress. This value is assumed to be:

$$\bar{\varepsilon} = \frac{0.5f_{yp}}{0.85E_o} \qquad \text{Eq. D.1}$$

where

$\bar{\varepsilon}$ = working strain

$f_{yp}$ = short-term tensile yield strength, psi (kPa)

$E_o$ = short-term tangent modulus in tension,psi (kPa)

The factor of 0.85 is introduced to account for non-linearities in the stress-strain curve mentioned above.

Other approaches to determining strain limits have been developed. In Europe (D.5) extensive testing under sustained stress (creep) in a variety of aggressive environments has lead to generalized recommended strain limits of 0.9% for amorphous plastics (PVC) and 2% or greater for crystalline plastics (PE). An experimental/analytical approach to defining strain limits has recently been developed in the U.S. (D.3), however, this has not been implemented on materials presently used for pipe. Overall, however, a review shows that the criterion given in Eq. D.1 appears to be reasonably consistent with the European and U.S. approaches. Furthermore, it tends to provide a conservative bias on certain filled compounds, for example, where there is uncertainty of long-term strength properties.

The significant aspects of the strain limit criterion as discussed in significant detail elsewhere (D.2, D.3), are:

- The limit defines, in essence, a "proportional limit" for plastics stress-strain behavior, which is a familiar term used in conventional structural materials. For plastics it is more appropriate to call it the **viscoelastic limit** (D.3). At strains above the viscoelastic limit, stress-strain behavior becomes increasingly nonlinear, and cannot be described by simple conventional methods based on elasticity theory. At strains below this limit, conventional elastic formulas may be used, provided the time-dependent viscoleastic modulus is used in the calculations.

- **First damage**, such as microcracking or crazing, develops at tensile stresses and strains above this strain limit. Microfractures alter some properties of the material which result generally in a reduction in ductility.



Furthermore, the material becomes increasingly subject to embrittlement by aggressive agents when such flaws are present. The mechanical properties are permanently altered from those furnished.

Exploratory studies performed during this project (Appendix C), and other research, have demonstrated that failure during constant strain conditions may not occur at strains well above this limit, providing the environment is not aggressive. On the other hand, notched samples of a filled PVC pipe failed in a short time at strains of about twice the working strain given by Equation D.1.

In the approach proposed herein, the strain limit as obtained in tension is taken as the criterion for maximum compression and bending as well. As such, the strain limit is taken as the working strain herein. As noted earlier, short-term bending strength is usually significantly higher than tension strength. Since bending is the primary stress mode for most buried plastic pipe, the use of a higher working strain in bending would relax the more stringent design criterion based on tension. Insufficient information is available to justify an increase in the strain limit in bending; reasoning indicates that if damage (crazing and microcracking) is strain dependent, such damage would be expected to develop at the same strain, whether the material is stressed in bending or tension. Thus, it is appropriate to use the tensile strain limit for bending, until further study indicates otherwise.

Information on the development of first damage in compression is extremely sparse. Reasoning indicates that damage should develop at much higher strains in compression than in tension. In lieu of any hard information, the strain limit in compression is taken as that determined in tension. This is judged to be conservative, and it proves limiting in many design situations where the maximum stress is compressive.

**Working Strains**

According to the simple relation given in Eq. D.1, the working strain for the material is readily established providing the basic short-term yield stress and apparent modulus of elasticity are known. As noted in previous discussions, and in

Table D-1, ASTM specifications frequently do not provide even these basic properties. Nonetheless, it is of interest to estimate potential working strains in order to evaluate pipe according to this criterion, and such estimates are made in Table D-2.

Where possible, the estimated working strain in Table D-2 is based on minimum strength and modulus properties, as specified. In the case of ABS, the modulus is an estimate provided by one materials supplier, for the grade of material shown. In the case of PE for corrugated tubing, the modulus is that calculated from ring-bending tests on the one specific product used in the field tests (Appendix B). In the case of smooth-wall PE materials, manufacturer's data was used. Thus, these working strains need verification for any specific plastic compound.

**Relationships Between Working Strain and Deflection Limits**

Analysis of the results of field tests (Appendix E) on buried pipe, indicates that a simple relationship can be used to relate bending strain in the pipe wall to pipe deflection in the field. This relationship is used here to obtain appropriate estimates of maximum deflections based on the strain limit criterion. For cross sections having thin elements in the pipe wall (corrugated tubing, composite, wall pipe), ring compression strains imposed by earth or surface wheel loads may result in very large reductions in these maximum values.

The basic relationship between strain and deflection of the invert, developed in Appendix E is:

$$\varepsilon_i = 4.27 \frac{t}{d} \times \frac{\Delta}{d} \times MF \qquad \text{Eq. D.2}$$

where

$\varepsilon_i$ = invert bending strain, in./in. (mm/mm)

$\frac{\Delta}{d}$ = maximum deflection, expressed as a ratio of the mean diameter





**TABLE D-2 - ESTIMATED SHORT-TERM PROPERTIES AND WORKING STRAINS FOR MATERIALS FOR PLASTIC PIPE**

| Material | System Specifications | Material Grade or Class | Specified Min. Tensile Strength - $f_{yp}$ (psi) | Modulus of Elasticity - $E_o$ (psi) | Estimated - Working Strain - (%) |
|---|---|---|---|---|---|
| ABS | ASTM D2680 Composite | 223 | 5000 | 320,000* | 0.9 |
| | ASTM D 2751 Smooth Wall | 322 | 4000 | 250,000* | 0.9 |
| | | 133 or 223 | 5000 | 320,000* | 0.9 |
| PE | ASTM F 405 Corrugated | $P_{33}, P_{34}$ | 3200 | 85,000** | 2.2 |
| | | $P_{23}, P_{13}$ | 1800 | Unknown | – |
| | No Spec Smooth Wall | Unknown | 3000* | 100,000* | 1.8 |
| PVC | ASTM D 3033 or D 3034 | 13364 | 6000 | 500,000 | 0.7 |
| | | 12454 | 7000 | 400,000 | 1.0 |

* Information supplied by manufacturer or materials supplier

** Calculated from ring bending tests

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$

$t$ = wall thickness, in. (mm)

$d$ = mean diameter, in. (mm)

MF = moment factor to account for bedding; varies from 0.75 for well bedded pipe to 1.5 for pipe placed on a flat bedding without haunching.

The bending strain at the springline does not appear to be affected by the nature of the bedding, and its magnitude is approximately equal to the strain in very well bedded pipe. For this case, MF = 0.75, thus:

$$\varepsilon_s = 3.2 \frac{t}{d} \times \frac{\Delta}{d} \qquad \text{Eq. D.3}$$

where

$\varepsilon_s$ = bending strain at the springline

The above equations are valid for any wall cross section which is symmetrical about the neutral axis. In the case of ABS composite pipe, the inner shell of the wall is thicker than the outer shell. As a result, the neutral axis is displaced inward from the centerline. The neutral axis also may not be at mid-depth of corrugated tubing walls. It can readily be shown that the more general formula for the maximum strain in this case is:

$$\varepsilon_i = 8.54 \frac{Y}{d}\frac{\Delta}{d}\ MF \qquad \text{Eq. D.4}$$

$$\varepsilon_s = 6.41 \frac{Y}{d}\frac{\Delta}{d} \qquad \text{Eq. D.5}$$

where $Y$ = distance from neutral axis to extreme fiber, in. (mm)

For symmetrical sections, $Y = \frac{t}{2}$, and Eq. D.4 and D.5 reduce to Eqs. D.2 and D.3 respectively.



The above formulas apply to overall maximum bending strains in the pipe wall. The effects of perforations must also be accounted for. As noted earlier, ring compression strain in corrugated PE tubing and ABS composite pipe may reduce these deflections drastically. Perforations can be in the form of holes or circumferentially oriented slots. These create stress concentrations which increase the stress or strain above the average maximum values existing in the wall. The magnitude of stress or strain increases depending on size of the hole and slot and geometry, as follows:

- Circular hole in solid wall in bending (i.e. smooth-wall pipe) for DR-35 and DR-41 pipe with 3/16 to 3/8 inch (4.8 to 9.5 mm) diameter holes, the strain concentration factor varies between 2 and 2.5. A typical value of 2.25 is assumed.

- Circular hole in wall in uniform tension (i.e.: one shell of ABS composite pipe, or corrugated tubing). The classical value for the strain concentration factor for this case is 3.0.

- Slot with rounded ends (i.e. corrugated tubing). The stress concentration factor for an elliptical slot having an aspect ratio of 8:1, assuming a 1 inch (25 mm) by 1/8 (3 mm) inch wide circumferential slot is 1.33. Higher aspect ratios, found on many pipe, reduce this value.

By introducing perforation factor (PF), and substituting the working strain ($\bar{\varepsilon}$) Eqs. D.4 and D.5 can be rearranged to provide the following final formulas for maximum deflection:

$$\frac{\Delta_{max}}{d} = 0.117\,\bar{\varepsilon}\,\frac{d}{Y} \times \frac{1}{MF} \times \frac{1}{PF} \quad \text{(governed by invert strain)} \qquad \text{Eq. D.6}$$

or

$$\frac{\Delta_{max}}{d} = 0.156\,\bar{\varepsilon}\,\frac{d}{Y} \times \frac{1}{PF} \quad \text{(governed by strain at springline)} \qquad \text{Eq. D.7}$$

where PF = strain concentration factor for perforations, as noted above.

Eq. D.6 and D.7 account for bedding effects and for most cases, they are sufficient for determining the maximum strain in currently available smooth-wall pipe. In the case of corrugated PE tubing and ABS composite-wall pipe, the area of the pipe is small relative to overall wall depth, and relative to that of smooth-wall pipe. The effects of ring compression can be significant, and must be considered.

As noted in Appendix E, ring compression stress is assumed to act immediately upon loading; this stress causes a time-dependent increase in compression strain in the pipe wall. As the pipe creeps in compression, it reduces in diameter, which appears to relieve some of the embedment pressure as the pipe grows smaller (App. E). Thus, it is expected that pipe behavior under ring compression gradually shifts from a creep mode to relaxation mode. As indicated in Appendix E, a reasonable assumption is that short-term compression strains double over the long term.

In the working strain approach, the long-term ring compression strain plus the ring bending strain should be held below the working strain $\bar{\varepsilon}$. To find the maximum permissible deflection the long-term ring compression strain is first determined and subtracted from the working strain. Then, the maximum deflection is calculated using this difference in strain in place of the working strain (Eq. D.6 or D.7). The effects of stress/strain concentrations due to perforations are neglected when the perforations lie fully in the compression zone.

**Deflection Limit Based on Working Strain**

Table D-3 summarizes the calculated deflection limit for each pipe system considered in the field test program. In some cases, such as ABS and PVC smooth-wall pipe, pipe classes and materials which are included in the basic system specification, but which were not tested, are also included for information purposes. Eqs. D.6 and D.7 were used to calculate maximum deflection limits, based on the working strains derived in Table D-2 and the section properties of each pipe, as calculated from specified minimum dimensions. In the case of corrugated PE tubing, however, it was necessary to measure thickness variation





**TABLE D-3 - ESTIMATES OF DEFLECTION LIMITS BASED ON WORKING STRAIN CRITERION (MF = 1)**

| Pipe System | DR | Minimum Stiffness (lb/in./in.) | Material Type of Grade | Deflection Limit (%) No Perforation | Perforation | Comment |
|---|---|---|---|---|---|---|
| ABS Composite ASTM D 2680 | - | 200 | 223 | 2.2 | 0.7 | Estimate neglects local bending of inner and outer shells, ring compression strains, and shear effects. |
| ABS Smooth Wall ASTM D 2751 | 23.5 | 150 | 133, 223, 322 | 4.7 | 2.8 | |
| | 35 | 45 | 133, 223, 322 | 7.2 | 4.2 | |
| | 42 | 20 | 133, 223, 322 | 8.6 | 5.1 | |
| PE Corrugated ASTM F 405 | - | 30 | P33 or P34 | 7.7 | 5.9 | Estimate based on 8 in. tubing made by one manufacturer, and neglects ring compression strains. |
| PE Smooth Wall No Spec | 32 | - | Unknown | 13.1 | 7.8 | |
| PVC Smooth Wall ASTM D 3033 or D 3034 | 35 | 46 | 12454 | 8.0 | 4.7 | |
| | | 58 | 13364 | 5.6 | 3.3 | |
| | 41 | 28 | 12454 | 9.4 | 5.6 | |
| | | 35 | 13364 | 6.6 | 3.9 | |

Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 in. = 25.4 mm and proportions of the actual corrugated cross-section under a calibrated microscope, and then to calculate the properties. Thus, results are valid only for that specific tubing made in one production run by one manufacturer. In the case of ABS composite pipe, any effects of the cement filler were ignored, as were the effects of shear. Both effects may be very significant, however, and should not be ignored in any comprehensive investigations.

Table D-3 is derived for a moment factor, MF = 1, which is a representative coefficient for properly bedded and haunched pipe. The permissible deflections would be reduced for a poorly bedded pipe (i.e. MF = 1.5 or greater).

It is of interest to compare the deflection limit for certain of the non-perforated pipe shown in Table D-3 with limits frequently recommended or specified for buried plastic pipe. This is done below. Note should be made that the ring compression effects discussed in the previous section are neglected in the comparison.

**ABS Composite Pipe:** Calculated deflection limit is 2%, whereas in practice, deflection limits are typically set at 3 to 5%.

**ABS Smooth-Wall Pipe:** Deflection limits vary from 4.7 to 8.6%. Experience with this pipe is limited, but deflection limits for smooth-wall plastic pipe have been generally set at between 5 and 10%.

**PE Corrugated Tubing:** Calculated deflection limits for perforated tubing are 5.9%, deflections up to 20% have been suggested for agricultural applications without technical justification, and greater deflections have been measured.

**PE Smooth-Wall Pipe:** The calculated deflection limit is 13%. One manufacturer of this pipe recommends design for strain limits similar to but slightly more conservative than those derived by the simplified methods given here. Thus, the manufacturer's recommended limits might be slightly lower than that given here.



**PVC Smooth-Wall Pipe:** Deflection limits vary from 5.6 to 9.4% depending upon material and wall thickness. Recommended limits frequently vary from 5.0% to 7.5% for this type of pipe; sometimes a maximum of 10% is permitted if only a small portion of the line reaches this value.

The above comparison shows that the deflection limits based on the working strain approach are generally within the range of values used in the field rules of thumb, and experience. While the genesis of the criterion proposed herein is presently the subject of controversy, it results in deflection criteria which are, for the most part, quite consistent with the state of the art. The feature of the strain limit approach is that it provides a consistent rational basis for comparing potential performance of pipe structures having different wall properties, perforation configurations, materials and bedding conditions. This is not achieved by rules of thumb, or existing deflection criteria.

There is one major inconsistency between deflection limits obtained from the working strain criterion and those used in practice. This relates to corrugated PE tubing. The specific tubing examined here (one manufacturer, one size, one production run) would be limited to 5.9% for normal bedding; an 8% limit would be appropriate for a high quality shaped bedding groove. However, proposed deflection limits for agricultural drains are as high as 20%. Some agricultural drains have collapsed, and reportedly some have fractured at high deflections. The 20% limit for polyethylene tubing appears to be on the raw edge of success or failure, and this is not permissible in the transportation drainage application.

**Evaluation of Potential Long-Term Performance in Field Tests**

As noted earlier, no failures or signs of distress were observed in any of the pipe removed from field tests, which lasted several months to two years. It is of interest to determine how the deflections of the test pipe compare to the limits calculated from the working strain criterion. Table D-4 makes this comparison. The following are significant results:

TABLE D-4 - COMPARISON OF FIELD TEST DEFLECTIONS AND DEFLECTION LIMITS

| Pipe System | DR | Material Type or Grade | Test | Haunch Provided | Deflection (%) Field Maximum* | Calculated Limits Unperforated | Calculated Limits Perforated |
|---|---|---|---|---|---|---|---|
| ABS Composite | – | 223 | ME-1 | Yes | 2.4 | 2.4 | 0.9 |
| | | | NH-2 | Yes | 1.3 | 0.8 | 0.8 |
| | | | NH-2.1 | Yes | 2.0 | 0.6 | 0.6 |
| | | | NH-2.1 | No | 3.4 | 0.3 | 0.3 |
| ABS Smooth Wall | – | Unknown | ME-1 | Yes | 6.5 | 9.5 | 4.2 |
| PE Corrugated | – | P33 | ME-1 | Yes | 11.5 | 9.1 | 8.3 |
| | | | NH-2 | Yes | 5.5 | 0.7 | 0.7 |
| | | | NH-2.1 | Yes | 6.6 | 0 | 0 |
| | | | NH-2.1 | No | 9.0 | 0 | 0 |
| PE Smooth Wall | 32 | Unknown | ME-1 | Yes | 9.0 | 17.5 | 7.8 |
| | | | NH-2 | Yes | 2.2 | 12.1 | 8.9 |
| PVC | 35 | 13364 | ME-1 | Yes | 4.1 | 7.5 | 3.3 |
| | | | NH-1 | Yes | 2.7 | 7.5 | 3.3 |
| | | | NH-2 | Yes | 2.2 | 6.1 | 3.6 |
| | | 12454 | ILL-1 | Unknown | 5.4 | 5.3 to 10.7 | 4.7 |
| | 41 | 12454 | ILL-1 | Unknown | 7.6 | 6.3 to 12.5 | 5.6 |
| | | | ME-1 | Yes | 3.0 | 12.5 | 5.6 |
| | | | NH-1 | Yes | 5.7 | 12.5 | 5.6 |
| | | | NH-2 | Yes | 3.1 | 10.2 | 6.1 |
| | | | NH-2.1 | Yes | 5.7 | 9.8 | 6.1 |
| | | | NH-2.1 | No | 10.1 | 4.9 | 4.9 |

* Maximum deflection is the 99-percentile deflection or Average + 2.33 x Standard Deviation.

