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Behavior and Design of Buried Concrete Pipes Phase II

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Nebraska Department of Roads

Behavior and Design of Buried Concrete Pipes Phase II- Final Report

University of Nebraska Lincoln

Behavior and Design of Buried Concrete Pipes Phase II

NDOR Project Number

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DRAFT FINAL REPORT

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13. Abstract:

Currently, RCP can be designed according to two methods: Direct Design Method and Indirect Design method. These two methods generally give different answers for design of pipe that is carrying the same load. Furthermore, while the design methods and the resulting designs for the same loads are completely different, there is only one commonly used standard available for specification of pipe (ASTM C76) and only one commonly used test for the quality control and acceptance of manufactured pipe (three edge bearing test, i.e. TEB). These manufacturing standards and quality control measures align better with the indirect design method; while they limit the effective use of the more modern direct design method to less than its full potential. As a result, some of the reinforced concrete pipe constructed, especially according to the newer direct design method –yet subjected to the limits of ASTM C76 and TEB, which are better suited with indirect design- is overly conservative, which in turn causes reinforced concrete pipe to lose its competitiveness against flexible pipe. This situation causes confusion and frustration among related parties, such as owners, designers, manufacturers, and contractors.

To address and resolve these problems, Nebraska Department of Roads and City of Lincoln administration hired the University of Nebraska researchers, the authors, to perform experimental and analytical research.

Authors designed a full scale reinforced concrete pipe (RCP) installation, according to the direct design method (DD) with specific criteria explained in this report, which is installed at the City of Lincoln Landfill in order to monitor the behavior of pipe in installed conditions and over time. Applied soil pressures are measured to make sure they are within Heger pressure distribution limits. Strains in the outer and inner reinforcement are monitored to study the behavior of the pipe. Crack development and joint displacement, if applicable, are also monitored.

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Executive Summary

Currently, RCP can be designed according to two methods: Direct Design (DD) Method and Indirect Design (ID) method.

These two methods generally give different answers for design of pipe that is carrying the same load. Furthermore, while the design methods and the resulting designs for the same loads are completely different, there is only one *commonly used*[1] standard for the specification of pipe (ASTM C76) and only one *commonly used* test for the quality control and acceptance of manufactured pipe (three edge bearing test, *i.e.* TEB[2]). Both of these measures align better with the indirect design method; and they limit the effective use of the more modern direct design method to less than its full potential. As a result, some of the reinforced concrete pipe designed according to the direct design method –yet subjected to the limits of ASTM C76 and TEB (which are better suited with indirect design) may end up being overly conservative. Aside from the direct design method's lack of compatibility with the commonly used quality control measures, DD method also has some inherent conservatism. Some of this is due to ensuring the safety of the pipe. Since it is a strength design method, naturally, there are factors of safety included in terms of load and resistance factors. However, some conservatism comes from not taking full advantage of the materials' (steel and concrete) true behavior in the pipe. For example, if both cages of reinforcement are in tension, as observed in this study- and this doubled capacity is not accounted for in the current design equations; than it is natural that the results of the DD would be more conservative than the empirical method ID, which would naturally take advantage of the material's true behavior.
In other words the question asked to the research team has been:

How can structural systems that have been designed according to an old, yet well-established method (ID), in the past and has proven safe for years is now considered "not adequate" when designed according to a rational, modern method developed according to strength design limit states? Naturally, the question has been accompanied with some rightful frustration among related parties, such as owners, designers, manufacturers, and contractors; who would like to understand what method is the better one to use. This frustration is augmented with the fact that once concrete pipe had no competition; yet now, it is subjected to competition with flexible pipe (steel, PVC, etc…).

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[1] Although there is ASTM C1417, which suggests material and dimension tests; it is not well- known or commonly used.
[2] NDOR does not require TEB for pipe designed according to their specs- they require material tests instead.

At the end of the day, the answers provided by both designs are “safe” and the matter becomes one of an efficiency, economy, and flexibility of design. Both design methods are currently allowed. Even within the state of Nebraska, our research reveals that, NDOR and City of Lincoln use different methodologies for the design and quality control of reinforced concrete pipe. NDOR specifications recommend and utilize DD for the design of concrete pipe, but after the initial design is carried out according to DD, the specs refer to ASTM C76 Class Types to allow for easy communication with the manufacturers. NDOR specs do not require TEB tests for quality control of pipe designed according to DD, however, once the manufacturers receive a design spec labeled with “class types”, the natural and easiest way for them to assure they present the requested pipe is by performing TEB tests. In the case of City of Lincoln, our review of their procedures reveals that their consultant designers mostly prefer ID; utilizing ACPA fill height tables, historic bedding classes, at the end specifying pipe according to ASTM C76 classes; and then requiring quality assurance via TEBs.

In order to address and resolve the question regarding the best way to design and specify concrete pipe, Nebraska Department of Roads and City of Lincoln administration hired the University of Nebraska researchers, the authors, to perform experimental and analytical research. This report summarizes the findings of UNL researchers.

Authors designed a full scale reinforced concrete pipe (RCP) installation, using the direct design method (DD) with specific criteria explained in this paper. This full scale test installation is located at the City of Lincoln Landfill in order to monitor the behavior of pipe in installed conditions and over time. Applied soil pressures are measured to make sure they are within Heger pressure distribution limits. Strains in the outer and inner reinforcement are monitored to study the behavior of the pipe over time. Crack development and joint displacement, if applicable, are also monitored.

Several observations are made through this full scale experiment:

1. The measured soil pressures are generally lower than the predicted values according to Heger distribution- partially due to the fact that the actual bedding achieved by the contractors are stronger (somewhere between Type1 and Type2) than the specified bedding (Type 3).
2. Strains in the reinforcement are in the elastic range, *i.e.* the steel has not yielded. The highest steel strain measured is only 22.5% of the yield strain.
3. TEB testing was employed on an identical specimen to one of the installation pipe segments. Results of this test showed that despite the identical design, the steel of the pipe experiences strains higher than the

yield strain (0.002) at loads as low as the 0.01 in crack load. Yielding of steel in reinforced concrete indicate overstress, while the full scale pipe monitored in the landfill proves that this level of structural distress is not reached in installed conditions.