Notes:

1. Deflections do not include those due to wheel loads.
2. MF = 0.75 for haunched pipe; MF = 1.5 for pipe without haunching.



**Effects of Omission of Haunching:** In tests where haunching was purposely omitted (NH 2.1—no haunching) all of the pipe exceeded the calculated maximum deflection limits. The lack of haunching resulted in poor support of the pipe bottom, large deflections relative to haunched pipe, and as indicated in strain gage tests (Appendix B) large strains as well. Haunching should be provided for buried flexible plastic pipe.

**Corrugated and Composite-Wall Construction:** The corrugated PE tubing and the ABS composite pipe failed to meet the maximum deflection criteria by wide margins, except at shallow burial. The primary reason for this is that elements of the wall construction of these pipe are thin and highly stressed in resisting ring compression forces under high earth weight. In these cases combined compression strains due to ring bending and ring compression exceed the working strain. In fact, for the corrugated tubing at deep burial, the ring compression strain alone slightly exceeds the working strain.

The foamed cement filler in the composite-wall pipe probably shares some of the ring compression and reduces calculated stresses; significantly more research would be required to determine the extent of this reduction. Furthermore, more research is indicated on the use of the proposed working strain in compression, as derived from tension properties.

**Smooth-Wall Pipe:** All non-perforated smooth-wall pipe which were supported by haunched bedding met deflection criteria, and usually by comfortable margins.

**Smooth-Wall Pipe with Perforations:** Seven out of 12 of the smooth-wall pipe which were haunched met the deflection criteria for perforated pipe, but usually the margin was not large. The remaining five pipe did not meet the criteria, and all were buried at shallow depths.

Pipe stiffness of perforated pipe should be increased to minimize installation deflections and to reduce deflections due to traffic loads. Furthermore, materials providing high strain limits should be used. These modifications are necessary since actual field installation conditions and deflections will probably not be controlled to the extent provided on project field tests.

Overall, this theoretical evaluation leads to the following conclusions:

**Corrugated PE Tubing:** The materials and/or section properties of corrugated tubing should be upgraded, and furnished in several "strength" classes to provide needed stiffness to minimize installation deflections, and to provide cross-sectional areas needed to meet ring compression loads associated with varying heights of cover. Some improvements can be made by increasing requirements for stiffness, but proper improvements can only be made concurrent with quantitative characterization of both materials and section properties of this product.

**ABS Composite:** The analysis of this product is hindered by the complex structural configuration of the wall, the unknown degree of interaction between the plastic and foamed cement elements, and the lack of structural characterization of both of these elements.

The analysis indicates that the plastic is highly over-strained relative to working strain if it acts alone to resist imposed loads and deflections. (Note that shear effects and local bending and buckling of the curved inner and outer shells have been neglected in this analysis, but are judged to be extremely important design considerations.) The section properties of this product must be upgraded significantly in order to meet the criteria adopted herein. Furthermore, materials properties and section properties are in need of structural characterization to permit proper engineering evaluation of this product.

**ABS Smooth-Wall Pipe:** This pipe should be made stiffer when perforated. Furthermore, characterization of structural properties of the material is needed for detailed materials characterization.

**PE Smooth-Wall:** This pipe, which was least stiff of all test pipe, can undergo large deflections, mainly because of its high strain limit. This pipe displayed very small deflections under deep burial (NH-2). This may be the result of vertical ovalling induced during installation. It showed significant cumulative deflection during shallow burial at ME-1. This pipe remains as an attractive candidate for the transportation drainage application, but it is presently not considered in further detail because it is not covered in ASTM specifications.



**Smooth-Wall PVC Pipe—Unperforated:** This pipe met deflection criteria when installed with proper haunching. Pipe stiffness furnished ranged between 42 for the DR 41 pipe to 77 for the DR 35 pipe, even though specified stiffnesses are 28 and 46, respectively. A minimum pipe stiffness of 50 (based on minimum dimensions and modulus) should be used in further specifications to ensure that pipe stiffness furnished is in the range of that furnished in the test pipe. A 12454-B plastic compound of the type used in pressure pipe should be used in this pipe because it provides a high strain limit and also provides reasonable assurance that the strain limit is valid for the long-term.

It remains possible that an even higher pipe stiffness will be required to minimize installation deflections imposed during construction. Furthermore, a higher stiffness may be required to minimize cumulative movement under repetitive traffic loads or shallow cover. A minimum pipe stiffness of 100 lb/in./in. is recommended as a starting point in any development of stiffer pipe.

**Smooth-Wall PVC Pipe—Perforated:** While this pipe came close to meeting deflection criteria for perforated pipe, in some cases deflection was excessive. This means that pipe furnished at a minimum stiffness of 50 lb/in./in. (345 kPa), as above, for unperforated PVC pipe, must be installed with great care in the field in order to meet deflection criteria. The PVC material noted above provides a high, and somewhat reliable strain limit, which in turn, maximizes permissible deflections.

A minimum pipe stiffness of 100 lb/in./in. (690 kPa) will probably ultimately prove more appropriate for field use than the 50 lb/in./in. (345 kPa) value noted above. The higher stiffness will reduce installation deflections and any cumulative deflection under wheel load.

**Evaluation of Test Results on Pipe Removed from Field Tests**

Overall, the field test program was designed to be as realistic and practical as possible, and this resulted in some compromises in obtaining a controlled evaluation of pipe removed from the job. First, time constraints for implementation and the requirements for practical installation required that most pipe be obtained from available stock piles in the northeast. As a result, all pipe were not necessarily from the same manufacturer's lot, and age and conditions of storage were not necessarily the same for a given type of pipe. Next, pipe were handled and stored a number of times. Some PVC pipe, for example, were purchased in Hartford, Connecticut, shipped and stored in Hampton, New Hampshire, shipped to Old Town, Maine, and installed there for test, dug-up from the Maine site, shipped and stored again in New Hampshire, and finally returned to Massachusetts for testing. Control samples were subjected to considerably less handling. Thus, test results on samples removed from the field may reflect conditions of handling, storage, dig-up, and manufacturing variability, in addition to any effects of burial itself. The results are examined below, recognizing the above.

Table D-5 summarizes the results of all laboratory tests performed on pipe. Significant results are as follows:

- All control samples passed all tests except for smooth-wall ABS, which failed flattening and impact requirements. Possible reasons for failure are deficiencies in the material composition, or prior exposure to sunlight. The OD was slightly oversize, but this is not significant. The poor use performance of this pipe was demonstrated prior to installation - a man stood on the spigot end and it fractured.

- Samples removed after field tests passed stiffness requirements, except for ABS composite from NH-2, which was 1% less than the 200 lb/in./in. stiffness. This stiffness is some 20% lower than that of all other test samples of this pipe. Possibly, this may indicate web rupture during the NH-2 field test, which applied the greatest earth weight of all tests, from which samples were removed and tested.

- A number of samples removed after field tests failed either flattening or impact tests. All were from either NH-1 or ME-1. The significance of this is discussed below.



There are several important points which bear on the failures which occurred in flattening and impact tests on samples removed from NH-1 and ME-1, as follows:

- Both flattening and impact tests, as noted in the various ASTM specifications, are considered "quality control" tests, hence they are performed typically, at the time of manufacture, on fresh samples of pipe. Subsequent exposure to UV, handling and abrasion, and stress and strain can all cause decreases in the properties from those measured on fresh samples. As an example of this, the ASTM D 3034 PVC sample which was removed from ME-1 failed at a gouge in the pipe wall at the springline during the flattening test.

- Some authorities on impact testing of PVC indicate that it is possible that impact resistance may decrease with time, even when the pipe is stored unstressed, indoors. Furthermore, recent raw material changes brought about by health regulations (PVC monomer problem) and other factors of manufacture may reduce impact resistance, particularly of larger pipe, perilously close to specified minimums which were set for earlier formulations. The problem of impact strength is presently under evaluation in extensive test programs being conducted by industry.

- A V-block holder was used to support the PVC samples during impact tests, per ASTM D 3033 and D 3034. It has been recently determined that ASTM was mistaken in specifying the V-block. A flat plate holder support, which is much more forgiving in impact tests, was used in back-up tests for these specifications. Thus, tests performed here were more severe that those intended by ASTM.

## D.3 Durability to Chemicals

Pipe manufacturers and suppliers of the plastics materials used in pipe frequently provide extensive tables intended to describe the chemical resistance of plastic compounds. Typically, the tables contain a chemical resistance rating for the plastic compound after being exposed to each chemical compound. Room

**TABLE D-5 - SUMMARY OF LABORATORY TESTS**

| Pipe | Sample | O.D. (in.) | t (in.) | Stiffness Factor (lb/in./in.) | Flattening | Impact (ft-lb) |
|---|---|---|---|---|---|---|
| PVC ASTM D 3033 | Specification | 12.24±0.018 | .299 min | 28 min | No failures @ 60% deflection | 220 Tup A V-Block Holder |
| | NH-2 Control | 12.25 | .349 | 51 | all passed | all passed |
| | NH-2.1 Control | 12.24 | .313 | 38 | all passed | all passed |
| | NH-1 | 12.24 | .352 | 52 | all passed | 4 of 6 failed |
| | NH-2 | 12.25 | .324 | 40 | all passed | all passed |
| | ME-1 | 12.23 | .330 | 42 | all passed | 3 of 6 failed |
| PVC ASTM D 3034 DR 35 | Specification | 12.5±0.018 | .360 min | 46 min | No failures @ 60% deflection | 220 Tup A V-Block Holder |
| | NH-2 Control | 12.50 | .385 | 75 | all passed | all passed |
| | NH-1 | 12.48 | .381 | 66 | all passed | 5 of 6 failed |
| | NH-2 | 12.50 | .387 | 78 | all passed | all passed |
| | ME-1 | 12.48 | .398 | 76 | 1 of 3 split @ springline | all passed |
| | ME-1/Perf * | 12.48 | .395 | 82 | 2 of 2 cracked at perforations | all passed |
| ABS Composite D 2680 | Specification | 17.62±0.07 | None | 200 min | No failures @ 7.5% deflection | None |
| | Control | 17.63 | 1.41 | 242 | all passed | – |
| | NH-2.1 Control | 17.64 | 1.40 | 252 | all passed | – |
| | NH-2 | 17.63 | 1.41 | 198 | all passed | – |
| | ME-1 | 17.60 | 1.41 | 242 | all failed | – |
| Corr. PE ASTM F 405 | Specification | I.D. 8.0±.24 | None | 30@5% | None | None |
| | Control | 8.13 | – | 32 | – | – |
| | NH-2 | 8.15 | – | 35 | – | – |
| | ME-1 | 8.12 | – | 30 | – | – |
| Smooth ABS ASTM D 2751 | Specification | 6.275±.011 | .180 min | 45 min | No failure @ 40% deflection | 90 Tup B flat holder |
| | Control | 6.305 | 0.196 | 55 | 2 of 3 failed | all failed |
| | Control/Perf. | 6.280 | 0.198 | 59 | all passed | 3 of 5 failed |
| | ME-1 | 6.282 | 0.193 | 51 | all passed | all failed |
| | ME-1 Perf. | 6.230 | 0.200 | 60 | all passed | not tested |
| Smooth PE | | | | No Specification | | |
| | Control | 15.97 | 0.539 | 18 | – | – |
| | NH-2 | 16.10 | 0.544 | 18 | – | – |
| | ME-1 | 15.96 | 0.536 | 16 | – | – |

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$

temperature exposure (73°F, 20°C) is typical, and elevated temperature exposures are frequently considered as well. Criteria for the chemical resistance rating are frequently weight loss or gain, change in tensile strength or elongation, loss in impact strength, or other evidence of deterioration, all of which have resulted from exposure of plastic compounds to the chemical in question.

The above tables are, at best, tools for the preliminary determination of chemical durability, and certainly any exposure which results in a low rating should be reviewed. The problem with the typical chemical resistance table, as described above, is that it does not include the effects of stress or strain magnitude on chemical durability (i.e. stress-cracking). The interaction of stress and environment is the determinant of plastics' durability to some chemicals. Failure to recognize this has been a chief cause of failure of plastic products, including early reinforced plastic mortar (RPM) pipe in the sewer application.

Some of the chemicals or common materials that can attack, degrade or destroy plastics used in pipe are given below. Exposures which may also accelerate stress cracking are designated by "+".

- ABS - concentrated oxidizing acids, ketones, esters, chlorinated hydrocarbons, gasolene+, vegetable oils+, glacial acetic acids+, kerosene+, aromatic hydrocarbons+, and alcohols+.

- PE - strong oxidizing acids, oils, polar reagents such as detergents+, alcohols+, esters+, ketones+, and silicones+.

- PVC - ketones, esters, aromatic and chlorinated hydrocarbons+, and vegetable oils+.

The above list is by no means complete, but it provides a guideline to those kinds of materials which bear special consideration when assessing chemical durability.

With the exception of oils or petroleum derivatives, the aggressive agents noted above are not common to "normal" transportation drainage, and hence the user



risk is that of accidental spillage on the highway. Tests indicate that highway run-off waters contain trace quantities of oils, lubricants, hydraulic fluids, tire rubber, fuel residue, asphalt decomposition products, silt, soil stabilizers, growth control materials, heavy metals and feces (D.9). Measured concentration of oils, a problem contaminant, is typically 0.01% by weight or less and any chemical deterioration of plastic pipe resulting from such dilute concentrations is expected to be small during exposure to storm water.

The effects of possible deposits of deleterious oils and aromatic hydrocarbons on pipe surfaces during runoff or after evaporation of run-off waters cannot be evaluated within the state of the art. Exposure of pipe to attack by such products remains a risk, although the risk is probably lessened by continued flushing by storm and drainage water, and the small initial concentration of problem contaminants.

Plastic pipe compounds are resistant to road de-icing salts, and they are used frequently for transport of brine solutions.

Determination of the resistance to plastic pipe to the soil environment is complicated by the extremely wide variation in soils chemistry (e.g., pH = 2 to 10). In general, however, pipe compounds are resistant to alkalies, and all but the strongest acids. Burial tests (pH 5.3 and 8.1) for 8 years reveal no degradation of the generic plastic compounds used in pipe. Chemicals in the soil do not appear to deteriorate plastic pipe (D.6, D.7); chemical attack by particularly aggressive soils may need further evaluation.

Our discussions with a limited number of users indicate that performance of plastic pipe has been adequate for periods up to a decade. There are unconfirmed reports that ABS composite pipe failed when exposed to aggressive effluents from a dry-cleaning plant. Problems with RPM pipe have been attributed to exceeding strain limits on exposure to sewer acids — a problem which developed early in the history of that product. The satisfactory experience record of pipe examined during this study tends to confirm that if chemical deterioration was a fundamental problem, it would result in some reports of premature failures, which do not appear to be widespread.

## D.4 UV Resistance

Plastic pipe intended for burial are generally considered unsuitable for applications which are exposed to sunlight. The problem of exposure to UV during storage appears to be real and potentially very serious.

Ultraviolet radiation deteriorates all plastics, although this degradation can be retarded very significantly by proper formulation of the plastic compound. PE cable covering and PVC house siding are formulated to last for decades while exposed to sunlight, for example. Existing specifications for buried plastic pipe do not require any level of UV protection except for PE tubing specifications which require carbon black.

UV exposure robs the plastic of ductility, elongation to failure, and impact resistance. This may be accompanied by stiffening of the material. The lowered impact strength is important, typically, only during installation and handling. The more important result is the lowered ductility – this is unwanted because it decreases reliability in any structure. Study, discussions with experts, and possibly the erratic test results on materials removed from Phase II field tests and controlled tests on the effects of UV degradation by Illinois DOT, all lead to the conclusion that significant ductility and strength losses may occur in a period of a few months of exposure to UV. Such exposures may occur in a manufacturers or distributors yard. Clearly, stringent controls on UV exposure of all plastics pipe are required until a suitable level of UV resistance can be specified.

Key indicators of UV degradation are loss of impact strength and loss of resistance to flattening tests. Presently, the best available means for checking on UV deterioration is by performing impact and flattening acceptance tests on samples as delivered to the job. Once on the job, the materials should be protected by light-tight covers which allow air circulation, if the material is to be exposed to sunlight for more than a few weeks.



## D.5 Abrasion Resistance

Rate of erosion in piping is proportional to flow and quantity, size and shape of particles in an abrasive slurry. Hence, abrasion resistance of a given material is a function of both flow rates and characteristics of debris expected in the installation.

Typical flow rates in highway applications vary from a few feet per second for underdrains up to a maximum of about 20 feet per second (6.1 m/s) for culverts.

In general, most experience with plastics pipe involves relatively low flow rates. Sewer pipe is one such application, and here, the flow is normally slow (a few feet per second) and the effluent slurry is not usually abrasive. In the case of corrugated polyethylene tubing used for agricultural drainage, flow rates are very slow, although transport of any deposits of silt can be abrasive. There is a substantial and growing experience record in the mining industry, where PVC and PE pipe are used to handle water slurries containing highly abrasive tailings.

The Saskatchewan Research Council (D.8) has performed erosion studies which compare abrasion performance of several types of plastic pipe with steel and aluminum pipe. The test set-up consisted of a closed loop of test pipe, with a sand slurry continuously circulated by a pump.

- Silica sand gradation: Both coarse, $D_{50}$= 0.58 mm, (30 mesh, 3mm) and fine $D_{50}$ = 0.31 mm (48 mesh, 0.8mm), 40% by weight in a water slurry.

- Velocities: Either 7 or 15 ft/s (2.1 to 4.6 m/s).