4. Concrete has cracked at several locations, as expected for any reinforced concrete structural element that engages steel in tension; however, cracks are smaller than 0.01 in wide.

The study also revealed some areas of potential future research. For example:

1. The authors' extensive literature review revealed that the 0.01 in crack limitation is not backed up well with proof that beyond this specific width any type of failure may occur, therefore the *0.01in limit may be arbitrary and unnecessary (hypothesis)*. In order to test this hypothesis, the design criteria used for the full scale testing omits this limit state. As the behavior of pipe is observed, the lack of additional stress, major cracking or spalling, or failure of the pipe despite the higher loads than the design loads provide further evidence that the crack control criteria does not affect the safety of the pipe.
2. There can be tension in both reinforcement cages; however, this is not accounted for in the direct design equations. This situation highlights areas of improvement in DD, which would bring the DD and ID results closer together.
3. A better quality control test than TEB, one that represent's better the pipe's behavior in installed conditions. In the lack of such a different method, *and* if the DD method is used for design, ASTM C1417 should be used for acceptance criteria.

Conclusions drawn from the study are as follows:

1. The pipe in the test installation, designed according to DD with unique and daring criteria has reserve steel capacity of 77.5% in installed conditions. This is due to a combination of factors: a) There is indeed room in DD method for improvement such that the material behaviors are better represented, limit state criteria is re-visited, and as a result the designs are closer to those from ID. b) The actual bedding in the field is stronger than that of the specified, thus he pipe is stronger than expected against the loads. c) Installed conditions are more favorable for the pipe than the TEB conditions, and even some of the field handling conditions. Thus some additional capacity is necessary -and available from the nature of the method- if the quality assurance and handling procedures are not changed.
2. Based on our discussions with our sponsors (and typically the owners of the pipe installation projects in the State of Nebraska), our experience with the contractors does not reflect the general situation. The actual conditions were

superior to those requested by the designers, yet, the owners worry that the opposite may be true more often. Therefore, they (especially City of Lincoln), in an attempt to err on the conservative side, tend to specify pipe for a poor bedding (ex: Type 3 or 4) but request that the bedding is superior (ex: Type 1). The authors suggest this may be an inefficient way of design and construction. If NDOR or City come up with one standard bedding (we suggest Standard Installation Type 3, relatively poorer) and communicate to the contractors that this is the minimum requirement and will be monitored; the contractors –without too much trouble- would achieve Type 3 bedding, because compaction requirements are not very stringent. If the design is also carried out for Type 3 then, it would be an efficient system. The owners should rest assured that there are enough safety factors to account for the potential minor deviations in design criteria in both design methods, and this process would not cause failure, especially because they require a relatively easy-to-achieve installation type.

3. In installed conditions, both the inner and outer reinforcement of most segments are in tension; however, the DD method does not account for this. Even in TEB, where the loading condition is more critical causing higher bending stresses in the pipe wall, in most locations that were monitored, the strain distribution is such that both reinforcements are in tension. This is one of the reasons why, *sometimes*, the DD method results are more conservative than the ID[3]. The differences between ID and DD become further pronounced for pipe with diameters smaller than 36inch (i.e. single cage pipe); because the behavior is more complex. Thus, if the "true" material behavior of steel is incorporated into the DD results, the results gathered for small diameter pipe would more accurately represent the true capacity of these structures, and the results would be closer to those gathered from ID[4].
4. TEB is not a good representation of the pipe's behavior in installed conditions and may cause unnecessary conservatism, especially if the pipe is designed according to DD.
5. Crack control criteria in DD can be eliminated, especially if the pipe is lined: Crack control criteria is one of the limit states in the strength design based DD method along with flexure, shear, diagonal, and radial tension. While all of the other limit states follow, in general, the criteria used for the design of other structural concrete elements, the stringent 0.01 in criteria seems arbitrary

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[3] It must be noted that the conservatism in DD and ID switches depending on the loads, i.e. fill height. DD presents a continuous function where there is an answer for every set of selected design parameters, while the ID results form a discrete function defined by classes and ASTM standards.

[4] A case study is carried out to show-case this point and added to the appendices of the report.

(no evidence in literature for why it is set at this limit), especially when checked through an experiment (TEB) that does not reflect the pipe's actual behavior in installed conditions

6. Designers should either use DD with ASTM C1417, or ID with ASTM C76 and TEB to specify safe, economical, and practical reinforced concrete pipe. Using DD along with ASTM C76 and TEB is not an appropriate design procedure.
7. A new ASTM standard (as user friendly as ASTM C76), and a new acceptance test (as practical as TEB) may facilitate the adoption of DD by more practitioners and owners; as well as eliminate misunderstandings or misuse of methods. It is recommended by the authors of this report that NDOR and City of Lincoln team up with ACPA and DOTs in order to lead the nation, approach ASTM/ NCHRP for a national project, and perform work towards resolving these issues.
8. An online survey on pipe design practice is prepared and pipe designers, manufacturers, and contractors were invited to participate. The small pool of responses to the RCP survey of practice does not allow detailed statistical analysis; however, some insights are gathered and summarized in the report. One important finding is a confirmation that there is mix-and-match approach in using DD, ID, TEB, and ASTM C76.
9. Direct design method is the rational method to choose for the design of the pipe, thus should be continued to be used by NDOR and should be adopted by COL designers for all pipe – except small diameter (smaller than 36inch diameter), single cage pipe. The behavior of small diameter pipe needs to be further studied and DD should be updated to reflect the results of such research. The structural behavior of the single caged small diameter pipe is more complex than the larger diameter pipe, for which DD has been proven as an effective design method. Therefore, at this time, the authors propose that NDOR and COL design and specify reinforced concrete pipe as follows: *Direct design* is used for all pipe larger than 36 in (double cage); and *indirect design* is used for pipe that is smaller than 36 in and/or has single cage of reinforcement.
10. Based on the experimental and analytical research, and extensive study of the relevant literature, the authors have developed expanded tables for reinforced concrete pipe larger than 36 inch (42- 108 inch) for NDOR to adopt in their specifications as they see fit. These tables are prepared using direct design method, obeying all limit states – including the 0.01inch crack control criterion. Concrete strengths of 4, 5, 6, 7, and 8 ksi; standard installation types 1,2,3; and fill heights of 5-20 ft with 2.5 ft increments are included in the tables.