The wear rates were measured in terms of loss of thickness, and are given in Table D-6.

Overall, the results indicate the following:

TABLE D-6 - WEAR RATES OF PLASTICS AND METALS UNDER ABRASIVE SLURRIES

| Material | Wear Rates - (mm) | | | |
|---|---|---|---|---|
| | Coarse Sand | | Fine Sand | |
| | 7 fps | 15 fps | 7 fps | 15 fps |
| Steel | 0.65 | 1.81 | 0.04 | 0.02 |
| Aluminum | 1.81 | 7.48 | 0.14 | 0.86 |
| Polyethylene | 0.06 | 0.46 | nil | 0.06 |
| ABS | 0.36 | 2.07 | 0.07 | 0.51 |
| Acrylic | 0.99 | 4.10 | 0.17 | 1.42 |

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- The wear rates are very small, varying from about 0.1 to 4 mm per year under continuous flow of abrasive slurry. Most drain age applications would have intermittent exposure.

- Polyethylene pipe has good abrasion resistance compared to the other plastics tested. It is reported that it has replaced metal for mine tailing slurries for this reason.

The above study indicates plastics used for pipe considered in the study are comparable or better than metals in resistance to abrasion by sand slurries. PVC, while not covered in the Saskatchewan tests, has a modulus, yield strength, and ultimate strength (the critical parameters in abrasion resistance) in the range of ABS and acrylic. Hence, the abrasion resistance of PVC should show a similar resistance to that of ABS and acrylic pipe resins tested. Overall, however, abrasion test data should not be interpreted quantitatively without detailed consideration.

The Saskatchewan study is based on sand slurries circulating at reasonably high velocities. In situations where larger aggregates are transported, abrasion or scour would be expected to be more severe for both metal and plastic pipe.

In experiments performed in Germany, the abrasion resistance of PVC, concrete (coated and uncoated), and stoneware pipe were compared. Pipe of 300 mm nominal diameter were filled 2/3 full with an abrasive slurry of water and "Rhine gravel/sand". The pipe were tilted $\pm 22^{\circ}$ from a horizontal position such that the slurry oscillated continuously from end to end of the pipe. The loss of wall thickness was taken as the measure of abrasion.

The results of the German tests indicate that the wear rate was less for rigid PVC pipe than for the coated and uncoated concrete. Wear rate for PVC was about twice that of stone wear initially, but after 260,000 cycles of abrasion, the wear was identical for the two materials. Also, at about 260,000 cycles, PVC had a lower mean rate than the stoneware.

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The above studies and experience in the mining industry indicate that plastics used for pipe are resistant to water-bourne slurries of sand, at flow rates similar to those encountered in typical drainage applications. Further study would be necessary to confirm this finding if larger aggregates are transported at high velocities, particularly if the stream changes direction at elbows and the like. Furthermore, the data quoted above should not be considered sufficient to provide positive assurance that any one material will provide superior abrasion resistance to another in a given practical situation.

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# APPENDIX E

## BACKGROUND ON STRUCTURAL DESIGN FOR EARTH LOAD

This Appendix presents a rationale for the structural evaluation and design of buried plastic pipe subjected to earth loads. It provides the background and commentary on Chapter 3. The approach taken in this Appendix is as follows:

- First, structural design criteria are formulated and discussed.
- Next, selected methods for the analysis and design of plastic pipe subjected to earth loads are presented. Selection of these methods was based on study and evaluation of information obtained during this project, including important results from project field tests.
- Finally, the methods are evaluated in light of field test data to demonstrate both their adequacy in predicting behavior, and their limitations.

The criteria presented herein are summarized in Chapter 2 of the report, and the general approach to structural design and evaluation presented herein is refined and condensed in Chapter 3.

A comprehensive review of the state of the art in analysis and design of buried conduit was performed for NCHRP in 1971 by Krizek et al (E.1). This work serves as a basic reference herein, and the reader is referred to this document for background. This Appendix basically modifies and adapts some of the methods presented by Krizek to reflect the time-dependent behavior of plastics, the significant results of project field tests, and recent advances in the state-of-the-art concerning buried flexible pipe.

## E.1 Design Criteria for Plastic Pipe

Many criteria for the structural analysis and design of flexible plastic pipe are similar to traditional criteria for flexible metal conduit, while others are not. Criteria for buried plastic pipe are reviewed below. This review is presented in light of traditional criteria for flexible metal pipe in order to provide a perspective on the special considerations needed for plastics.

### Material Properties

The majority of flexible pipe are either metal or plastic. With metal pipe, the material properties remain constant with time. Plastics behavior is much more complex because stiffness and strength properties are both time-dependent and stress or strain-dependent. This subject has been treated in detail in Appendix D, and will not be repeated here.

### Handling

A traditional design criterion for metal pipe is the "handling criterion," which is based on experience. To meet the criterion, the parameter $d^2/EI$ (d = pipe diameter; EI = circumferential bending stiffness of pipe wall) should be less than a required minimum value. The handling criterion of metal pipe varies with corrugation, and is unaccountably different for steel and aluminum. This criterion has not been applied to plastic pipe; although, possibly, the high stiffness of ABS composite pipe may have been selected in light of it.

Krizek has shown that the design of most small diameter metal pipe is governed by the handling criterion. It can also be shown that most plastic pipe intended for burial do not meet the handling criterion for metal pipe of the same diameter. This has significant bearing on the analysis and design of plastic pipe, which will become evident in later discussion on deflection variability, and installation deflections.



### Deflection

A 5% change in diameter has been a traditional "safe" deflection limit for flexible pipe under earth loads. This limit derives from rationale developed for corrugated metal pipe where collapse in the buried condition was assumed to be imminent at deflections of 20 percent, and the 5% limit, then, provided a safety factor of 4 against failure by collapse. Deflection limits of 5% (and sometimes more) have also been commonly accepted for most types of plastic pipe. Krizek (E.1) has shown that the factor of safety of 4 against collapse is conservative because it is based on the assumption that the deformation of the pipe is linearly related to the earth load applied. The true relationship between load and flexible pipe deformation is non-linear; most deflection occurs during the early stages of an installation while the soil surrounding a buried pipe is under minimal confinement. For example, a pipe which deflects 5% under 10 ft (3m) of soil will not deflect as much as 20% if the load is quadrupled. Thus, the real safety factor on collapse is more than 4, if a 5% safe deflection criterion is adopted.

Further examination of the "5% design/20% ultimate" deflection limit criterion reveals that it is not universally applicable to plastic pipe intended for burial, for the reasons given below:

- During a short-term parallel plate loading test which applies diametral compression to a ring of pipe, PVC sewer pipe deflects 30% or more before the wall reverses curvature in bending. If this point is taken as the point of collapse in the buried condition, the ultimate deflection limit is 30%, not 20%.

- Specification ASTM D 2680 permits rupture of ABS composite pipe at any deflection above 7.5% in the parallel plate test. The 5% deflection criterion provides very little margin of safety, in this case.

- The long-term properties of plastics, which are certain to change with magnitude and duration of stress and strain, are not recognized in either of the above simplified approaches to deflection limits.

Since the ultimate deflection of plastic pipe varies significantly, and since time-dependent properties of plastic materials also vary greatly, the use of any single limit for deflection of the general category of buried plastic pipe is not justified.

Appropriate reasons for setting deflection limits for plastic pipe are given below.

- Prevention of loss of seals at joints, and junctions with ancillary structures. Maximum deflection recommendations based on this criterion should be based on review of information provided by the manufacturer.

- Minimization of loss of support to pavement when pipe is installed with shallow cover below the pavement. Assessment of this is not within the scope of this project.

- Cleaning—if usage of cleaning equipment requires a minimum diameter, this should be considered in the selection of a deflection limit.

- Index of stress or strain in pipe wall. As indicated in Appendix D, the deflection of a pipe is indicative of the strain in the pipe wall. Thus, a deflection limit for a plastic pipe indirectly limits strain as well.

**Buckling**

Very few failures of flexible metal and plastic pipe have been attributed to buckling. Buckling rarely governs design, but it should not be neglected.

**Ring Compression**

Corrugated metal pipe has a small cross-sectional area, relative to smooth wall pipe, and a design check is usually made for stress due to circumferential thrust. Ring compression (circumferential thrust) is also a criterion for design of plastic pipe. For smooth-wall plastic pipe, strains resulting from circumferential thrust are typically small, and usually may be neglected. For corrugated tubing, however, circumferential thrust may produce significant stresses and strains.



And, since the modulus of elasticity of plastics is low, compression stress may induce significant diametral shortening (deflection) as well.

**Ring Bending**

Most design methods for flexible metal pipe neglect stresses due to bending. In metals, ductility allows plastic hinge formation, usually without detriment to the long-term performance of the material. Many present design methods for plastic pipe follow this reasoning, without similar justification. As noted in Appendix D, strain is adopted as a principal structural design criterion herein, and thus bending strains must be considered.

**Ring Shear**

Ring shear is present in any pipe which is subject to ring bending; bending derives from shear. The magnitude and distribution of ring shear in a buried flexible pipe, has not been considered in state-of-the-art analyses for buried flexible pipe; although such information can be derived. In the case of smooth-wall plastic pipe, shear effects are probably small. However, for corrugated tubing which has thin walls, shear may be a significant design criterion. In ABS composite pipe, the effects of shear must be considered, since the thin webs are allowed to rupture at any level of deflection during a parallel plate test.

Overall, the analytical treatment of shear effects in corrugated and composite pipe can be evaluated, but such an evaluation is not within the scope of this project.

## E.2 Analysis and Design Theory

A number of analytical methods for determining the behavior of buried flexible pipe under earth loads are available. These range from semi-empirical methods such as proposed by Spangler (E.2) and Watkins (E.3) to more rigorously theoretical methods such as the Burns elasticity solution (E.4). Finite element computer analyses have also been developed (E.5).

One of the first comprehensive analysis and design methods for buried plastic pipe was developed by Molin in Sweden for the Nordic Evaluation Group, whose mission was to evaluate and set standards for plastic pipe in Nordic countries. Molin's analysis approach (E.6) is based on a modified form of Spangler's method, in which the very low stiffness of plastic pipe is accounted for. Furthermore, Molin considered non-linear stress-strain behavior of soils, thermoplastic and reinforced plastic pipe, the effects of bending on the pipe wall, including limiting strains, and buckling. While this work remains as a classic in identifying and dealing with the key parameters in plastic pipe design, it has not been widely accepted in the U. S. Unfortunately, much of the background for this method is in Swedish, and it is not readily available to the U. S. researcher. Many of the concepts advanced by Molin, however, are recognized herein.

Several other analysis and design methods have been proposed for specific generic types of pipe. As examples; Watkins, Szpak and Allman (E.7) deal with smooth-wall PE pipe, Fouss (E.8) deals with corrugated PE tubing; the Unibell Plastic Pipe Association (E.9) deals with PVC pipe; Johnson (E.10) deals with fiberglass reinforced plastic pipe; and United Technology Corp. (E.11) deals with RPM pipe. The approach developed herein is intended to be general, and hence work by these researchers on specific types of pipe is utilized where appropriate for this generalized method.

Project field tests and other work performed in the same period show that most analysis methods do not predict the behavior of very flexible pipe, as are most plastic pipe, adequately for design. As will be shown later, the behavior of small diameter pipe considered in this project is generally governed by deflection variations induced by handling and installation. These effects can be so large as to overshadow the effects of pipe-soil interaction, as predicted by existing conventional theory. (The work of Krizek, mentioned earlier, recognizes but specifically excludes discussion of behavior which is not related to load.) Since the goal of the present effort is to provide practical methods by which the effect of primary design variables can be evaluated, a precise analytical solution of the pipe-soil interaction problem is not required. The discussion below centers on practical methods for the evaluation and design of buried plastic pipe.





**Theories for Earth Loads on Pipe**

Two methods are in common use for the determination of earth loads on buried pipe. The oldest is the Marston-Spangler theory, which is described in detail in Reference E.12. This theory takes many forms to account for variations in load resulting from types of installation such as trench, embankment, and combinations of these conditions (e.g., positive projecting, negative projecting, etc.).

The second method for determining earth loads is the "soil-prism" theory (E.13), which is described by the following simple relationship:

$$p_s = \gamma_s H \qquad \text{Eq. E.1}$$

where:

$p_s$ = free field vertical soil stress due to earth load, psi (kPa)

$\gamma_s$ = weight of earth per unit volume, lb/in.$^3$ (kg/m$^3$)

H = height of fill over pipe, in. (mm)

The essence of this theory is that the load on a buried pipe is equal to the weight of the soil prism directly above it. As explained later, project field test results indicate that this theory was reasonably valid for the conditions at NH-2.1. Furthermore, since the load response of very flexible plastic pipe is small relative to variability introduced during installation, the merits of any refinements offered by the Marston-Spangler load theory, compared to the prism load theory, are limited.

**Iowa Deflection Formula**

The Iowa deflection formula was first proposed by Spangler (E.2). It was later modified by Watkins and Spangler (E.14), and has been frequently rearranged. One of its common forms is:

$$\frac{\Delta}{d} = \frac{D_l K p}{\frac{EI}{r^3} + 0.061 E'} \qquad \text{Eq. E.2}$$

where:

$\frac{\Delta}{d}$ = fractional change in horizontal diameter

$D_l$ = deflection lag factor

K = bedding constant

p = free field soil stress, psi (kPa)

E = modulus of elasticity of pipe material, psi (MPa)

I = moment of inertia of pipe wall per unit length, in.$^4$/in. (mm$^4$/mm)

r = mean pipe radius, in. (mm)

E' = modulus of soil reaction, psi (kPa)

The Iowa deflection formula relates the increase in horizontal diameter (deflection) to the applied earth load. Typically, vertical and horizontal deflections in buried pipe are approximately equal. Thus, this formula is commonly used to estimate either vertical or horizontal diameter change under earth loads.

**Embedment Stiffness:** The **modulus of soil reaction,** E', is a measure of stiffness of the embedment material which surrounds the pipe. This modulus is required for the calculation of deflection and critical buckling stress. E' is actually a hybrid modulus which has been introduced to eliminate the spring constant used in the original Iowa formula. It is the product of the elastic foundation modulus used in Spangler's early derivation, and the radius of the pipe. It is not a pure material property.

Values for E' were originally determined by measuring deflections of actual installations of metal pipe and then backcalculating the effective soil reaction, using the Iowa deflection formula. Since E' is not a material property, it cannot



be uniquely measured from a soil sample; thus, determination of E' values for a given soil has historically presented a serious problem for designers of flexible pipe.

In 1975, Howard (E.15, E.18) proposed a comprehensive table of recommended E' values which are used at the Bureau of Reclamation. E' is given as a function of soil type, and level of compaction. The values proposed by Howard, reproduced as Table E-1, are based on measurements of a large number of pipelines installed by the Bureau of Reclamation. This table provides the designer with guidelines for estimating E' which have been unavailable heretofore. The percentages shown at the bottom of the table will be discussed subsequently.

To circumvent the problems inherent in working with the hybrid modulus, E', there has been an increasing use of the constrained soil modulus, $M_s$. The constrained modulus is a constitutive material property which is taken as the slope of the secant of the stress-strain diagram obtained from a confined compression test of the soil (Fig. E-1). It also may be calculated from the Young's modulus ($E_s$) and Poisson's ratio ($\nu_s$) of the soil by the elasticity formula:

$$M_s = E_s \frac{(1 - \nu_s)}{(1 + \nu_s)(1 - 2\nu_s)} \qquad \text{Eq. E.3}$$

This means that the soil modulus can be determined from common consolidation test, triaxial laboratory tests, or from a field plate bearing test on the actual soil in which the pipe will be embedded. Measurement of Poisson's ratio, however is quite difficult, and it is usually estimated using experience and engineering judgement.

Since $M_s$ is taken as the secant modulus, it accounts, in part, for non-linearities in stress-strain response of the soil around the pipe. As shown in Figure E-1, determination of $M_s$ is based on the actual load applied to a pipe. Decreasing the applied load results in a decreased value for $M_s$. This illustrates that most deflection occurs in the early stages of installation at low cover depths.

## TABLE E-1 - BUREAU OF RECLAMATION VALUES OF E' FOR IOWA FORMULA
### (for initial flexible pipe deflection)

| Soil type-pipe bedding material (Unified Classification System 1/) | Average E' for degree of compaction of bedding ($lb/in.^2$) 4/ | | | |
|---|---|---|---|---|
| | Dumped | Slight <85% Proctor <40% rel. den. | Moderate 85-95% Proctor 40-70% rel. den. | High >95% Proctor >70% rel. den. |
| Fine-grained Soils (LL > 50) 2/ 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 percent 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 percent coarse-grained particles; Coarse-grained Soils with Fines GM, GC, SM, SC 3/ contains more than 12 percent fines | 100 | 400 | 1,000 | 2,000 |
| Coarse-grained Soils with Little or No Fines GW, GP, SW, SP 3/ contains less than 12 percent fines | 200 | 1,000 | 2,000 | 3,000 |
| Crushed Rock | 1,000 | 3,000 | 3,000 | 3,000 |
| Upper Limit of Average Deflection | +2% | +2% | +1% | +0.5% |
| Upper Limit of Deflection | +4% | +4% | +3% | +2% |

1/ ASTM Designation D 2487, USBR Designation E-3.