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1. Introduction

Currently, there are two methods available and widely used for buried concrete pipe design: 1) Indirect Design (ID) method, which is an empirical method based on three-edge bearing test (D-loads) and ASTM C76 standards. The pipe is tested to 001-inch crack limit for acceptance. This method was developed in 1930's and is still widely used. 2) Direct Design (DD) Method, which is a semi-empirical and semi-theoretical design method, where five separate limit states are considered (flexure, shear, diagonal tension, radial tension, and crack control) for the strength design of pipe as a reinforced concrete structural element. This method was developed in 1970's.

Both methods are used by designers today; however, the answers gathered do not always match. The empirical nature and inherent limits of the ID method do not agree with current advancements in the field (concrete strengths that are higher than those in ASTM C76, better understanding of cracking behavior and corrosion control, better models for material constitutive laws, etc…), while the DD method does not have any accompanying acceptance/ quality control test or ASTM standard *as commonly adopted as* the TEB or ASTM C76[5]. While commonly adopted in the field, regardless of the initial design method, these manufacturing standards and quality control measures align better with ID, limiting the effective use of the more modern DD method to less than its full potential. As a result; several considerably different answers are possible for the design of the same pipe with equal loading. This situation inevitably causes all responsible parties (e.g. owners, designers, manufacturers, and contractors) several *dilemmas*:

1. Designers, departments of roads, and other regulating agencies are faced to choose one method or the other, which give different answers.
2. If DD is used as it should be, ASTM C76 and TEB, which are strictly ID related phenomena should not be used. But these are well-known and easy to use procedures and have been around for a long enough time that the entire "concrete pipe community" can communicate around.
3. DD has not been fully studied for smaller pipe, specifically those with single cage reinforcements (i.e. 36 inch or smaller), which have more complex behavior than pipe with double reinforcing cage. Due to the lack of understanding in their behavior, small diameter RCP, when designed according to DD, tends to be overly conservative compared to ID.

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[5] Although there is ASTM C1417, which suggests material and dimension tests; it is not well-known or commonly used.

4. The key parameters that affect the final structural capacity of the concrete pipe, such as installation type (support system), concrete strength, and true behavior of steel, are not always thoroughly evaluated and optimized such that the safest and most economical concrete pipe designs are achieved *consistently* in the State of Nebraska; so that a fair competition ground is given to it next to flexible pipe (e.g. metal, PVC).

1.1. Objectives

The ultimate goal of this project is to propose a unified and efficient design procedure for reinforced concrete pipe that satisfies both designers and pipe producers in the state of Nebraska through the following sub-goals:

- To update and expand the NDOR fill height tables based on the results of the University of Nebraska parametric study and the latest version of PipeCAR.
- To evaluate the efficiency and feasibility of design procedures used by City of Lincoln consulting engineers analytically and empirically.
- To expand the current and future project findings to sanitary sewer pipes by studying additional considerations, such as pipe joint design and deeper fill heights.

1.2. Report Overview

Numerous tasks are carried out to accomplish the goals of this study. The results of these tasks are presented in the following sections of this report. Section 3- Background presenting a brief summary of the literature (including authors' findings in the first phase of study); Section 4- Review of City of Lincoln design procedures on a sample design; Section 5- Experimental full scale RCP installation; Section 6- Survey of Practice Results; Section 7- Proposed NDOR RCP Design Procedures and Tables; Section 8- Conclusions.

2. Background

In this section brief background on reinforced concrete pipe design methods, standard installations, manufacturing standards and quality control testing (Three-edge bearing) are presented.

2.1. Review of Concrete Pipe Design Methodologies

RCP has been primarily designed using semi-empirical techniques for the past century and has shown good performance over the years. In this section, the development of the available design methods for buried concrete pipe is briefly presented in chronological order.

Beginning in 1910, Anson Marston developed a method for calculating earth loads above a buried pipe based on the understanding of soil mechanics at that time. In the late 1920's a research project at the Iowa State University was conducted with the objective of determining the supporting strength of buried rigid pipes in an embankment installation when subjected to earth pressures, using Marston's theories. The results of this research were given in a comprehensive paper by M.G. Spangler (Spangler 1933), where, a general equation for the bedding factor was presented. His work included the definition of four standard bedding types that are similar to those defined earlier by Marston. The reader is referred to the literature (ACPA 1993, 2000) for details of the historic bedding types. Marston and Spangler's works form the basis of the indirect design method currently used for RCP.

According to the indirect design method, the required supporting strength of the pipe is a function of the magnitude of the earth pressure and its distribution around the pipe. **Supporting strength (D-load)** is the required strength is defined in terms of the total load, a bedding factor, pipe's diameter, and a factor of safety (Equation 1). The same D-load is also directly related to the TEB test as shown in Equation 2. As can be seen TEB is a method directly related to indirect design method, while it is not relevant to direct design method.

$$D_{load} = \frac{W}{B_f} \times \frac{F.S.}{D} \qquad \text{(Eq. 1)}$$

$$D_{load} = \frac{TEB \quad load}{D} \qquad \text{(Eq. 2)}$$

Wall thickness, concrete strength, and reinforcement requirements corresponding to the required strength are given in ASTM C76 (ASTM 2005). Thus in the indirect design method, first the ACPA fill height tables are utilized to determine the suggested *pipe class* (D-load) based on the fill height and the pipe diameter. Then ASTM C76 standard is utilized to find the inner and outer reinforcement areas based on the pipe class, pipe diameter, and the wall type/thickness. Since each class and pipe diameter combination has a specific concrete strength (f'_c) attached to it in ASTM C76, this value can only range between 4,000 psi and 6,000 psi. Pipe designed according to indirect design is then accepted if the pipe passes the design D-load at the three-edge-bearing test.

The indirect design method has been a generally accepted procedure in the past; however, developments in the understanding of soil properties, as well as advancements in structural analysis techniques have led to significant improvements in the design of concrete pipe that are not reflected in the indirect design method. In the 1970's, the American Concrete Pipe Association (ACPA) instituted a long-range research program with the objective of evaluating the performance of concrete pipe-soil installations and improving the design practice. In this research, the structural behavior of concrete pipes and soil-structure interactions were examined. As a result of this research program, new standard installation types and the Heger earth pressure distribution (Section 2.2) were recommended, which differ considerably from those originally developed by Marston and Spangler. Consecutively, four new standard installations, Heger earth pressure distribution and the direct design procedure were incorporated in a 1993 American Society of Civil Engineers Standard entitled "ASCE Standard Practice for Direct Design of Buried Precast Concrete Pipe in Standard Installation (SIDD)" (ASCE 15- 1998). These installations and the Heger pressure distribution will be discussed in section 2.2.

According to the **direct design method**, the required strength of the concrete pipe is determined from the effects of the bending moment, thrust, and shear in the pipe wall. Wall thickness, concrete strength, and reinforcement design are evaluated using rational procedures based on strength limit states that were developed in the ACPA long-range research program.

2.2. Comparison of ID, DD, and DD with ASTM C76 standard (NDOR) designs

Currently, both the indirect and the direct design methods are used for the design of RCP and both methods have elements related to the other. The modern standard installations, which were developed to eliminate the limitations of the historic installations (*i.e.* Bedding classes), and were incorporated in the direct design method, are also used in the indirect design method with acceptable performance. On the other hand, in lack of more popular tools, direct design pipe is still quality-controlled against TEB and ASTM C76 which are initially intended for, and work better with, indirect design.

The design criteria and variables of indirect design and direct design are compared in Table 1.

Table 1 Comparison of Indirect Design and Direct Design Methods in terms of design input, tools and other related criteria

	Indirect Design	**Direct Design**
Design input	a. Pipe diameter b. Fill height c. Standard installation type	a. Pipe diameter b. fill height c. standard installation type d. wall thickness e. concrete strength, f. steel strength, g. spacing, h. load factors (AASHTO Standard or LRFD)
Design Tool	ACPA fill height tables	PipeCAR software available from ACPA
Design Output- 1	**Pipe class** and **D-Load** to be used in ASTM C76 to	Inner and outer reinforcement areas
Design Tool	**ASTM C76**	N/A
Design Output- 2	Wall thickness, reinforcement area, concrete strength, and reinforcing spacing requirements	N/A
Acceptance Criteria	TEB (D-load)	ASTM C1417 or Compliance with design specifications similar to any reinforced concrete design (e.g. cylinders for f'c.)
Standard Installation Type/ Bedding	According to ACPA both methods should use Standard Installations	
Concrete (f'_c)	4,000 - 6,000 psi	Variable
Design basis for (A_{so})	Set to 60 % of inner reinforcement	Structurally designed
0.01-in crack with considered? As a limit state? As an acceptance criteria?	It is an acceptance criteria used at TEB linked to the design D-load.	a. Arbitrarily adopted as a limit state. No theoretical reason behind why 0.01 in crack should demonstrate failure or be adequate for corrosion. b. Does not really apply theoretically as an acceptance criteria also, arbitrarily adopted

As stated before, the answers given by the two methods are usually different. This is not surprising after studying each method and the following acceptance procedures listed in Table 1; however, as a result of the differences, there is an ongoing discussion on how pipe design results according to indirect design and direct design values compare: which one is more conservative. The authors reviewed the NDOR specifications and compared to indirect design (Table 2).

Table 2 Fill Height Table Comparison between methods

	Class III				Class IV				Class V			
pipe diameter (inches)	fill height (feet)				fill height (feet)				fill height (feet)			
	NDOR	**STD**	**LRFD**	**ID**	**NDOR**	**STD**	**LRFD**	**ID**	**NDOR**	**STD**	**LRFD**	**ID**
15	12	12	13	14	15	15	16	22	21	21	22	33
18	12	12	13	15	17	17	18	22	24	24	25	34
21	13	13	13	15	19	19	20	22	26	26	27	34
24	13	13	12	15	19	19	20	22	26	26	27	34
27	13	13	13	14	17	17	17	22	26	26	27	34
30	12	12	12	14	14	14	15	22	25	25	25	33
36	10	10	11	14	16	16	17	22	24	24	25	33
42	10	10	11	14	15	15	16	22	23	23	24	33
48	10	10	11	14	14	15	15	21	22	23	24	33
54	10	10	11	14	14	15	15	21				
60	9	10	10	14	14	15	16	21				
66	9	10	10	14	14	16	16	21				
72	9	10	10	13	14	16	16	21				
78	9	10	11	13								
84	9	10	10	13								
90	9	10	11	13								
96	9	10	11	13								
102	10	11	11	-								
108	10	11	11	-								

The methods used in the table are explained as follows:

NDOR: This method mainly obeys direct design method, however, to make it easier to communicate with manufacturers, after the PipeCAR results are gathered, ASTM C76 is visited to gather the next higher class of pipe, i.e. reinforcing area, f'c, etc.. This is then related back to PipeCAR to back-track a fill height that complies with the ASTM C76 reinforcement value.

STD: This method uses direct design method (PipeCAR) using AASHTO STD load factors

LRFD: This method uses direct design method (PipeCAR) using AASHTO LRFD load factors

ID: Indirect Design

At a first glance, direct design + ASTM C76, which is the method preferred by NDOR designers, seem more conservative. The details of the

design assumptions, however, make it clear from where do the differences generate. First of all, the conservatism between indirect design (ID) and direct design (DD) methods alternate depending on the fill height vs. total reinforcement area (Figure 1).