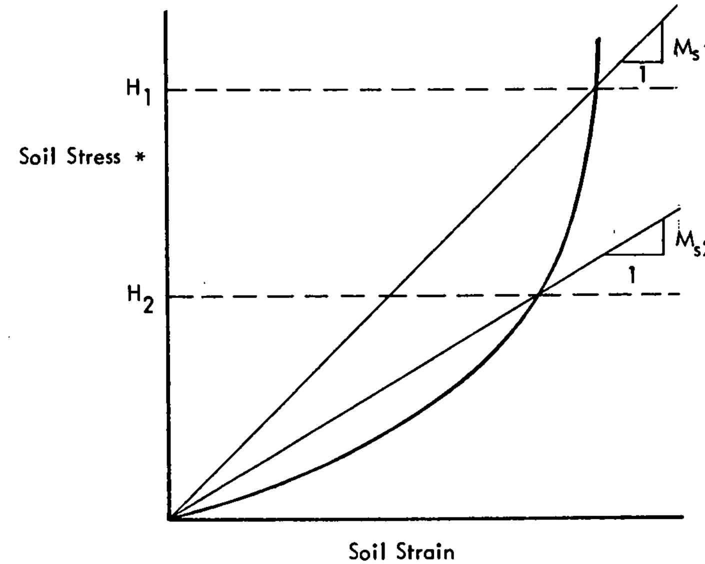
2/ LL = Liquid limit.

3/ Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).

4/ 1 $lb/in.^2$ = 6.9 kPa

Note:
- A. Values applicable only for fills less than 50 feet (15 m).
- B. Table does not include any safety factor.
- C. For use in predicting initial deflections only, appropriate Deflection Lag Factor must be applied for long-term deflections.
- D. If bedding falls on the borderline between two compaction categories, select Lower E' value or average the two values.
- E. Percent Proctor based on laboratory maximum dry density from test standards using about 12,500 $ft\text{-}lb/ft^3$ (598,000 $joules/m^3$) ASTM D 698, AASHTO T-99, USBR Designation E-11).
- F. 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 $lb/in.^3$ = 0.028 $g/mm^3$






* Proportional to height of cover

FIG. E-1 DETERMINATION OF CONFINED COMPRESSION MODULUS

Many researchers (E.1) have studied the relationship between E' and $M_s$, but their recommendations have varied widely (E' = 0.7 to 1.5 $M_s$). This is expected since $M_s$ is a "pure" soil property, while E' is empirical. Based on the comparison described in Section E.3, it appears justified to assume the two values equal for the calculations discussed herein.

$$E' = M_s \qquad \text{Eq. E.4}$$

**Deflection lag factor—$D_l$:** The deflection lag factor accounts for the increase in deflection which results from the time-dependent consolidation of the soil surrounding the pipe. Pipe deflection increases with time, and the amount depends upon soil type and level of compaction, trench geometry and other factors. Spangler recommended use of a deflection lag factor between 1.0 and 1.5, as a result of his tests which lasted 10 years, but values up to 6 have been recommended. The deflection lag factor is not related to time-dependent creep behavior of plastics.

The E' values given in Table E-1 and discussed above were obtained from measurements on pipe which had been installed from one day to several years. Many measurements on plastic pipe installations indicate that while deflections may continue to increase indefinitely, a major portion of the deflection typically develops in a few months or less after installation. Thus, it is probable that a significant (but variable) portion of the time-dependent deflection had already taken place at the time of Howard's measurements.

**Bedding constant—K:** The bedding constant modifies deflections to account for the effects of soil support conditions at the bottom of the pipe. Spangler recommended values from 0.083 for 90° bedding (full support) to 0.11 for 0° bedding (line support at invert). Since the predicted deflection is directly proportional to the bedding constant, this means a change from 90° bedding to 0° bedding could increase the predicted deflection by 0.110/0.083 = 1.33, or 33%.



**Deflection Variability**

Both project field tests, and the recent work of Howard, indicate that field deflections can be much greater than the mean deflections calculated from average E' values. In Howard's approach it is assumed that the Iowa formula predicts only the mean component of deflection. In order to predict maximum deflection (the goal of design), both of the factors at the bottom of Table E-1 (upper limit of average deflection, upper limit of deflection) must be added to the predicted mean. Thus, these factors reflect the following:

- There is an inherent variability in the deflections of a buried pipe, which is induced by or which results from the process of installation
- the variability increases as the percent compaction of the backfill decreases.

In addition, subsequent review of project field test results shows that variability reduces as pipe stiffness increases. As will be shown in Section E.3, these variability factors are large and can overshadow the deflections due to load related pipe-soil interaction. Since the deflections due to variability are the result of characteristics of both pipe and soil in an installation, they are termed here **installation deflections.**

**Ring Compression Theory**

The **ring compression theory** proposed by White and Layer (E.13), assumes that bending effects can be ignored and that the ultimate strength of corrugated metal pipe is governed by circumferential or ring compression thrust. This thrust is calculated from elementary theory for a ring under hydrostatic pressure, using the prism load discussed earlier. The formula is:

$$T = p_s \frac{d_o}{2} \qquad \text{Eq. E.5}$$

where:

$T$ = total thrust force, lbs/in. (N/mm)

$p_s$ = free field soil stress at pipe springline (soil prism load), psi (kPa)

$d_o$ = outer diameter of pipe, in. (mm)

Evaluation of compressive thrusts by the ring compression theory is also applicable to plastic pipe. For plastics, this ring compression acts as a creep load, and the effect is to increase compression strain with time under load. For plastics, however, ring compression is only one stress resultant that must be treated. Ring bending usually governs design for smooth-wall pipe.

### Ring Bending Theory

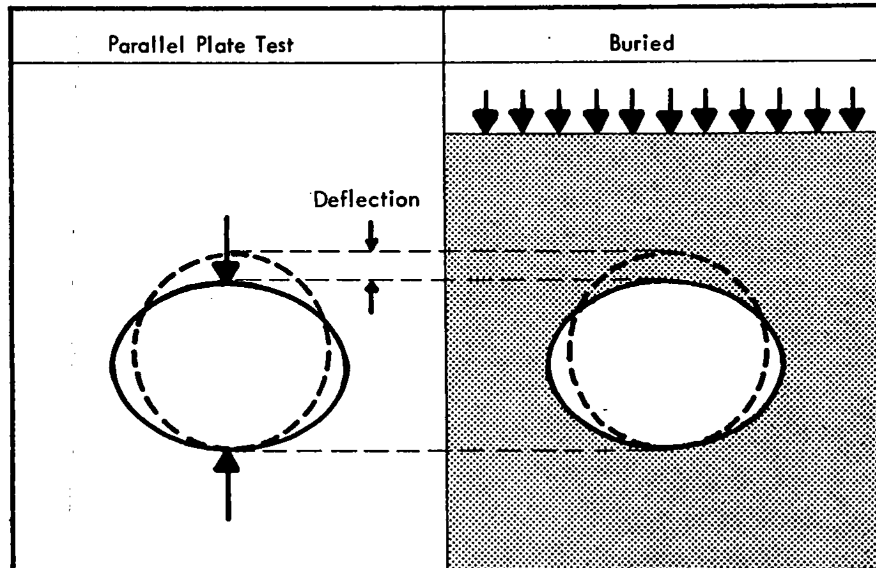
Spangler presented a formula for bending moment in the same paper which presented the Iowa deflection formula (E.2). The bending formula, however, predicts unaccountably high moments for very flexible pipe, and it is not considered further herein.

A simplified approach has been used to evaluate bending stress and strain in buried plastic pipe. The approach is based on **ring bending** theory, which describes behavior of a ring subjected to diametral compression, which is produced in two-edge bearing and parallel plate tests. In-ground deflections are predicted by theory, and then this predicted deflection is used in conjunction with the common ring bending formulas to estimate moments (E.7). That is, it is assumed that the bending stresses and strains in the buried condition are proportional to those which occur in ring bending at the same deflection (Fig. E-2). The constant of proportionality, called the moment factor, is used to account for the effects of bedding on the moments in buried pipe, and will be evaluated in Section E.4. The ring bending formulas are:

$$\Delta_y = 0.149 \frac{W r^3}{EI} \qquad \text{Eq. E.6}$$








Parallel Plate Ring Bending Strain x MF = Buried Ring Bending Strain where MF = 0.75 to 1.5, depending on bedding quality.

FIG. E-2 SIMPLIFIED MODEL FOR BENDING STRAIN IN BURIED PIPE

$$M_I = 0.318\ Wr \qquad \text{Eq. E.7}$$

where:

$\Delta_y$ = vertical deflection, in. (mm)

$W$ = load on pipe per unit length, lbs/in. (N/mm)

$M_I$ = moment at invert and crown, in.-lb/in. (N-mm/mm)

The formulas can be combined with beam theory and the moment factor to give the following strain-deflection relationship:

$$\varepsilon_b = 8.54 \left(\frac{I_c}{d\,S}\right)\left(\frac{\Delta}{d}\right) \times MF \qquad \text{Eq. E.8}$$

where:

$S$ = pipe section modulus per unit length, in.$^3$/in. (mm$^3$/mm)

$I_c$ = moment of inertia of pipe wall per unit length, in.$^4$/in. (mm$^4$/mm)

$\varepsilon_b$ = ring bending strain, in./in. (mm/mm)

$MF$ = empirical moment factor to account for bedding

For a smooth-wall section, the above equation reduces to:

$$\varepsilon_b = 4.27 \left(\frac{t}{d}\right)\left(\frac{\Delta}{d}\right) \times MF \qquad \text{Eq. E.9}$$

**Effects of perforations:** The above analysis is applicable to overall strains in the pipe wall. In the case of underdrain pipe, additional account must be made for the stress concentrations caused by the perforations. Perforations can be in the form of holes or circumferentially oriented slots. These create stress concentrations which increase the stress or strain above the average maximum values existing in the wall. The magnitude of the increase expressed as strain rather than stress, depends on the size and geometry of the hole, as follows (E.20):



- Circular hole in solid wall in bending (i.e., smooth-wall pipe such as PVC DR-35 and DR-41): the strain concentration factor varies between 2 and 2.5. A typical value of 2.25 is assumed.

- Circular hole in wall in uniform tension (i.e., one shell of ABS composite pipe, or corrugated tubing): the classical value for the strain concentration factor for this case is 3.0.

- Slot with rounded ends (i.e., corrugated tubing): the stress concentration factor for an elliptical slot having an aspect ratio of 8 : 1 (assumes a 1 inch (25 mm) circumferential slot, 1/8 in. (3 mm) wide) is 1.3. Higher aspect ratios found on many pipe reduce this value.

Stress or strain concentrations provide sites for crack propagation. Since crack growth in compression is not a realistic possibility, the perforation factors above need only be applied to the net tension (bending tension minus ring compression) at the location of the perforation. Since tension can only be caused by bending, which is variable around the circumference of the pipe, the location of perforations is important, as discussed below.

Slot locations for present corrugated PE tubing are frequently located 120° apart circumferentially, and on the inside corrugation. The critical tension occurs only when the perforation is located at the invert or crown. Thus, the invert bending strain should be used to compute net tension.

Hole locations in smooth-wall pipe (specification SGH PVC-TD in Appendix A2) are located in the lower half of the pipe, but they are arranged and the pipe is placed so that they are not at or near the invert. In this case, the springline bending strain should be used since perforations are located near springlines.

If perforations are located at the midpoints between the springline and invert, the effects of stress concentrations may be neglected altogether, because bending stresses are small at this point of inflection.

## Elasticity Solution

Burns and Richard derived a solution for stress resultants and deflections of buried pipe, based on theory of elasticity (E.4). The model used in the Burns and Richard approach is a circular conduit embedded in a homogeneous, isotropic, linearly elastic soil. The solution provides two sets of equations, one for the case of zero friction at the soil-pipe interface (full-slip) and one for full friction (no-slip). The equations are somewhat cumbersome and since they are available in (E.1) they will not be given here. It should be noted that the equation for moment shown in (E.1) for the no-slip case is in error; the first term inside the brackets should be the same as for the full-slip case.

The Burns solution which considers only an idealized and uniform soil embedment does not account for the effects of variations in bedding, which are extremely important, and which are bound to occur in the field. As will be discussed later, an empirical factor is used herein to account for the effects of bedding variation.

Like the Iowa formula, the Burns solution is based on linear theory, and thus, the soil is assumed to be linear and elastic. As discussed, and shown by a soil stress-strain curve (Fig. E-1), the use of a stress-dependent $M_s$ accounts, in part, for non-linear behavior. Alternately, non-linear behavior can be handled by iteration, by applying the load incrementally, and by using an appropriate soil modulus for each increment.

## Buckling

The buckling behavior of buried flexible pipe has received some theoretical treatment which remains largely unsubstantiated by test. Three formulas for buckling stress which are in current use are those developed by the Bureau of Public Roads (E.16), Meyerhof and Baikie (E.1) and Chelepati (E.17). A number of design methods for plastic pipe use the Chelepati formula, or variations thereon. This formula is given below:

$$p_{cr} = C\sqrt{M_s \frac{EI}{d^3}} \qquad \text{Eq. E.10}$$



where:

$p_{cr}$ = critical buckling pressure, psi (kPa)

$C = 6\sqrt{B\,C}$

$$B = \left[1 - \left(\frac{r}{r_o}\right)^2\right] \Bigg/ \left\{(1 + \nu_s)\left[1 + \frac{r}{r_o}^2 (1 - 2\nu_s)\right]\right\}$$

$$C = \left[(1 + \nu_s)(1 - 2\nu_s)\right] / (1 - \nu_s)$$

$r$ = mean pipe radius, in. (mm)

$r_o$ = distance from springline to ground surface, in. (mm)

$\nu_s$ = Poisson's ratio for soil

$M_s$ = constrained modulus of soil (can be taken equal to E'), psi (kPa)

$E_v$ = modulus of elasticity of pipe material, psi (MPa)

Watkins, Szpak and Allman (E.7) proposed a method similar to the Chelepati solution but they applied a factor to account for the reduction in buckling strength which results from ovalling and wall thickness variations, as follows:

$$C_D = \sqrt{\left(\frac{d_{min}}{d_{max}}\right)^3 \left(\frac{t_{min}}{t_{max}}\right)^3} \qquad \text{Eq. E.11}$$

where:

$C_o$ = correction factor

$d_{min}$, $d_{max}$ = minimum and maximum outside diameters of deflected pipe, in. (mm)

$t_{min}$, $t_{max}$ = minimum and maximum wall thicknesses, in. (mm)

If the wall thickness is assumed constant and the deflection is 10%, $C_D$ = 0.74. Thus, a deflection of 10% results in a 26% reduction in buckling capacity.

Since buckling rarely governs a design, the following simplified formula is recommended for a preliminary evaluation. If this formula proves to govern design, a more detailed analysis can be made.

$$P_{cr} = C_B \; C_D \sqrt{M_s\,(PS)} \qquad \text{Eq. E.12}$$

where $C_B$ is a simplified constant from Eq. E.11 assuming $\nu_s = 0.35$ and $r/r_o = 0.33$ (equivalent to a depth cover of one pipe diameter). $C_B$ is equal to 0.50 for deep burial (a different value for $C_B$ will be presented in Appendix G for shallow burial), $C_D = (d_{min.}/d_{max.})^3$ (it is assumed that $t_{min.}$ is used in the calculation, and no correction is required for variation), and PS = pipe stiffness = $53.7\ EI/d^3$. An appropriate safety factor should be applied when using this formula.

The above theory is for general buckling of the pipe. It does not deal with local buckling of pipe elements which may be a critical consideration in corrugated or composite wall pipe. Evaluation of local buckling of the nature which may occur in such pipe, is beyond the scope of this project.

## E.3 Evaluation of Deflection Theory in Field Tests

The data gathered in project field tests provides a useful base for evaluating the Iowa and Burns and Richard formulas for deflection introduced above. The test installations included a wide range of variables, including pipe type and stiffness, soil type and density, and installation conditions. The field data also provides a basis for developing, evaluating, and refining the empirical constants required in practical application of the analysis methods.

**Iowa Formula**

The validity of the Iowa deflection formula (Eq. E.2) is evaluated as follows: First, the key coefficients (bedding factor, deflection lag factor) in the equation are evaluated based upon an overall review of the test data. These constants are then used in the formula, together with calculated loads, and with E' interpolated from Table E-1, to predict <u>average</u> deflection for each pipe at each site. Finally,



the predicted and measured average deflections are compared to test the validity of the approach.

**Bedding factor:** The data presented in Table B-5 provides a basis for direct evaluation of the bedding shape and its influence on pipe deflections. Comparison of the mean and maximum deflections for the haunched and unhaunched case indicates that the omission of haunching increases the pipe deflection more than the 33 percent predicted by the bedding factor derived by Spangler. Review of this data indicates that the maximum bedding factor for flat bedding should be increased to 0.13 from the value of 0.11 proposed by Spangler. Since the bedding factor can vary from 0.083 to 0.13, the bedding shape may change deflections by as much as 60%. In subsequent evaluation of field test results, K is taken as 0.083 for haunched pipe, and 0.13 for pipe where haunching was purposely omitted.

**Deflection Lag Factor/Cumulative Deflections:** As will be shown, deflections can increase from initial values for at least two reasons. First is deflection lag defined earlier, which is associated with the time-dependent or "viscoelastic" response of the soil under sustained earth and pipe pressure. Although plastics' stress-strain behavior is time-dependent, this has very small influence on time-dependent deflection response. The second, termed here "cumulative deflection," accrues with time from cyclic stresses due to surface applied wheel loads.

The following information was obtained from project field tests:

- In Maine, the several types of pipe buried 2 feet below the unpaved surface of a turn-around for maintenance vehicles, showed significant cumulative deflections with time. The DR-41 PVC pipe, which was embedded in a more dense material than the other pipe, and the stiff ABS composite pipe, showed significantly less cumulative deflection than the other pipe.

- Initial deflections of NH-1 pipe, installed five feet below the I-95 bypass for 14 months, were not obtained. However, the portion of the pipe which was embedded in stiff, well-compacted material under the heavily travelled lanes, deflected more than adjacent pipe which had less stiff embedment and which was not subject to traffic.