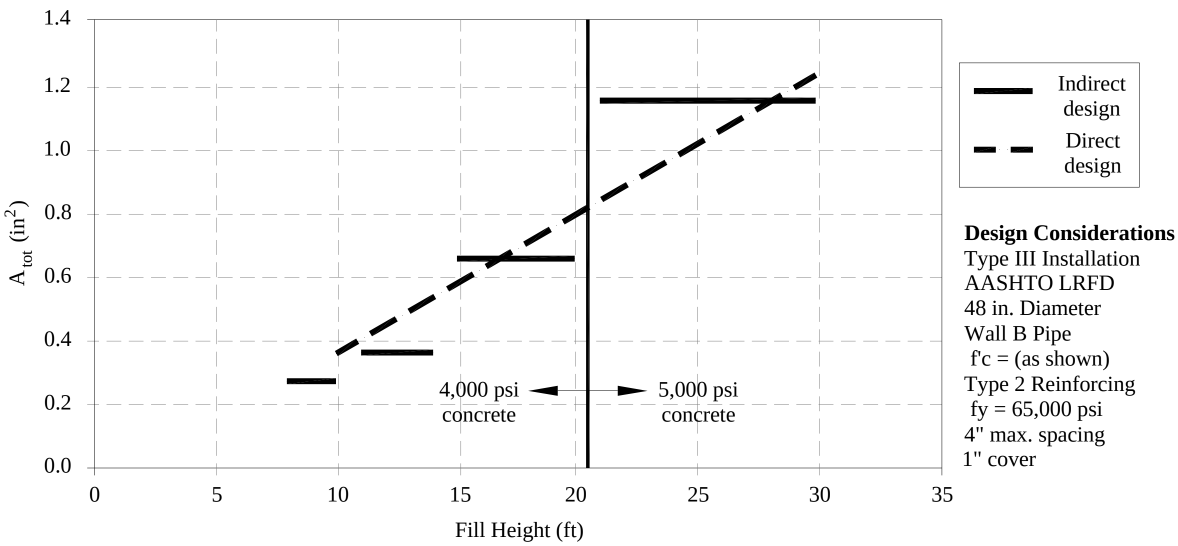

Figure 1 A_{tot} vs. Fill Height comparison between ID and DD

As can be seen, limited with class types, D-loads (due to available empirical results from 1930s), and essentially ASTM C76, indirect design method shows a stepped function. Direct design, as any other structural design where the designer can vary all of the inputs, however, presents a continuous function. It must be emphasized here that the direct design values are intentionally kept limited to those ASTMC76 classes (i.e. concrete compressive strength values) to make the comparison meaningful. If the concrete strength is varied, as is possible with DD, there can be design answers for each fill height that is equally cost effective to those gathered by ID.

2.3. Standard Installations and Heger Pressure Distribution

During the design process, the designer is required to assume a certain pipe-soil interaction resulting in a specific distribution of the earth pressure around the pipe. Standard installations were developed to ensure the fulfillment of this assumption and to ensure clear communication between the designer and the contractor. There are four standard installation types according to the percent compaction, and the material of bedding and haunch soil under the pipe. Type 1 standard installation is considered the best quality installation among the four categories, while type 4 is considered the lowest quality. Tables 3 and 4 present the Standard Installation requirements.

Table 3 Description of Standard Embankment* Installations Types 1-4 (ASCE 15-98)

Installation type	**Bedding thickness**	**Haunch and outer bedding**	**Lower side**
Type 1	D_o/24 minimum, not less than 3 in. (75 mm). If rock foundation, use D_o/12 minimum, not less than 6 in. (150).	95% SW	90% SW, 95% ML, or 100% CL
Type 2	D_o/24 minimum, not less than 3 in. (75 mm). If rock foundation, use D_o/12 minimum, not less than 6 in. (150).	90% SW or 95% ML	85% SW, 90% ML, or 95% CL
Type 3	D_o/24 minimum, not less than 3 in. (75 mm). If rock foundation, use D_o/12 minimum, not less than 6 in. (150).	85% SW, 90% ML, or 95% CL	85% SW, 90% ML, or 95% CL
Type 4	No bedding required, except if rock foundation, use D_o/12 minimum, not less than 6 in. (150 mm)	No compaction required, except if CL, use 85% CL	No compaction required, except if CL, use 85% CL
*The design used in the project assumes embankment conditions. Even if it were not embankment conditions, the earth loads for trench conditions should be based on embankment conditions per ASCE 15-98 guidelines.			

Table 4 Equivalent USCS and AASHTO Soil Classifications for SIDD Soil Designations

SIDD Soil	Representative Soil Types		Percent Compaction	
	USCS	**AASHTO**	**Standard Proctor**	**Modified Proctor**
Gravelly sand (SW)	SW, SP, GW, GP	A1, A3	100 95 90 85 80 61	95 90 85 80 75 59
Sandy silt (ML)	GM, SM, ML; also GC, SC with less than 20% passing #200 sieve	A2, A4	100 95 90 85 80 49	95 90 85 80 75 46
Silty clay (CL)	CL, MH, GC, SC	A5, A6	100 95 90 85 80 45	90 85 80 75 70 40
Silty Clay (CL) but not allowed for haunch or bedding	CH	A7	100 95 90 45	90 85 80 40

Utilization of Standard Installation (SI) provides correlation factors to correlate the actual field earth pressure distribution and magnitude to the assumed distribution during the design process. These correlation factors are named according to the design method used in designing the pipe.

For indirect design (ID), the factors would be called the Bedding Factor (B_f). In the indirect design, the supporting strength is obtained from the results of three edge bearing (TEB) tests (ACPA Technology Handbook). The required strength is then defined as D-Load in terms of the total load, bedding factor, and a factor of safety.

For direct design (DD), using Heger earth pressure distribution (Figure 2), the factors would be called the Heger earth pressure distribution non-dimensional coefficients. Determining these coefficients leads to the identification of the earth pressure distribution used for calculating the acting pressure on the pipe.

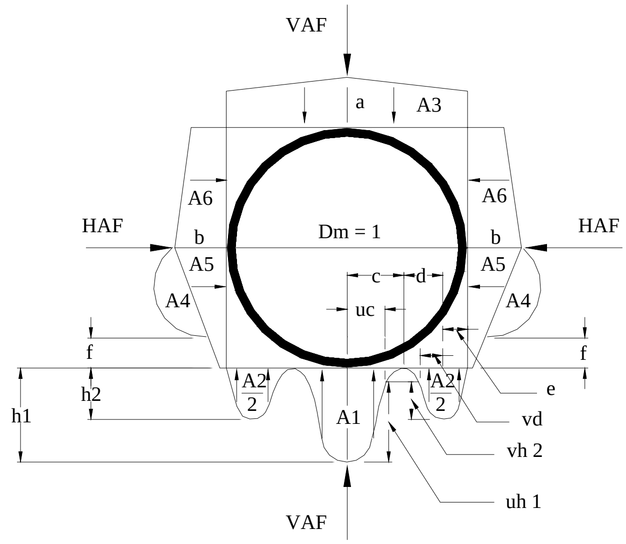

Figure 2 Heger earth pressure distribution (ASCE 15-98)

The coefficients addressed in Figure 2 are given in Table 5. To calculate the actual vertical and horizontal earth loads, coefficients must be multiplied with the prism load (PL) as given by equation 1.