- The NH-2.1 pipe, which was installed in dumped and uncompacted sand embedment, displayed significant increases in deflection after the top of the trench was trafficked by construction vehicles, when these pipe were covered with four feet of earth. Very small increases in deflections were recorded on the addition of 19 ft (5.8m) of earth cover.

- In Illinois field tests on shoulder underdrain installations, very small time-dependent increases in deflection occurred in shallowly buried pipe and tubing installed in sand. Illinois measurements were made starting immediately after installation, which frequently involved construction traffic such as sand trucks and equipment used in paving.

- Illinois conducted field tests on an RPM storm sewer buried in sand 3 ft (0.9m) below the pavement of a city street. This very flexible pipe continues to show significant yearly increases in deflection 5 years after installation.

Considering the above it appears that deflection lag is accelerated by construction traffic, and may be negligible thereafter under sustained earth loads. Although field data is extremely limited, continued traffic appears to cause a continuous increase in deflection, beyond that which would occur solely under earth load. Unfortunately, the specific conditions of traffic, pipe type, embedment stiffness and cover which renders cumulative deflections tolerable cannot be determined from the state-of-the-art.

Finally, Howard's values of E' are based on deflection measurements which, in limited cases, were made on pipe installed for a few years. Thus, the Bureau of Reclamation E' values undoubtedly contain some lag deflections, but to an extent unknown.

In consideration of all of the above, a deflection lag factor of 1.0 is used in conjunction with Howard's E' values in the subsequent evaluation of field test results. For materials covered herein, a lag factor of 1 to 1.5 is assumed appropriate.



**Embedment Stiffness—E' and $M_s$:** In the evaluation of the Iowa formula, values of E' were interpolated from Table E-1, based on the soil type and degree of compaction measured on materials at each test installation. Laboratory confined compression tests were also performed on each embedment material used for the field installations (Appendix B). The confined compression modulus was obtained by determining the secant modulus of the stress-strain curve for the depth of cover provided at each site (See Fig. E-1).

Values of $M_s$ obtained as above are cross plotted against E' in Figure E-3. The comparison of E' vs. $M_s$ indicates that there is a reasonably good correlation considering the disparate sources of the data. The best fit relationship is approximately E' = 0.85 $M_s$. Determination of E' involves judgment in interpolating values from Table E-1, however, and the values obtained for $M_s$ would vary under different earth loads since $M_s$ is non-linear. Thus, the correlation made here between $M_s$ and E' is not intended to be precise, but rather a practical comparison. The high degree of variability in soils and the poorer correlation which would be expected over a broad range of cover heights renders the use of a coefficient such as 0.85 more refined than is justified. Thus, for purposes of further discussion, $M_s$ and E' are assumed to be equal.

**Earth Load Deflections**

Table E-2 compares the average earth load deflections measured in field tests for each pipe type with the deflections predicted by the Iowa formula in which the constants and coefficients discussed above are used. The comparison shows the following:

- Measured average deflections were higher than predicted average deflections at NH-1 (PVC pipe buried 5 ft (1.5m) below the I-95 bypass). The differences were significant, particularly for the Class I and Class II embedment materials which were below traffic lanes.

- Measured average deflections are reasonably close to the predicted average deflections at NH-2 and NH-2.1, where the pipe were ultimately buried

TABLE E-2 - PREDICTED VS. MEASURED DEFLECTIONS – MODERATE TO DEEP BURIAL

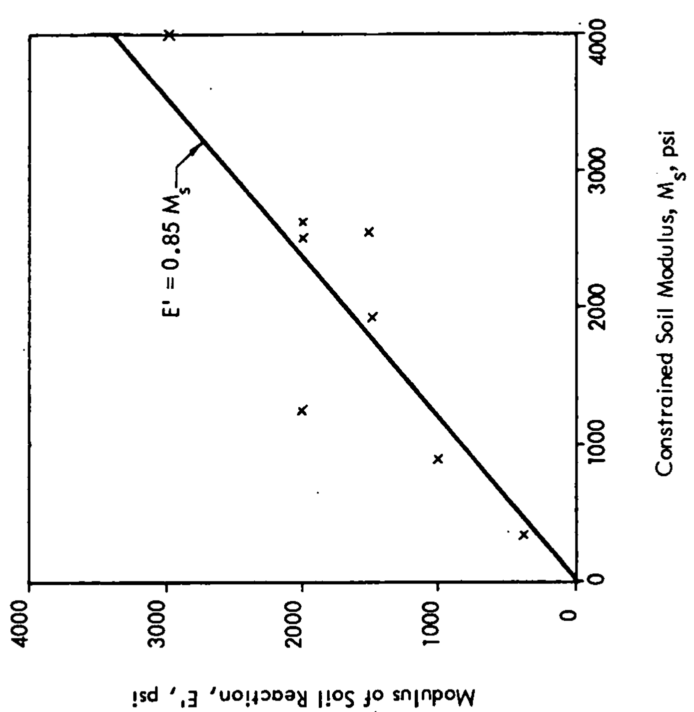
| Test Site | Cover / Traffic | Pipe Type | Pipe Stiffness (lb/in./in.) | Embedment | | Haunching | Average Deflection (%) | | Maximum Deflection (%) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Class (ASTM D2321) | Compaction* (%) | | Predicted (Eq. E.2) | Measured Average | Estimated (Avg.+Table E-3) | Measured (99-Percentile) |
| NH-1 | 5 ft / Interstate Traffic above Classes I and II Materials only | PVC DR-41 | 44 | I | – | Yes | 0.3 | 2.9 | 3.2 | 5.7 |
| | | | | II | 94 | Yes | 0.4 | 2.4 | 3.3 | 4.3 |
| | | | | III | 88 | Yes | 0.8 | 1.9 | 3.9 | 4.3 |
| | | PVC DR-35 | 77 | I | – | Yes | 0.3 | 2.0 | 3.2 | 2.7 |
| | | | | II | 94 | Yes | 0.4 | 0.5 | 3.3 | 1.9 |
| | | | | III | 88 | Yes | 0.7 | 0.3 | 3.9 | 1.3 |
| NH-2 | 20 ft / Temporary Construction at 4 ft Cover | PE Smooth | 18 | III | 92 - 95 | Yes | 1.4 | 0.8 | 5.0 | 2.2 |
| | | PE Corr. | 31 | | | | 1.4** | 2.9 | 5.4 | 5.5 |
| | | PVC DR-41 | 44 | | | | 1.4 | 1.7 | 3.9 | 3.1 |
| | | PVC DR-35 | 77 | | | | 1.3 | 1.3 | 3.8 | 2.2 |
| | | ABS Comp. | 230 | | | | 1.1 | 0.8 | 1.9 | 1.3 |
| NH-2.1 | 23 ft / Temporary Construction at 4 ft Cover | PE Corr. | 31 | III | 80 - 89 (dumping) | Yes | 3.7** | 2.2 | 9.9 | 6.6 |
| | | | | | | No | 5.8** | 5.7 | 16.2 | 9.0 |
| | | PVC DR-41 | 44 | | | Yes | 3.3 | 3.4 | 6.8 | 5.7 |
| | | | | | | No | 5.3 | 4.4 | 10.5 | 10.1 |
| | | ABS Comp. | 230 | | | Yes | 2.2 | 1.0 | 4.1 | 2.0 |
| | | | | | | No | 3.5 | 1.8 | 6.4 | 3.4 |

* Compaction is % of maximum dry density (AASHTO T-99). Not determined for Class I material at NH-1.

** Deflection does not include effects of circumferential shortening due to high ring compression.

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$

E-25




Note: 1 psi = 6.9 kPa

FIG. E-3 CORRELATION BETWEEN E' AND $M_s$ OF EMBEDMENT SOILS

E-24

about 20 and 23 ft (6 and 7m) respectively, after receiving construction traffic with 4 ft (1.2m) of cover.

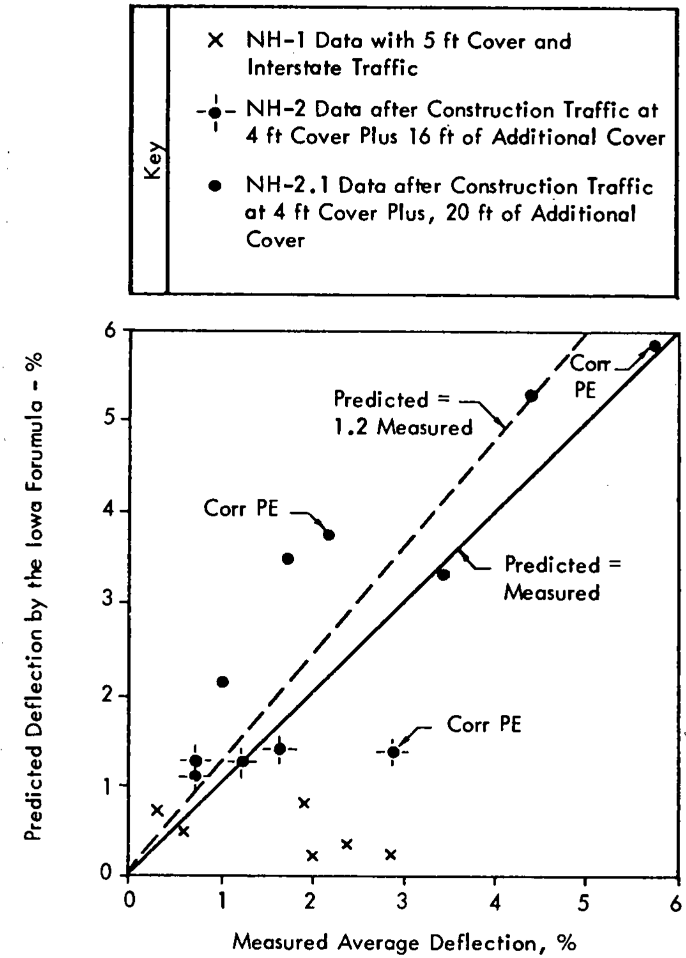
- For NH-2 the Iowa formula predicts relatively small differences in deflection due to changes in the magnitude of pipe stiffness, while the magnitude of actual deflections generally displayed a definite trend with pipe stiffness. Except for the smooth-wall PE, the average deflections decreased with increasing pipe stiffness.

- The smooth-wall PE in the NH-2 study deflected only slightly considering its low pipe stiffness. This is thought to be due to vertical ovalling during installation, however, early deflection data is not available for verification of this.

Figure E-4 shows the correlation between measured average deflections and deflections predicted by the Iowa formula. An estimated best-fit straight line through the origin indicates that the predicted deflection is 20% greater than the mean, if NH-1 data points (five feet of burial and interstate traffic) are neglected. For practical purposes, the Howard values of E' when used in conjunction with the Iowa deflection formula and appropriate constants developed herein provides a reasonable estimate of average deflection for most cases.

As noted, the average deflection of some installations were significantly greater than predicted by the above relationship. The interstate traffic loads applied to pipe at moderate burial depths may be the cause of the high deflections at NH-1 (see Appendix G). The high deflection for the corrugated PE at NH-2 may be the result of normal scatter, excessively high stress due to the combined effects of ring compression and ring bending which far exceeds the estimated working strain, significant circumferential and diametral shortening due to large ring compression stress (estimated to be greater than 1%), variations in pipe diameter as manufactured, insufficient stiffness to resist the extremely heavy construction traffic of NH-2, ineffective longitudinal distribution of localized loads due to the low longitudinal stiffness inherent in the corrugations, or inexperience of the installation personnel who worked with this very flexible material for the first time during NH-2.






Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. E-4 CORRELATION BETWEEN PREDICTED AND MEASURED AVERAGE DEFLECTIONS

In sum, the Iowa formula provides a reasonable estimate of average deflection provided that the coefficients discussed above and E' values taken from Table E-1 are used in the equation. As shown by the behavior of the NH-2 corrugated PE tubing installation, and the NH-1 pipe at moderate burial under interstate traffic, this assumption is not valid for all conditions, and this, at present, can only be explained in qualitative terms.

**Maximum Deflection:** The maximum measured field deflection is defined herein as the 99-percentile deflection, which is equal to the average deflection plus 2.33 times the standard deviation. The standard deviation represents a variety of factors which lead to scatter including variations in the pipe as manufactured, differences in deflection between the pipe barrel and the bell and spigot joint (which is generally much more rigid), variations in deflection induced while installing the pipe, variations in the bottom and side support provided, and errors in measurement. While in the future many of these contributions to scatter, and hence maximum deflection, ideally should be isolated and treated individually, in this study most of them were lumped together, and considered as a single contribution, termed "installation deflections."

The Bureau of Reclamation approach to determining the maximum deflection (Table E-1) was evaluated against project field data. In this study, appropriate Bureau values for "upper limit of average deflection" and the "upper limit of deflection" were added to the average field deflections. The resulting deflection was then compared to the maximum (99-percentile) deflections from field data. With the exception of pipe subjected to traffic, the Bureau's approach predicts maximum deflections higher than those measured. In the case of the stiffer pipe, however, the Bureau approach resulted in deflections which were much larger than measured.

The above finding suggests the use of allowances for installation deflection which vary not only with level of compaction, as do the Bureau values, but also with pipe stiffness. Such factors were synthesized from the Bureau data and the results of Project field tests. They are proposed in Table E-3 for haunched and unhaunched pipe respectively. In recognition of the higher bedding constant required for pipe



TABLE E-3 - TENTATIVE ALLOWANCES FOR INSTALLATION DEFLECTIONS

| Haunch Condition | Pipe Stiffness (lb/in./in.) | Installation Deflection (%) Less than 85% of Maximum Dry Density or Dumped | 85 to 95% of Maximum Dry Density | Greater than 95% of Maximum Dry Density |
|---|---|---|---|---|
| Haunched | Less than 40 | 6 | 4 | 2.5 |
| | 40 to 100 | 4 | 3 | 1.5 |
| | Greater than 100 | 2 | 1 | 0.5 |
| Not Haunched | Less than 40 | 10 | 6 | 4.0 |
| | 40 to 100 | 6 | 5 | 2.0 |
| | Greater than 100 | 3 | 2 | 1.0 |

**Notes**

1. Maximum dry density determined in accordance with AASHTO T-99
2. Haunching omitted condition not recommended for design.
3. Dumped materials, and materials less than 85% of Maximum Dry Density (AASHTO T-99) not recommended for design.
4. 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.C28 g/mm$^3$

without haunches, the allowances for unhaunched pipe were taken as 0.13/0.083 = 1.6 times the allowances for the haunched condition.

A comparison of "estimated" maximum deflections with predicted maximums based on the proposed allowances for installation deflections is presented in Table E-2. Except for the DR-41 pipe in NH-1, the estimated maximum deflections exceed or are very close to the measured maximums for all haunched pipe at NH-1, at NH-2, and at NH-2.1. The estimated maximum deflections are not as good for the NH-2.1 pipe which were not haunched, but higher variability would be expected for this case.

The above deflection estimates are highly empirical, and they are based on very limited data. The general significance of the above findings are as follows:

- Every reduction in quality of the installation (primarily lower density) results in increases in the average deflection, as is shown by the Iowa formula, and in the variability of the system (standard deviation). The latter results in a maximum deflection which is considerably more than the average predicted by the deflection formulas alone.

- Theory predicts a smaller trend in deflection with pipe stiffness, than was observed in the field tests. This discrepancy appears to be the result of installation-related variables which are not accounted for by theory. That is, the stiffer pipe provides a firm surface against which to compact embedment soil. This provides more uniform soil density, and, in general, lower average and total deflections. It is here that the low stiffness of plastic drain pipe relative to metal pipe of similar diameter may have the greatest influence.

- Installation deflections may be substantially independent of load. This means there is an inherent variability in any system which will provide a certain amount of deflection regardless of depth or height of cover. For example, very flexible pipe in a loose soil can be expected to deflect 6 percent even if no earth load is in place above the crown.



**Burns Theory for Deflection**

The Burns theory for deflection of elastic rings surrounded by an elastic medium (described earlier) was also examined in light of the field tests. In this evaluation $M_s$ was used as the modulus of the soil. In addition, a Poisson's ratio of 0.35 was assumed based on a review of the literature on this property.

The Burns theory does not account for the effects of bedding other than that provided by an ideal elastic solid; hence, in the evaluation of the theory as applied to the un-haunched condition at NH-2.1, the predicted deflection for the ideal case was multiplied by an empirical coefficient obtained from a ratio of bedding factors used with the Iowa Formula. The coefficient was 1.6, which is the ratio of the bedding factor for poor bedding (0.13) to the bedding factor for full $90^{\circ}$ bedding (0.083).

A comparison of the Burns deflections calculated as above with the average Iowa deflections shown in Table E-3 indicates that the Burns deflections are between 2/3 and 1.0 times those estimated by the Iowa formula. This level of agreement is judged excellent in light of the major differences in the assumptions involved in the two approaches.

## E.4 Evaluation of Ring Bending and Ring Compression Strains

Strain gage data from the NH-2.1 test program has been presented and results have been summarized in Appendix B. This data provided extremely valuable information on the magnitude, distribution, and time-dependence, of ring bending and ring compression strains, and the important influence of bedding shape on these strains, as is discussed below.

### Ring Bending Strains

**Time Dependence:** The data which was presented in Figure B-9 illustrates that bending strain is essentially constant when the loading effects due to construction traffic and earth loads have stabilized. This is further evidence that a plastic pipe remains in a fixed oval indefinitely once loads have stabilized.

**Distribution:** The circumferential distribution of ring bending strains, which was presented in Figure B-10b, is relatively symmetrical, and logical. This lends confidence in the validity of the measurement, and as important, it demonstrates that there is no unusual behavior introduced by plastic materials.

**Effects of Bedding:** Figure B-10b also demonstrates that a well-haunched pipe exhibits significantly less peak bending strain at the invert than does pipe without haunching, but that the nature of the bedding has small effect on the strains at the crown and springlines.

**Magnitude:** Figure E-5 contains a plot of invert bending strain versus deflection for the instrumented test pipe at NH-2.1. The figure also shows the linear strain-deflection relationships for the ring bending theory, and lines which define strains which are 1.5 and 0.5 times the ring bending theory. The Burns and Richard theory, which considers a perfectly bedded pipe, yields a strain/deflection relationship which is approximately equal to 0.5 times that obtained from ring bending theory.

Figure E-5 shows that the data for the unhaunched pipe is widely scattered, varying between 0.4 and 1.6 times ring bending. The data for the haunched pipe is much more uniform, varying between 0.4 and 0.6 times the ring bending value. This indicates the following:

- The omission of haunching produces significantly higher invert strains than found in a haunched pipe, and the strains are also much more erratic.
- Strains in a haunched pipe are relatively low, and they conform closely to the idealized bedding case assumed in the Burns and Richard theory.

This evaluation indicates that the ring bending theory can be used to approximate bending strains in a buried pipe provided that the theoretical values are modified by a **Moment Factor** to account for bedding conditions. The data, which is very limited, suggests design values for this moment factor of 1.5 for unhaunched pipe and 0.75 for haunched pipe. An intermediate value of 1.0 might be used for a typical installation where haunching is specified but field control is uncertain.



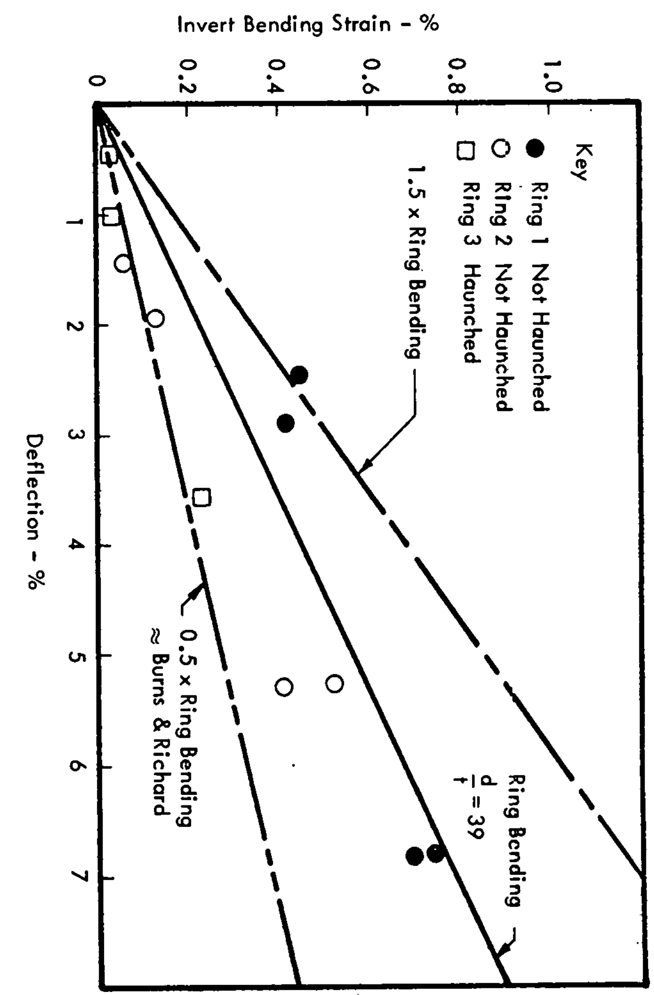



FIG. E-5 INVERT BENDING STRAIN VS. DEFLECTION FROM NH2.1 DATA

## Ring Compression Strains

Following are key results obtained from analysis of ring compression strain data:

**Time Dependence:** The changes in ring compression strain with time have been presented in Appendix B, Figure B-9. The strains shown there are plotted to the same scale as ring bending strains, which is logarithmic with time. The trends shown for ring compression strain are similar to those for bending discussed above, except that ring compression strains increased slightly during periods of no activity.

Figure E-6 shows ring compression strains for haunched and unhaunched pipe plotted against time on a linear scale to facilitate evaluation. The figure also shows the theoretical ring compression strain, based on the assumption that the applied prism load is constant, which assumes a state of pure creep. For calculation of the theoretical strains, it was assumed that the load was applied instantaneously in 2 discreet increments (E.19). The first increment is applied at the time of initial pipe installation and the second is applied at the time the embankment was installed. This figure shows:

- In the short-term, immediately after the embankment was installed, the ring compression/prism load theory results in a conservative prediction of thrust for the haunched pipe, and is very close to the measured thrust for the unhaunched pipe.

- In the long-term, the measured strains increase with time, but at a lesser rate than as predicted by theory.

- The measured thrust strains showed a significant increase after the period of construction traffic. During this period, the measured strains for both installation conditions exceeded those predicted by the ring compression-prism load theory.This may be one source of the cumulative deflections noted earlier.





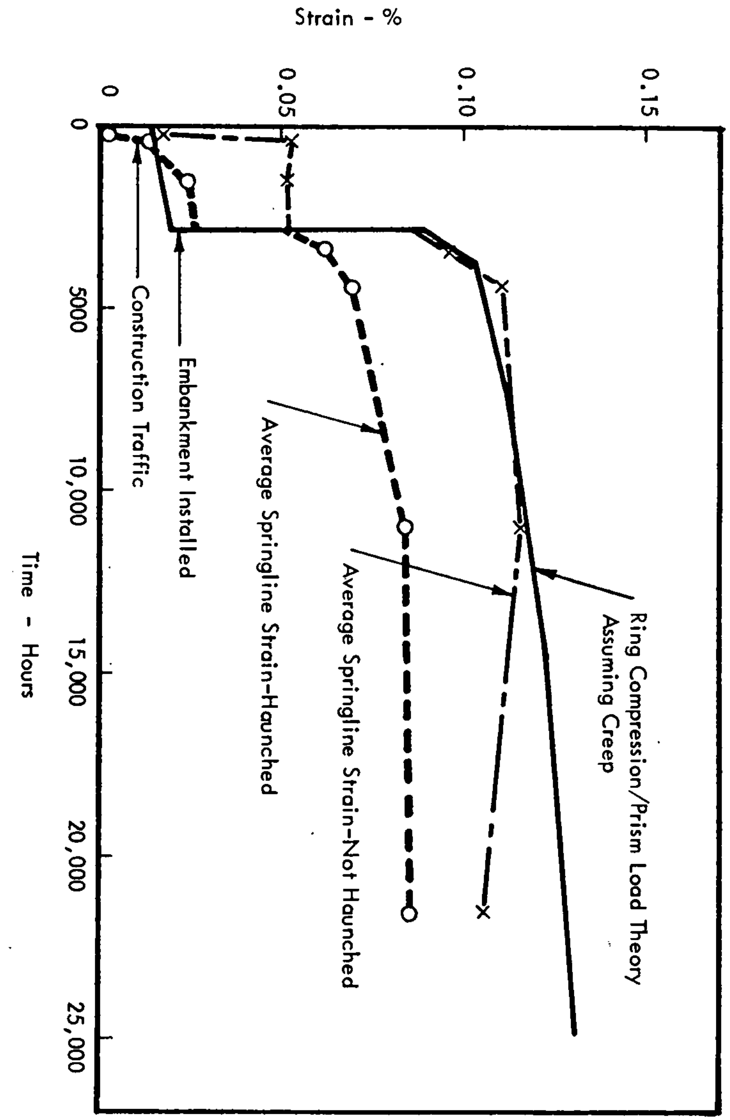



FIG. E-6 CHANGE IN RING COMPRESSION STRAINS WITH TIME AT NH2.I

The above analysis indicates that the ring compression-soil prism theory provides conservative predictions of compressive thrust strains. However, the assumption of pure creep or constant load is too conservative. Long-term behavior under compressive thrust appears to be a mix of creep (constant load) and relaxation (constant strain). Although much more substantiation is needed, it appears that it may be assumed that ring compression strains increase by a factor of 2 in the long-term, at least for the rigid PVC material tested.

It is clear from the examination of Figure E-6, that the ring compression-soil prism theory does not account for the obvious reduction in compression strain due to haunching. However, for smooth-wall pipe the contribution of compressive strains to the total strain is small.



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# APPENDIX F

## LABORATORY STUDIES OF PIPE RESPONSE TO CONCENTRATED LOADS

### Objective

Behavior of pipe under shallow burial conditions is a critical consideration for transportation drainage, but this behavior is not well understood. A limited laboratory study was undertaken (F.1) to investigate this problem. The objectives were two-fold:

- To characterize pipe behavior under concentrated surface loads.
- To determine whether or not available analysis methods for deeply buried pipe can be modified to cover the concentrated load case.

### Scope

The test program was an exploratory laboratory study designed to examine the major variables which affect pipe behavior under shallow burial conditions, depth of cover, embedment stiffness, and pipe type. The results of the laboratory tests were compared to theoretical predictions obtained from existing theory for deeply buried pipe, to determine the conditions under which such a thoery could be applied to the problem of concentrated loads.

### Materials

The test pipe, both nominally 6 in. (150 mm) in diameter, were:

- Smooth-wall PVC sewer pipe, ASTM D 3034 DR-35, Resin 13364 ($E_{min}$ = 500,000 psi (3,450 MPa)).
- Corrugated-wall PE tubing, ASTM F 405, Pipe Stiffness = 40 psi (276 kPa) at 5% deflection.

Embedment material was concrete sand (ASTM C 33). The tests were conducted with this embedment at 90% and 100% of maximum dry density (AASHTO T-99), referred to herein as the **loose** and **dense** conditions, respectively.

### Apparatus

The tests were conducted in a 35 in. (0.89 m) diameter, 30 in. (0.76 m) deep cylindrical steel tank, as shown in Figure F-1. Instrumentation used was as follows:

- Load was applied to the soil with a 10,000 lb (4540 kg) capacity mechanical jack through a 10 in. (0.25 m) diameter plate. Load was measured with a load cell instrumented with strain gages.
- Circumferential pipe strains were measured in some tests on the PVC pipe using foil resistance strain gages. The gages were mounted inside and outside the pipe at the crown, invert, and springlines.
- Soil stresses near the pipe-soil interface were measured with 1.5 in. (38.1 mm) diameter diaphragm-type stress cells, instrumented with strain gages.
- Pipe deflections were measured with dial gages, accurate to $\pm$ 0.0005 in. (0.013 mm).

### Procedure

Samples of each pipe were tested for pipe stiffness and wall thickness in accordance with ASTM product specifications. In addition, confined compression tests were performed on soil samples to allow determination of the **constrained modulus** ($M_s$, see App. E). Standard equipment for soil consolidation tests was used.



Each pipe was embedded in sand, in the test tank. Six inches of sand bedding was placed and compacted in the bottom of the tank. All pipe except one were placed in a groove in the bedding which conformed to the lower $90^{o}$ arc of the pipe. One pipe was placed on flat bedding. After each pipe was placed, the soil stress gages and the backfill were installed. The backfill was placed in 6 in. (150 mm) lifts for the loose condition and 2 in. (50 mm) lifts for the dense condition. The depths of cover for the tests were 6, 12 and 18 in. (150, 300, and 450 mm) over the crown of the pipe. The test for the effects of flat bedding was made with 12 in. (300 mm) of cover with loose embedment.

Load was applied to the surface of the soil, directly above the middle of the pipe. Loading was increased in increments until either the soil failed in bearing, or a maximum load of 10,000 pounds (4540 kg) was reached. For the loose sand tests, load was applied in 1,000 pound (454 kg) increments, until soil bearing failure occurred, typically at a load of 5,000 (2,272 kg) pounds. The load for the dense sand tests usually reached 10,000 pounds without soil bearing failure.

All instrumentation was read after each load increment was applied. Measurements were made of the vertical and horizontal deflections (changes in diameter) of the pipe at the centerline of the load, and at 6 in. (150 mm) and 12 in. (300 mm) offsets from the load axis. For the dense tests after maximum load was reached, the load was released, and then reapplied in a single increment, to the maximum value.

Strains were measured in the PVC pipe in all tests with 12 and 18 in. (300 and 450 mm) of cover.

### Results

Results of tests for physical properties of the pipe are presented in Table F-1. Both pipe met applicable specification requirements and the PVC pipe was 50% stiffer than required. Soil stress-strain curves are presented in Figure F-2.

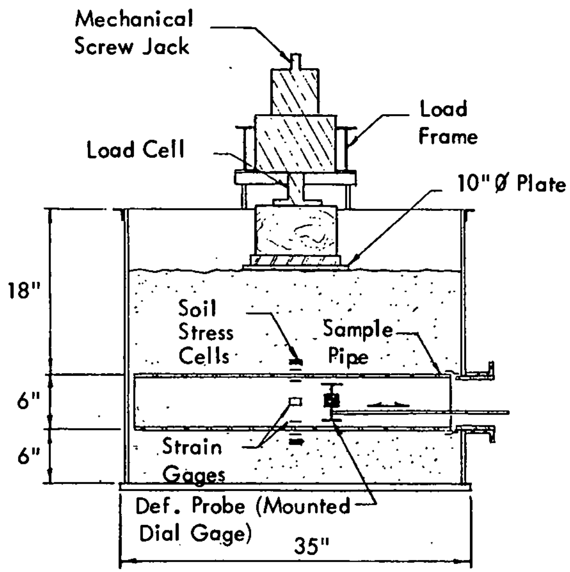



**FIG. F-1 CROSS SECTION THROUGH TEST TANK AND LOAD APPARATUS**

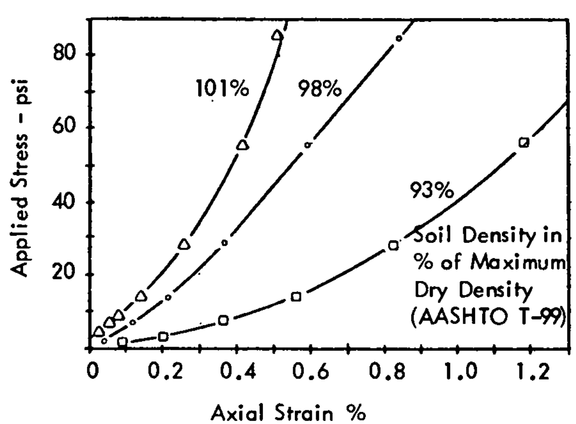



**FIG. F-2 STRESS-STRAIN CURVES FROM COMPRESSION TESTS ON EMBEDMENT MATERIAL**

Note: I lb/in./in. = I psi = 6.9 kPa; I lb = 2.2 kg; I in. = 25.4 mm; I ft = 0.3048 m



**TABLE F-I - PHYSICAL PROPERTIES OF TEST PIPE**

| Sample No. & Type | Wall Thickness (in.) | | Pipe Stiffness - (lb/in./in.) | |
|---|---|---|---|---|
| | ASTM | Measured | ASTM | Measured |
| A-I Corrugated PE | None | - | 30 @ 5% deflection<br>25 @ 10% deflection | 40<br>33 |
| J-2 PVC | 0.180 min. | 0.188 | 46 min. | 68 |
| J-3 PVC | | 0.186 | | 69 |

Note: I lb/in./in. = I psi = 6.9 kPa; I lb = 2.2 kg; I in. = 25.4 mm; I ft = 0.3048 m



The soil stress cells provided somewhat erratic data, but always showed significantly higher stresses for the pipe in loose sand. Soil stresses mesured near the pipe-soil interface at the crown of the PE tubing are shown in Figure F-3.

Soil stresses near the pipe-soil interface (Fig. F-4) at the crown were significantly greater than stresses near the springlines and invert.

Pipe deflections decreased significantly with an increase in both depth of cover and soil density (Table F-2). The difference in ring stiffness of the two pipe systems had negligible influence on deflection at 6 in. (150 mm) cover. The stiffer PVC pipe deflected about one-half as much as the more flexible PE tubing at the greater depth covers.

In the dense sand condition, the second load cycle produced deflections up to 25% higher than the first cycle.

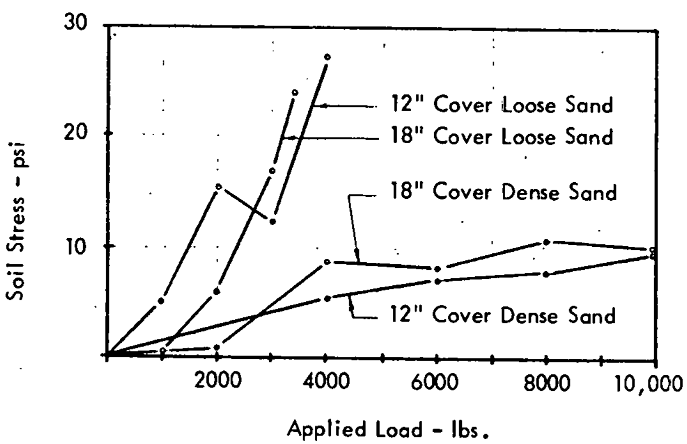
Trends in strain gages were consistent with deflection results. Peak bending strains always occurred at the crown, except in the pipe buried 18 in. deep in the dense soil, where the maximum strains occurred at the springlines. Table F-3 shows ring compression and ring bending strains, respectively, for the instrumented tests.

The pipe tested with flat bedding showed a slight increase in deflection and crown bending strains. The invert bending strains, however, increased 400%. Crown bending strains remained the greatest in magnitude.