English units $PL = \left[\frac{wD_o}{12}\right]\left[H + \left(\frac{0.107D_o}{12}\right)\right]$ (Eq. 1)

Where, w is the earth load in pcf, Do is the pipe diameter in inches, and H is the height of earth fill above the pipe.

Table 5 Arching Coefficients for the Heger pressure distribution (ASCE 15-98)

HEGER EARTH PRESSURE DISTRIBUTION COEFFICIENTS															
TYPE	**VAF**	**HAF**	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A**	**B**	**C**	**E**	**F**	**U**	**V**
1	**1.35**	**0.45**	**0.62**	**0.73**	**1.35**	**0.19**	**0.08**	**0.18**	**1.40**	**0.40**	**0.18**	**0.08**	**0.05**	**0.80**	**0.80**
2	**1.40**	**0.40**	**0.85**	**0.55**	**1.40**	**0.15**	**0.08**	**0.17**	**1.45**	**0.40**	**0.19**	**0.10**	**0.05**	**0.82**	**0.70**
3	**1.40**	**0.37**	**1.05**	**0.35**	**1.40**	**0.10**	**0.10**	**0.17**	**1.45**	**0.36**	**0.20**	**0.12**	**0.05**	**0.85**	**0.60**
4	**1.45**	**0.30**	**1.45**	**0.00**	**1.45**	**0.00**	**0.11**	**0.19**	**1.45**	**0.30**	**0.25**	**0.00**	**-**	**0.90**	**-**

It is important to note here that the standard installations (type 1-4) serve both methods (DD and ID) and they replace the historic bedding types. For a broader discussion on this subject, the reader is asked to refer to Erdogmus *et. al.* (2009).

2.4. Manufacturing Specifications and Quality control

While there are two accepted design practices in the field, there is only one commonly used manufacturing specification (ASTM C76). For special designs ASTM C655 is available but it is not as commonly adopted in the field.

Similarly, there is only one quality control procedure commonly used for the acceptance of RCP, regardless of the design method: Three-edge bearing test. For pipe designed according to DD ASTM C1417 is available but it is not as commonly adopted in the field. This section briefly summarizes the pros and cons of having these standards. For a more detailed read on these subjects, the reader is invited to refer to Erdogmus et. al. (2009).

Three-Edge Bearing (TEB) Test

Three-edge bearing test is the most commonly known and adopted quality control measure for all pipe, regardless of the design practice used. The TEB test (Figure 3) was developed at Iowa State University as an easy and inexpensive way to determine a minimum strength condition for pipe (Peckworth and Hendrickson 1964). It is common practice to use TEB test performance as a quality control criterion for concrete pipe; however, it was essentially developed along with the indirect design method. The acceptance limit of 0.01 inch crack, unfortunately, has not been rationally explained in any of the published documents, yet, it is strictly applied to all RCP manufactured today, regardless of the design methodology considered. Besides being an arbitrary number, 0.01 inch crack load from the TEB test is proven by past research to be overly-conservative because of the differences between the test setup and the actual field load conditions. As can be seen from Figure 2, the loading condition in the pipe wall during a TEB test is much more severe than the loading expected in the installed condition. The vertical loads applied to the top and bottom of the pipe in the test are concentrated loads while the loads in the installed condition will be distributed over some portion of the pipe. Similar to arch shapes, point loads create larger stresses and deflections in the circular pipe than uniformly distributed loads; and an installed pipe will rarely experience concentrated loads. Also, note that as the diameter of pipe increases, the ratio of wall thickness to diameter decreases; and the TEB test becomes a more severe loading condition for the pipe (Peckworth and Hendrickson 1964). For larger diameter pipes, shear stresses will govern the pipe strength in a TEB test, while shear or flexure limit states may control the pipe strength in the field (ACPA 1993). Generally, flexure will control for lower fill heights while shear will control for higher fill heights. This is an important consideration, because the bedding factor (an indirect design phenomenon) is fundamentally defined as a ratio of TEB load and field load which cause the same effect in the pipe wall. If the controlling limit state in the TEB test does not correspond to the limit state in the field, the bedding factor relationship is a false indication of supporting strength. Additionally, in the case where shear controls both the TEB test and the field condition, the

formulation of the bedding factor as a ratio of moments at the invert is inconsistent with the actual behavior of the pipe in the TEB test and the installed condition. Therefore, the use of bedding factors based on moments for this case is inappropriate.