### Evaluation of Elasticity Solution

A number of analysis methods for pipe-soil interaction were examined for their potential for describing behavior under concentrated surface-applied wheel loads. Athough the Burns and Richard solution (F.2, See also Appendix E) is based on a uniform loading condition, the solution provides a thorough description of the pipe-soil behavior, such as soil-stress, pipe stresses, and pipe deflections. Thus, the evaluation performed herein is intended to determine to what extent, and

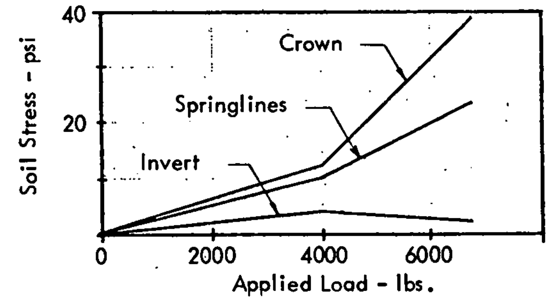
F-6




Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 lb = 2.2 kg; 1 in. = 25.4 mm

FIG. F-3 CROWN SOIL STRESSES FOR PE PIPE

F-7




Note: 1 psi = 6.9 kPa; 1 lb = 2.2 kg

FIG. F-4 TYPICAL PRESSURE DISTRIBUTION AROUND PVC PIPE WITH 6 IN. COVER IN DENSE SAND

F-8

TABLE F-2 - MAXIMUM DEFLECTIONS DUE TO 10,000 LB LOAD

| Pipe Type Stiffness (lb/in./in.) | Depth of Cover (in.) | Deflection % | |
|---|---|---|---|
| | | Loose * | Dense |
| PE, Corr. 40 | 6 | 10.2 | 4.2 |
| | 12 | 8.0 | 0.8 |
| | 18 | 2.0 | 0.6 |
| PVC 70 | 6 | 11.0 | 5.2 |
| | 12 | 3.6 | 0.5 |
| | 18 | 1.2 | 0.25 |

* Values extrapolated to 10,000 lb load for comparison purposes.

F-9

Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 in. = 2.2 kg

TABLE F-3 - PEAK RING BENDING AND RING COMPRESSION STRAINS IN PVC PIPE UNDER 10,000 LB LOAD

| Depth of Cover (in.) | Bending Strain (%) | | Ring Compression Strain (%) | |
|---|---|---|---|---|
| | Loose * | Dense | Loose * | Dense |
| 12 | 0.68 | 0.055 | 0.10 | 0.046 |
| 18 | 0.21 | 0.039 | 0.055 | 0.034 |

* Peak strains from tests in loose sand extrapolated to 10,000 lb load for comparison purposes.

Note: 1 in. = 15.4 mm; 1 lb = 2.2 kg

F-10

under what conditions the Burns and Richard solution can provide a practical description of buried plastic pipe under surface wheel loads.

Load on the pipe was taken as the calculated free field soil stress, under the centerline of the load, at the springline level of the pipe. The solution by Foster and Ahlvin for a load uniformity distributed on a circular area on an elastic halfspace was used in the load calculation (F.3). The theoretical soil stress was confirmed by tests without any pipe.

Soil stress-strain behavior was assumed to be linear, as defined by the constrained modulus. The modulus is typically computed as the slope of the secant from the origin of the stress strain curve, to a stress level which represents the confining pressure on the soil surrounding the pipe. This confining pressure makes the soil more stiff, and able to provide more support to the pipe. When considering a concentrated load directly over the pipe, the soil surrounding the pipe is under less pressure than the pipe, due to the concentrated nature of the load. Thus, for the purpose of this analysis, the effective vertical soil stress due to live load occurring at a lateral distance of two pipe diameters from the pipe center line was used for determination of the constrained modulus. This results in a modulus which is lower for the concentrated load case than would occur if the maximum pressure were applied by uniform earth pressure. Using this reasoning, $M_s$ was calculated as approximately 2,000 psi (13.8 MPa)for the loose soil condition, and 9000 psi (62 MPa) for the dense soil condition. Actual computed values are given in Table F-4. The results of the elasticity analysis are compared to the actual test results in Table F-4. The following are significant:

- The theoretical deflections for 6 in. (150 mm) of cover are much lower than observed in the tests.
- At 12 in. (300 mm) of cover, theoretical deflections are reasonably close to test values for the dense soil, and at 18 in. (457 mm) of cover the theoretical and test values are reasonably close for either soil condition.



**TABLE F-4 - COMPARISON OF ELASTICITY ANALYSIS WITH TEST RESULTS FOR 10,000 LB LOAD**

| Load Condition | Method | PVC Deflection % | PVC Ring Compression Strain (%) | PVC Ring Bending Strain (%) | Corrugated PE Deflection % |
|---|---|---|---|---|---|
| 6 in. cover | Burial Test | 11.0 | – | – | 10.2 |
| Loose soil | Elasticity Solution* | 3.6 | 0.22 | 0.32 | 5.2 |
| $M_s$ = 2,500 psi | Test/Theory | 3.1 | – | – | 2.0 |
| 12 in. cover | Burial Test | 3.5 | 0.10 | 0.68 | 8.0 |
| Loose soil | Elasticity Solution* | 1.4 | 0.075 | 0.13 | 2.0 |
| $M_s$ = 2,200 psi | Test/Theory | 2.5 | 1.3 | 5.4 | 4.0 |
| 18 in. cover | Burial Test | 1.2 | 0.055 | 0.21 | 2.0 |
| Loose soil | Elasticity Solution* | 1.0 | 0.043 | 0.086 | 1.4 |
| $M_s$ = 1,800 psi | Test/Theory | 1.2 | 1.3 | 2.4 | 1.4 |
| 6 in. cover | Burial Test | 5.3 | – | – | 4.3 |
| Dense soil | Elasticity Solution* | 1.0 | 0.19 | 0.076 | 1.6 |
| $M_s$ = 11,700 psi | Test/Theory | 5.3 | – | – | 2.7 |
| 12 in. cover | Burial Test | 0.5 | 0.046 | 0.055 | 0.75 |
| Dense soil | Elasticity Solution* | 0.4 | 0.067 | 0.029 | 0.6 |
| $M_s$ = 10,00 psi | Test/Theory | 1.3 | 0.7 | 1.9 | 1.2 |
| 18 in. cover | Burial Test | 0.25 | 0.034 | 0.039 | 0.55 |
| Dense soil | Elasticity Solution* | 0.24 | 0.039 | 0.020 | 0.4 |
| $M_s$ = 9,100 psi | Test/Theory | 1.0 | 0.9 | 2.0 | 1.4 |

Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 lb = 2.2 kg; 1 in. = 25.4 mm; 1 ft = 0.3048 m

- Theoretical ring compression stresses are within 30% of measured values for all tests where strains were measured.

- Agreement between theoretical and measured ring bending strain improved with depth, but at 18 in. (457 mm), measured strains were about twice the theoretical predictions.

## Discussion

The laboratory study into the behavior of buried plastic pipe under concentrated loads revealed the following:

- Under the load conditions considered herein, peak strains almost always occurred at the crown. This is different from a deeply buried pipe in which peak strains generally occur at the invert. This result is not surprising, considering the concentrated nature of the load and the rapid attenuation of the stresses with increasing depth of cover.

- Depth of cover, soil stiffness ($M_s$), and pipe stiffness all have a significant effect on pipe behavior under concentrated surface applied loads.

- For depths of cover greater than 18 in. (457 mm), elasticity theory as utilized herein is probably valid for predicting defelctions and ring compres sion strains, due to a single cycle wheel load if the soil modulus is greater than 2,000 psi (13.8 MPa). This will be discussed further in Appendix G.

In addition, the tests showed that the effects of rutting and cyclic loads may have significant influence on the design of pipe for shallow burial, as discussed below.

**Rutting:** In the loose condition, the soil failed at a load of about 5,000 pounds (2,272 kg). If bearing failure occurs in the field, the soil ruts and the tire moves closer to the pipe, which can cause major increases in the load on the pipe. Therefore, if a pipe is to be trafficked by construction vehicles, the backfill must



either be of high enough quality to avoid rutting, or the pipe should be deep enough such that rut depth is small compared to cover depth.

**Cyclic Loads:** In the dense soil case, when the load was applied a second time, the deflections increased an average of 25%. If a pipe is to be subjected to a large number of load cycles, the cumulative effect of a small increase in deflections per cycle could be significant (See Appendix B, ME-1 field study).

This study did not consider the dynamic effects of a concentrated load moving across a pipe installation. This undoubtedly has an influence on the shallow burial problem. The subject of design for concentrated loads will be considered further in Appendix G.



## REFERENCES

F.1 McGrath, T.J. "Effect of Concentrated Loads on Shallow Buried Polyvinyl Chloride and Polyethylene Tubing," Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA., 1975, 79 pp.

F.2 Burns, J.A., and Richard R.M., "Attenuation of Stresses for Buried Cylinders," Proceedings Symposium on Soil-Structure Interaction, Sept. 1974, University of Arizona, Tuscon, Arizona, pp 378-393.

F.3 Poulos, H.G. and Davis, E.H., Elastic Solutions for Soil and Rock Mechanics, John Wiley & Sons Inc., New York, 1974, pp 43-49.

# APPENDIX G

## DESIGN FOR CONCENTRATED SURFACE LOADS

The response of buried flexible pipe to surface-applied vehicle loads is a difficult analytical problem mainly due to the complexities introduced by the soil-structure analysis problem and the dymanic and cumulative effects of wheel loads as they affect soil behavior. The typical approach to design of flexible pipe for concentrated surface-applied live loads has been to establish minimum depths of cover based on experience. This has also been the approach taken in plastic pipe installation practices such as ASTM D 2321, which requires 36 in. (1 m) of cover over a pipe prior to traffic by vehicles, and 48 in. (1.2 m) of cover prior to compaction of a trench with a hydrohammer. Computerized finite element solutions are now being applied to this problem (G.1) and these should provide more detailed information on the soil-structure interaction problem which can be used to develop design rules. The application of finite elements is just emerging, and is not within the scope of this project. Furthermore, significant extension of these methods would be required to treat the complex problems introduced by cyclic movements of the soil. The scope of this project was the development of general design guides and the application of existing approaches to the problem, as possible.

The laboratory and field tests have been previously discussed in Appendices B and F. The results of these tests suggest that there are two classifications of traffic loads which should be recognized. One is the condition where a flexible plastic pipe may be subjected to a limited number of cycles of vehicle loads, such as during construction or during occasional traffic on a pavement shoulder, and the second is where a pipe will be permanently subjected to vehicle loads such as under the travel lanes of a highway. Design for these two conditions is discussed below.

### Limited Load Cycles — The Construction Condition

The limited laboratory tests and analysis presented in Appendix F indicate that the Burns and Richard theory can be used to predict behavior of a flexible pipe



with shallow cover due to a single application of a concentrated load, provided load attenuation and soil stiffness are properly modelled. The Burns and Richard elasticity solution was used in the evaluation of the laboratory tests, in favor of the Iowa Deflection formula, because it is less empirical, and because it offers a comprehensive solution for stresses and in the pipe-soil system. However, comparisons made in Appendix E showed that the Iowa Deflection/Ring Compression/Ring Bending theory, although highly empirical, provided results which were in reasonable agreement with the Burns theory for uniform earth loads. Since the former approach is more simply applied, it will be used here. The one difference is in the calculation of E'. Since values of E' from Table E-1 are not dependent upon load, the method of Appendix F to calculate a reduced $M_s$ to account for a lack of soil confinement around the pipe is not applicable. In the analysis discussed below, values of E' were arbitrarily reduced by a factor of 2 to account for this behavior.

Single cycle vehicle load data was obtained in the ME-1 and NH-2.1 field tests. Applying the approach used to account for load attenuation and soil stiffness in Appendix F, and the analysis methods of Appendix E noted above, calculations were made to predict strains due to live load. These are compared with test values in Table G-1. Deflections from these tests were too small to measure, and are not presented.

Table G-1 shows that predicted strains are higher than measured in all cases. This differs from the finding in the laboratory tests (Appendix F) where bending strain predictions were always low compared to measured bending strains, and deflection and ring compression predictions were reasonably accurate. However, in the laboratory tests, the data was taken on the first load cycle after pipe installation, while in the field tests the pipes had all been subjected to significant construction traffic prior to testing. This indicates that the pipe response to a single load cycle decreases with increasing load cycles, due to densification of the backfill around the pipe by traffic. This, in effect, increases soil stiffness (E' or $M_s$). This finding is reinforced by the ME-1 tests in which strains resulting from a single load application measured in May 1976 were significantly less than those measured earlier, in December 1975.

## TABLE G-1 - COMPARISON OF MEASURED AND PREDICTED STRAINS FROM LIVE LOAD TESTS ON SHALLOW BURIED PIPE

| Field Test | Method | Strain % | |
|---|---|---|---|
| | | Ring Bending | Ring Compression |
| MEI 2 ft Cover | Predicted* | 0.081 | 0.031 |
| | Measured Dec '75 | 0.055 | 0.012 |
| | Measured May '76 | 0.026 | 0.009 |
| NH2.1 4.5 ft Cover | Predicted* | 0.020 | 0.008 |
| | Measured July '76 | | |
| | Haunched | 0.009 | 0.005 |
| | Not Haunched | 0.008 | 0.003 |

* Predictions made according to methods presented in Appendices B and F

G-3

The above findings suggest that analysis methods for deeply buried pipe (uniformly applied load) can be adapted to estimate pipe behavior due to concentrated surface loads. In the use of such an approach, the following should be recognized:

- Repeated loadings appear to densify and stiffen the embedment around the pipe. This results in a response to cyclic load which decreases with each additional load application. As will be discussed subsequently, the cumulative stress and deflection increases for the same reason.

- The deep burial theories, as adapted, may underestimate pipe response when depth of cover is less than about 2 ft (0.6 m) (See Appendix F).

- These findings are based on tests conducted in soils with $M_s$ = 1,250 psi (8,625 kPa) or greater. They should not be extended to less stiff soils without prior verification by test.

Overall, the above approach appears to be appropriate for typical construction conditions, where the number of cycles is limited by the construction period, and for pavement shoulder installations, where traffic is only occasional. Specific limits on the maximum number of cycles for which the approach is valid awaits further advances in the state-of-the-art.

### Cumulative Effects – Permanent Installations

In Appendix E, the NH-I deflection data were compared to predictions made by deep burial theory, to determine if a pipe, buried 5 ft (1.5 m) deep below an interstate pavement could be modelled by deeply buried pipe theory. As shown in Table E-2, the measured mean deflections were greater than the predicted values, and the maximum measured deflections were less than predicted for the DR 35 pipe, and more than predicted for the DR 41 pipe. While the absolute magnitudes of these differences were not great, there remains a question as to whether the differences were caused by traffic, and whether deflections would have continued to increase had the pipe been allowed to remain in place.

G-4

Table G-2 presents a similar comparison of actual and predicted deflections for the ME-I pipe, and also shows the measured deflections to be generally higher than the values predicted by theory, especially for the two PE pipes, which were the most flexible pipe tested. The one pipe for which the measured deflection was lower than predicted was the PVC DR 41 pipe. This pipe was installed in embedment at a higher density than was the remainder of the pipe.

The backfill around the ME-I pipes was subject to frost penetration, but being a well graded sand with less than 5% fines, it should not have been frost susceptible. Thus frost effects probably did not contribute to the high deflections.

This leads to the following findings:

- Even though the per cycle pipe response to vehicle loads is very low, permanent deformations accumulate with time to substantial levels, as shown by the large increase in deflections at ME-I from May '76 to May '77 (Table B-7.)

- The deep burial theory proposed in Appendix E and modified to account for load attenuation and reduced soil confinement is inadequate for the prediction of cumulative behavior of pipe subjected to repeated live loads.

- The cumulative effects of repeated live loads appear to be minimized by the use of stiff pipe, and stiff embedment.

These cumulative effects due to repeated loads cannot be predicted within the state of the art. This should be a subject of future research.

**Evaluation of Metal Pipe Theory**

Watkins, Ghavami and Longhurst (G.2) used modelling techniques and dimensional analysis to develop an empirical formula for predicting the failure load on buried metal pipe subjected to wheel loads. They developed the equation:



**TABLE G-2 - COMPARISON OF PREDICTED VS MEASURED DEFLECTIONS AT ME-1**

| Pipe | Measured Pipe Stiffness lb/in/in | Mean Deflection (%) | | Maximum Deflection (%) | |
|---|---|---|---|---|---|
| | | Predicted | Measured May '77 | Predicted | Measured May '77 |
| ABS Composite | 250 | 0.6 | 1.5 | 1.6 | 2.0 |
| PVC DR-35 | 76 | 0.7 | 2.5 | 3.7 | 5.1 |
| ABS Sewer | 55 | 0.7 | 5.1 | 3.7 | 6.5 |
| PVC DR-41 | 45 | 0.7 | 1.4 | 3.7 | 3.0 |
| Corr. PE | 30 | 0.8 | 8.5 | 4.8 | 11.5 |
| Smooth PE | 18 | 0.8 | 6.9 | 4.8 | 9.0 |

Note: 1 psi = 6.9 kPa; 1 in. = 25.4 mm; 1 ft = 0.3048 m; 1 lb/in.$^3$ = 0.028 g/mm$^3$





$$\frac{W}{M_s d^2} = 160 \left(\frac{E\,I}{M_s d^3}\right)^{0.5} \left[.0071 \left(\frac{Z}{d}\right)^2 + 0.0014\right] \qquad \text{Eq. G.1}$$

where

W = failure load, lbs (N)

Z = depth of earth cover over the crown of the pipe, in. (mm)

Rearranging this formula proves revealing. If $Z/d > 1$, the constant term 0.0014 can be neglected as being small. By substituting the Boussinesq formula

$$p = \frac{3\,W}{2\pi Z^2} \qquad \text{Eq. G.2}$$

for incremental soil stress at a depth Z directly beneath a concentrated load, Equation G.1 can be rearranged as:

$$p = 0.54 \sqrt{M_s \frac{E\,I}{d^3}} \qquad \text{Eq. G.3}$$

where p represents the soil stress at which the pipe will fail, according to Watkins' theory. This formula is similar in form to the Chelepati buckling formula (see Section E.2), which, for $\nu_s = 0.3$ and $Z/d = 1$ is

$$p_{cr} = 3.8 \sqrt{M_s \frac{E\,I}{d^3}} \qquad \text{Eq. G.4}$$

This indicates that Watkins' formula relates to buckling capacity, and that it predicts failure under concentrated loading at about 15% of the deep burial buckling load. This result is consistent with the report of Krizek et al. (G.3) that a pipe subjected to concentrated loads has only 10 to 20% of the buckling capacity of a deeply buried pipe. On the basis of the above, the critical buckling stress for shallow burial conditions is reduced by reducing the coefficient $C_B$ in the buckling formula given for deep burial (Eq. E.12) to 0.07 (15% of 0.50).