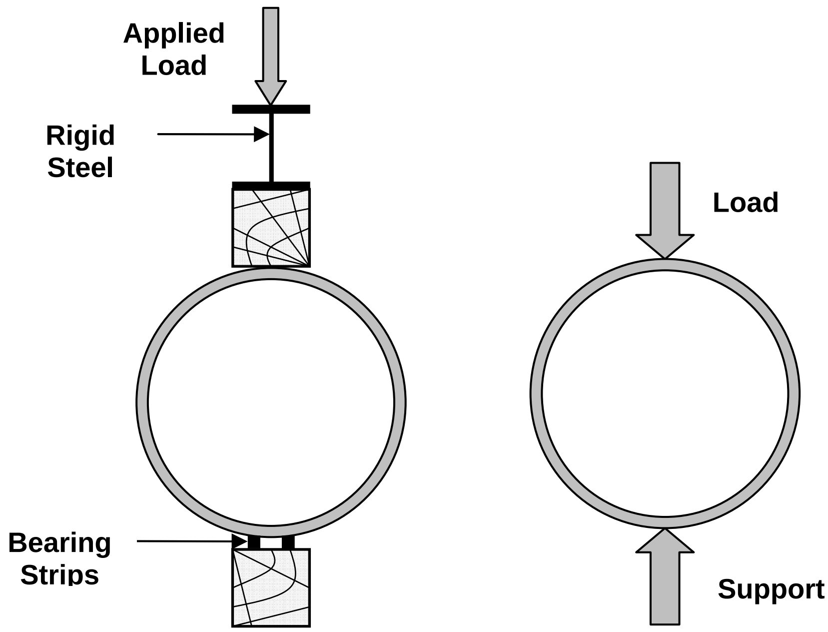

Figure 3 TEB test and associated pipe loading

Concrete Pipe Info #12 (ACPA 1991) is an ACPA publication that presents improvements for the bedding factor concept, where lateral soil pressure is considered both for trench and embankment installations. Modern construction equipment can provide high levels of backfill compaction that result in passive lateral earth pressures which should be accounted for in the design of RCP. Lateral pressure acting on the pipe will produce bending moments in the pipe wall which act opposite to those bending moments produced by vertical loads and therefore, will reduce the total bending moment within the pipe wall. The lateral pressure also produces an axial thrust component in the wall of the pipe where the maximum moment occurs, which is typically at the pipe invert. Similar to arches, the effect of axial force in a pipe wall is significant in design. Arch structures made of concrete rely on this axial compression for their load carrying capacity. When load effects create a combination of axial force and flexure, the pure compressive stresses created in the cross-section due to the axial thrust reduces the flexural tensile stresses and thus are beneficial. Axial compression in these

structures is an important consideration because this thrust reduces the tensile stresses in the structure and allows the material to span longer distances. In this formulation of the bedding factor, published in 1991, the benefits of lateral earth pressure on pipe supporting strength are considered. However, the beneficial axial thrust component is conservatively neglected. This formulation is based on the historical bedding classes and involves calculations which require the designer to make several assumptions about the installation characteristics, pressure distribution around the pipe, and soil properties.

In summary, it is the authors' opinion that TEB test and the 0.01inch crack acceptance limit is outdated, especially for pipe that is designed structurally using the direct design method.

Manufacturing Standards for RCP

ASTM C76 serves as the only accepted manufacturing standard. Special designs can be checked against ASTM C655, which directs the designer to the TEB testing and 0.01 inch crack limit, which has its own limitations as discussed above.

The dilemma in this issue is that, direct design allows more flexibility with the parameters involved in the pipe's behavior, such as concrete compressive strength, separate design of inner and outer reinforcement, etc. ; however, the D-load and pipe class system in the ASTM standards, which are indirect design parameters, do not allow the use of the inherent flexibility in the direct design method. As a result, a strength design method with its own load and resistance factors already built into the design, once subjected to the additional limitations from ASTM C76 and TEB will generally produce more conservative answers than the indirect design. This is a puzzling result for all parties involved in RCP design and manufacture, because pipe that has been once "passing" according to stringent design and quality control measures are now rendered "failing". This dilemma was the main motivation behind the research project at hand, as the Nebraska Department of Roads and City of Lincoln wanted to get to the bottom of the issues involved in the pipe design and contracted the University of Nebraska Research team to produce some answers and recommendations.

The intensive literature review summarized here and the observations made from the test pipe installation and numerous analyses conducted by the research team provide such answers and recommendations.

3. Independent Review of City of Lincoln RCP design procedures

A case study was employed in this project to evaluate the efficiency and the economy of current design methods. An independent design of the reinforced concrete pipe for a City of Lincoln project Upper SE Salt Creek Trunk Sewer was carried out by the authors.

Reinforced concrete pipe specifications for the project was as follows:

The design document allows for several kinds of pipe, as listed below:

- 48 inch diameter plastic lined reinforced concrete pipe (RCP)
- Plastic-lined reinforced concrete steel cylinder pipe (RCCP)
- Centrifugally cast fiberglass reinforced plastic mortar pipe (CCFRM)

Although these kinds of pipes are allowed, logically, changes in pipe type are only allowed at the manhole locations, where the line is naturally separated. Since the contractor was Concrete Industries, authors assumed that the entire pipeline will be composed of reinforced concrete pipe.

Details of the pipe installation were as follows:

Concrete as specified in Section 03001-3 is 4,000 psi, mixed in accordance with ASTM C94.

Pipe design criteria is stated as follows on the project specifications: "The criteria to be used for determination of construction loads for the concrete pipe (RCP or RCCP) sanitary sewer shall be the PCA Bulletin entitled "Concrete culverts and conduits for Type 1 Conduits".

Table 6 is given in the specifications (Page 02618-3), as the basis of concrete pipe design. Pipe is designed for the minimum D-loads listed as shown below with the corresponding earth fill depths for the 0.01 inch crack.

Table 6 Upper SE Salt Creek Trunk Sewer Original Design Table (Source: *Upper SE Salt Creek Trunk Sewer- City of Lincoln Project No. 502455 by Olsson Associates,* Page 02618-3)

Minimum Strength Classification vs. Maximum Cover Depth		
Pipe Diameter (inches)	Minimum Design D-load Classification (to produce 0.01 inch crack)	Maximum Cover Depth (feet)
48	1,350 (Class III)*	10
48	1,500 (Class IV)*	12
48	2,000 (Class IV)*	16
48	2,500 (Class V)*	19
For all jacked installation at railroad crossings, the minimum design D-load classification (to produce 0.01 inch crack) for all diameters shall not be less than 3,000.		

*The pipe class designations are not given in the original table provided in the specifications. These are results of our assessment based on the D-loads provided and the corresponding ASTM C76 tables.

Review of Design

Based on our initial analysis of the specified design, we identified the method of design followed by the designers as follows:

Our understanding is that this table is generated by assuming "Type 4-Bedding" and using the ACPA Fill height tables, which implies the use of indirect design method.

Type 4 bedding assumes the worst case for bedding conditions, *i.e.* it assumes that no special bedding is provided and that there no compaction is required for the supporting soil. However, the details given on Sheet 4 specify a fully compacted soil condition. Thus, with an initial review based on our experience and research on pipe design methods, we have observed a few points within the specified design:

1. The granular material compacted to a minimum of 100% may not be feasible or possible to achieve.

2. The haunches are areas that are hard to get to perfect compaction, if these areas are loose but the "middle bedding" area is stiff, this may cause stresses in the pipe that are more severe than anticipated. (Standard Installation requires a minimum compaction of 95% for these soils in a Type 1 installation, which is the most stringent installation classification.)