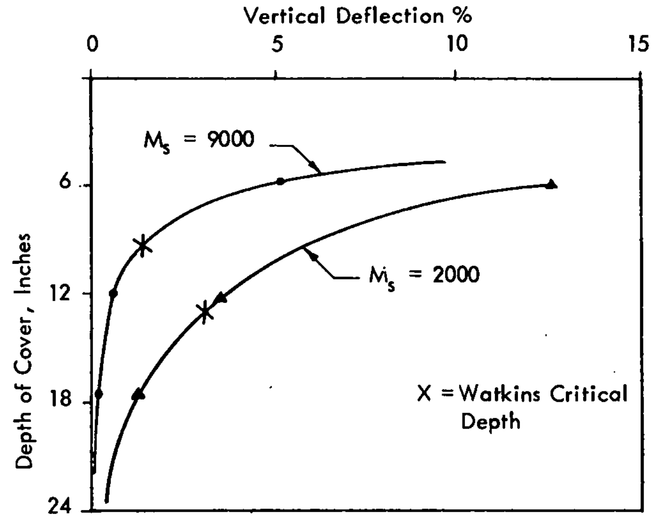
To apply the Watkins theory to the laboratory deflection data of Appendix F, Eq. G.1 was rearranged to predict a "critical depth" (depth at which failure will occur according to the theory) for a given pipe load and soil configuration.



$$Z = \left[\frac{W}{1.136 \left(M_s \frac{E\,I}{d^3}\right)^{0.5}} - 0.197\, d^2\right]^{0.5} \qquad \text{Eq. G.5}$$

Figure G-1 presents the change in deflection with depth for the laboratory tests on PVC pipe, and also shows the predicted critical depth for the load condition. The figure shows that the Watkins theory predicts a critical depth which coincides with the depth at which pipe deflections begin to increase very rapidly with decreasing cover.

The results of this study by Watkins on failure of metal pipe provides a basis for further research on plastic pipe. Any research on plastic pipe at shallow burial, must also address the problem of cumulative deflections and stresses under sustained cyclic wheel loadings. G-8




Note: 1 lb/in./in. = 1 psi = 6.9 kPa; 1 lb = 2.2 kg; 1 in. = 25.4 mm; 1 ft = 0.3048 m

FIG. G-1 PVC PIPE DEFLECTION UNDER 10,000 LB LOAD G-9

APPENDIX G REFERENCES

G.1 Katona, M. G., Forrest, J. B., Odello, R. J., and Allgood, J. R., "Computer Design and Analysis of Pipe Culverts." FHWA 3-1-1170, Interim Technical Report - Phase I Revised, Civil Engineering Laboratory/NCBC Port Hueneme, California, 1975.

G.2 Watkins, R. K., Ghavami, M., and Longhurst, G. R., "Minimum Cover for Buried Flexible Conduits." Journal of the Pipeline Div., ASCE, V. 94, October 1968. pp. 155-171.

G.3 Krizek, R. J., Parmelee, R. A., Kay, J. N., Elnaggar, H. A., "Structural Analysis and Design of Pipe Culverts." NCHRP Report 116 (1971). p. 66.
G-10

# APPENDIX H

## QUESTIONNAIRE AND SUMMARY OF RESPONSES ON EXPERIENCE WITH PLASTIC PIPE FOR DRAINAGE OF TRANSPORTATION FACILITIES

MEMORANDUM

29 November 1974

To: Members of AASHTO Operating Subcommittee on Materials

From: Richard E. Chambers

Subject: National Cooperative Highway Research Program, Project 4-11, FY '75
Buried Plastic Pipe for Drainage of Transportation Facilities

The Transportation Research Board of the National Academy of Sciences has contracted with our firm to develop and evaluate design, installation and performance criteria for the use of buried plastic pipe products for drainage applications in transportation facilities. The research will be conducted under the subject NCHRP project. The ultimate purpose is to develop a manual on the subject suitable for use by designers and specifying agencies.

Attached is a questionnaire which we are sending to AASHTO materials engineers, and other transportation agencies, and which is intended to determine the experience available thus far in the use of buried plastic pipe in drainage applications and for selecting agencies for follow-up contact. Your early response to the questionnaire will provide valuable assistance in our research. We're enclosing a self-addressed, stamped envelope for your use.

We would also appreciate your providing us with any design and installation specifications, or test reports generated by your agency regarding the use of buried plastic pipe. Any such information will provide much needed back-up data for our project.

We look forward to your assistance in obtaining performance experience on buried plastic pipe.

REC/ct

Encls.

SAMPLE

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM - PROJECT 4-11
BURIED PLASTIC PIPE FOR DRAINAGE OF TRANSPORTATION FACILITIES
SURVEY OF AASHTO OPERATING SUBCOMMITTEE ON MATERIALS Prepared by:

Simpson Gumpertz & Heger Inc. — Consulting Engineers
1696 Massachusetts Avenue, Cambridge, Massachusetts 02138 — 617/491-3000

1. Agency (Name and Address)
Name Illinois Department of Transportation
Address 126 East Ash Street
Springfield, Illinois 62706

2. Individual Completing This Form
Name Donald R. Schwartz
Title Engineer of Physical Research
Phone 217/782-6732

3. Has Your Agency Used or Performed Research on: Buried Plastic Pipe for Drainage Purposes? (X) Yes ( ) No
Plastic Man Holes and Catch Basins? ( ) Yes (X) No

4. If either answer to question 3 is NO, is the reason ( ) No track record in application
(X) No Experience ( ) Poor Experience ( ) Lack of design and installation guidelines ( ) Other ________

5. If either answer to 3 above is YES, please fill out the following table by checking appropriate boxes.

| Pipe Material Used or Tested * | | ABS | HDPE | PS | PVC | FRP | RPM | OTHER (name) |
|---|---|---|---|---|---|---|---|---|
| Diameter range | up to 12 inches | X | X | | | | | |
| | more than 12 inches | X | | | | | X | |
| Burial depth | up to 2 ft | | | | | | | |
| | 2 to 4 ft | X | X | | | | X | |
| | more than 4 ft | X | | | | | X | |
| Length installed | up to 500 ft | | | | | | | |
| | 500 to 5000 ft | | X | | | | X | |
| | more than 5000 ft | X | | | | | | |
| Burial conditions | under pavements | X | | | | | X | |
| | under R.R. beds | | | | | | | |
| | under shoulders | X | X | | | | | |
| | lab tests | | | | | | | |
| | other (specify) | | | | | | | |
| Usage | sub drains | | X | | | | | |
| | storm drains | X | | | | | X | |
| | culverts | | | | | | | |
| | other (specify) | | | | | | | |
| Age of Installation | specification or bid stage | | | | | | | |
| | 1 year | X | X | | | | | |
| | 1 to 5 years | | | | | | X | |
| | more than 5 years | | | | | | | |
| Performance | satisfactory | X | X | | | | | |
| | unsatisfactory | | | | | | | |
| | mixed | | | | | | X | |
| Burial load tests (Deflectometer) | completed | | | | | | | |
| | in progress | X | X | | | | X | |
| | contemplated | | | | | | | |
| Other performance tests | completed | | | | | | | |
| | in progress | | | | | | | |
| | contemplated | | | | | | | |

*ABS (Acrylonitrile Butadiene Styrene), HDPE (High Density Polyethylene), PS (Polystyrene), PVC (Polyvinyl chloride), FRP (Fiberglas Reinforced Plastics), RPM (Reinforced Plastic Mortar), OTHER (Use trade names if material type is not known).

Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

RESPONSES TO QUESTIONNAIRE ON EXPERIENCE WITH BURIED PLASTIC PIPE FOR DRAINAGE - BY AASHTO OPERATING SUBCOMMITTEE MEMBERS ON MATERIALS

| STATE | Reasons for not using Plastic Pipe: No Track Record | No Experience | Poor Experience | No Guidelines | Material Type * | Usage | Burial Conditions | Diameter Range (in.) | Burial Depth (ft) | No. of Ft Installed | bid | Age (years): 1 | 1-5 | 5 | Performance | Tests Performed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Alabama | | X | | | | | | | | | | | | | | |
| Alaska | | | | | RPM | storm drains | pavements | > 12 | > 4 | > 5000 | | | X | | satisfactory | No |
| Arizona | X | | | | | | | | | | | | | | | |
| Arkansas | | X | | | | | | | | | | | | | | |
| California | | | | | ABS | sewers | | < 15 | | | X | | | | satisfactory | No |
| " | | | | | PE | underdrains | | < 12 | | | | | | | | Yes |
| " | | | | | RPM | storm drains | shoulders and pavements | 48 | > 4 | < 500 | | | | X | satisfactory | Yes |
| Carolina, N. | | X | | | | | | | | | | | | | | |
| Carolina, S. | X | X | | | | | | | | | | | | | | |
| Colorado | | | | | PVC | underdrains | slope | < 12 | > 4 | < 500 | | X | | | satisfactory | No |
| Dakota, N. | | | | | PVC | underdrains and sewers | slope | < 12 | | 500-5000 | | | X | | unknown | No |
| Dakota, S. | | X | | | | | | | | | | | | | | |
| Delaware | | | | | PVC | underdrains | pavements | < 12 | | 500-5000 | | | X | | satisfactory | No |
| Florida | | X | | | | | | | | | | | | | | |
| Georgia | | | | | PE | underdrains | shoulders and lab tests | < 12 | < 2 | > 5000<br>< 50 | X | | | | satisfactory | Yes |
| Hawaii | | | | X | | | | | | | | | | | | |
| Idaho | | | | | PVC | horizontal drains | slope | < 12 | > 4 | > 5000 | | | | X | satisfactory | No |
| " | | | | | PE | underdrains | shoulders | < 12 | > 4 | 500-5000 | X | | X | | satisfactory | No |
| Illinois | | | | | ABS | storm drains | shoulders and pavements | < 12 & > 12 | > 2 | > 5000 | | X | | | satisfactory | Yes |
| " | | | | | PE | underdrains | shoulders | 12 | 2 - 4 | 500-5000 | | X | | | satisfactory | Yes |
| " | | | | | RPM | storm drains | pavements | 12 | > 2 | 500-5000 | | | X | | mixed | Yes |
| Indiana | X | X | | X | | | | | | | | | | | | |
| Iowa | | X | | | | | | | | | | | | | | |
| Kansas | | X | | X | | | | | | | | | | | | |
| Kentucky | | X | | | | | | | | | | | | | | |
| Maine | | | | | | | | | | | | | | | | |
| Maryland | | | | | PE | underdrains | slope | < 12 | 2 - 4 | | X | | | | | No |
| Massachusetts | X | | | | | | | | | | | | | | | |
| Michigan | | X | | | | | | | | | | | | | | |
| Minnesota | | | | | PVC | underdrains | ditches | < 12 | 2 - 4 | < 500 | | | X | | satisfactory | No |
| Mississippi | | X | | | | | | | | | | | | | | |
| Missouri | | X | | | | | | | | | | | | | | |
| Montana | X | X | | | | | | | | | | | | | | |
| Nebraska | | X | | | | | | | | | | | | | | |
| Nevada | | X | | X | | | | | | | | | | | | |
| New Hampshire | X | | | X | | | | | | | | | | | | |
| New Jersey | | | | | PVC | underdrains | shoulders | < 12 | < 2 | | X | | | | | |
| New Mexico | X | | | | | | | | | | | | | | | |
| New York | | | | | PVC | underdrains | shoulders | < 12 | 2, 2 - 4 | | X | | | | | No |
| Ohio | | | | | PE | underdrains | shoulders | < 12 | 2 - 4, > 4 | > 5000 | | X | | | | No |
| Oklahoma | | X | | | | | | | | | | | | | | |
| Oregon | | | | | ABS | leach bed | | < 12 | < 2 | > 5000 | | | | X | satisfactory | Yes |
| " | | | | | PE | underdrains | shoulders | < 12 | < 2 | > 5000 | X | | | | | Yes |
| Pennsylvania | | | | | PE | | shoulders | < 12 | 2 - 4 | < 500 | | | X | | mixed | Yes |
| " | | | | | PVC | fresh water | concrete encased | < 12 | 2 - 4 | < 500 | | | X | | | No |
| Rhode Island | | X | | X | | | | | | | | | | | | |
| Utah | | X | | X | | | | | | | | | | | | |
| Vermont | | X | | | | | | | | | | | | | | |
| Virginia | | X | | | | | | | | | | | | | | |
| Virginia, W. | | | | | | | | | | | | | | | | |
| Washington | | | | | PVC | horizontal drains | slope | < 12 | > 4 | < 500 | | | | X | satisfactory | No |
| Wisconsin | | | | | PVC | sewers | | < 12 | 2 - 4, > 4 | < 500 | | X | X | | satisfactory | No |
| Wyoming | | | | | PVC | underdrains | pavements and shoulders | < 12 | > 4 | < 500 | | | X | | satisfactory | No |

* KEY

ABS = Acrylonitrile-Butadiene-Styrene
FRP = Fiberglass Reinforced Plastic
PE = Polyethylene
PVC = Poly (Vinyl Chloride)
RPM = Reinforced Plastic Mortar

Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

| AGENCY | Reasons for not using Plastic Pipe: No Track Record | No Experience | Poor Experience | No Guidelines | Material Type * | Usage | Burial Conditions | Diameter Range(in.) | Burial Depth(ft) | No. of Ft Installed | bid | Age (years): 1 | 1-5 | 5 | Performance | Tests Performed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Toll Bridge Administration California Dept of Trans. | X | X | | | | | | | | | | | | | | |
| Forest Service, Wash. D.C. | | | | | ABS | horizontal drains | | <12 | >4 | 500-5000 | | | X | | satisfactory | No |
| Dade County Public Works Miami, Florida | X | X | | X | | | | | | | | | | | | |
| Cook County Hwy. Dept. Chicago, Illinois | | X | | | | | | | | | | | | | | |
| Indiana Aeronautics Comm. | X | | | | | | | | | | | | | | | |
| Indiana Toll Road Comm. | X | | | | | | | | | | | | | | | |
| Linn County Hwy Dept. Cedar Rapids, Iowa | | | | | PE | underdrains | pavements and shoulders | <12 | | < 500 | | | X | | satisfactory | No |
| | | | | | | | | | | | | | X | | satisfactory | No |
| " " " " | | | | | PVC | underdrains | cross roadways | <12 | 2 - 4 | | | | X | | satisfactory | No |
| Cerro Gordo County Hwy Dept. Mason City, Iowa | X | X | | | | | | | | | | | | | | |
| Maine Turnpike Authority | | | | | | | | | | | | | | | | |
| Maryland Dept of Transport | | X | | | | | | | | | | | | | | |
| Michigan Aeronautics Comm. | | | | | ABS | storm drains | pavements | < 12. | 2 - 4 | < 500 | | X | | | satisfactory | No |
| Genesee County Road Comm. Flint, Michigan | | | | | PVC | underdrains | pavements and shoulders | < 12 | 2 - 4 | 500-5000 | | | X | | satisfactory | No |
| Kent County Road Comm. Grand Rapids, Michigan | | | | | ABS | underdrains | shoulders | < 12 | < 2 | 500-5000 | | | X | | satisfactory | No |
| Oakland County Road Comm. Pontiac, Michigan | | | | | ABS | sewers | shoulders | < 12 | 2 - 4 | > 5000 | | | X | | satisfactory | No |
| | | | | | PVC | sewers | shoulders | < 12 | 2 - 4 | < 500 | | | X | | satisfactory | No |
| New Jersey Hwy. Authority | X | X | | | | | | | | | | | | | | |
| New Jersey Turnpike Authority | X | X | | | | | | | | | | | | | | |
| NY and NJ Port Authority | | | | | PVC | drains | pavements | < 12 | 2 - 4 | 500-5000 | | | X | | satisfactory | No |
| | | | | | FRP | fuel lines | pavements | < 12 | 2 - 4 | < 500 | X | | | | | |
| New York State Thruway Authority | | | | | PVC | underdrains | shoulders | < 12 | 2 - 4 | > 5000 | | | X | | satisfactory | Yes |
| Oklahoma Turnpike Authority | | X | | | | | | | | | | | | | | |
| Pennsylvania Turnpike Authority | X | | | | | | | | | | | | | | | |
| Texas Aeronautics Commission | | | | | | | | | | | | | | | | |
| Vermont Aeronautics Board | | X | | | | | | | | | | | | | | |

* KEY

ABS = Acrylonitrile-Butadiene-Styrene
FRP = Fiberglass Reinforced Plastic
PE = Polyethylene
PVC = Poly (Vinyl Chloride)
RPM = Reinforced Plastic Motar

Note: 1 in. = 25.4 mm; 1 ft = 0.3048 m

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