3. The bedding type described is not Type 4, which "requires no compaction", while the resulting pipe design (D-loads and corresponding fill heights) prescribes Type-4 bedding (worst case). However, the pipe could be specified taking advantage of the specified bedding requirements, or the specified pipe could be used without additional bedding preparation, since there is enough conservativeness in the design to allow for less control in construction. If the designers wish to keep an additional layer of conservatism to allow for the errors that can result due to the involvement of two different parties (the designer and the contractor), the authors propose the following practice:

-Specify and design for Type 3 bedding: Type 3 bedding is not hard to achieve. There is more chance the bedding will be stiffer (more compacted) than Type 3 requirements, than there is chance that a specified Type 1 bedding will not be as compacted as it should.

Other Discussions on Current Practice Reviews

It was brought to the team's attention through discussions at meetings, and later confirmed by the survey responses (Section 6 of this report) that many designers still use historic bedding classes and historic bedding factors. First of all, it should be reminded that "bedding factor" is a strictly indirect design

phenomenon, and if the designer is using Direct Design, bedding factors do not factor in the design. Second, as we stated before, it is not recommended to use historic bedding classes, neither by ACPA nor by the authors of this report, because the standard installations provide more effective communication between the designer and the contractor (as suggested above, i.e. Type 3), and because the quality control can be assured through quantitative measures.

Tables 7 and 8 present the bedding factors for historic bedding classes and standard installation bedding factors, respectively, as given by concrete pipe technology handbook published by ACPA (1993). Only types B, C, D are listed in the handbook, therefore only types B-D in historic bedding classes and types 2-4 for standard installations are listed here.

Table 7 Historic Bedding Factors (1930's- 1970's)

Bedding Class	Embankment, B_{fe}	Narrow Trench, B_{ft}
B	2.5 to 2.9	1.9
C	1.7 to 2.3	1.5
D	1.1 to 1.3	1.1

Table 8 Standard Installation Bedding Factors (1970's- present)

Installation Type	Embankment, B_{fe}	Narrow Trench, B_{ft}
2	2.8 to 3.2	1.9
3	2.2 to 2.5	1.7
4	1.7	1.5

Revisiting equation 1, it can be seen that bedding factor is inversely proportional to the supporting strength of the pipe. Thus, the larger the bedding factor, smaller the D-load required. Thus using historic bedding factors would create unnecessary conservatism if the designer specified a standard installation; and this is monitored through material types and compaction levels.
Another set of conservatism occurs, if the embankment installation is mixed with trench installations.
And a third level of conservatism may occur, if type 2 installation is specified but the pipe is designed according to poor quality bedding, i.e. type 4.

As such in an extreme case, where all of these alterations are applied all at once, a pipe segment may have about double the required capacity. This is before any factor of safety or quality control due to TEB is applied.

The authors' design suggestion is to use a clean and more-streamlined design method, as explained below:

If using ID:
- Use the Standard installations,
- Prefer Type 3 bedding as it is relatively easier to achieve
- Use the matching standard installation bedding factors in design, i.e. design the pipe for Type 3 bedding conditions.

If using DD:
- Use the Standard Installations
- Prefer Type 3 bedding as it is relatively easier to achieve
- Select the Heger pressure distribution coefficients matching Type 3 bedding in design (or simply Select Type 3 installation in PipeCAR)

4. Experimental Full Scale RCP Installation

A full size experimental pipe line is constructed at Lincoln landfill in Lincoln, Nebraska. This section presents the design criteria and assumptions, instrumentation details, construction history, and analysis of data from the installation.

4.1. Design of the Installation

The pipeline consists of eight 12-foot long pipe segments, each with a wall thickness of 5-in and a diameter of 48-in. The earth fill profile is designed to range between fill heights of 5 ft and 20ft (Figure 4), so that 1) the effect of fill height can be observed as a design parameter, and 2) as the fill heights vary from one end of a pipe segment to the other, one fill height should be selected for the design. In a case like this, the designer can choose the average fill height, lowest fill height (least conservative), or the highest fill height (most conservative). An optimum way to design is perhaps to design for the average fill height- for the purposes of this experimentation.

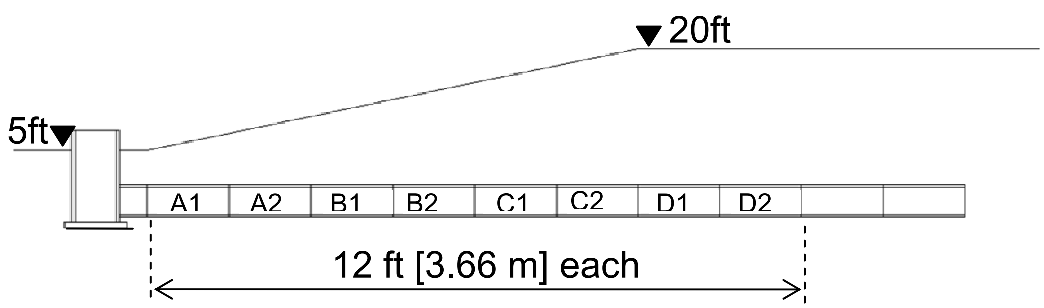

Figure 4 Schematic profile of the experimental pipe installation

Pipe segments are designed using **4 different methods** to compare design values. Each of these methods is explained below and a summary of parameters is given in Table 9. Table 10 shows a comparison among the reinforcement areas calculated using different design criteria and the final reinforcement areas.

Method 1: Method 1 strictly obeys the procedures of the ***Indirect Design Method***, where, first the ACPA fill height tables are utilized to determine the suggested *pipe class* based on the fill height and the pipe diameter. Then ASTM C76 standard is utilized to find the inner and outer reinforcement areas based on the pipe class, pipe diameter, and the wall type/thickness. Since each class and pipe diameter combination has a specific concrete strength (f'_c) attached to it in ASTM C76, for some pipes this value is 4,000 psi, while it is 6,000 psi for the others. The design parameters can be found in Table 9. The fill heights vary from one end of a pipe segment to the other (Figure 4), thus, to be conservative, the highest fill height that each pipe segment sees is utilized to gather the reinforcement areas (Table 10).

Method 2: Method 2 first utilizes Direct Design method using the software PipeCAR, however ASTM C76 is obeyed, therefore the concrete strength (f'_c) is limited to the range of 4,000psi- 6,000psi. When crack control governs the design, this criterion is obeyed. Once a reinforcement area is gathered from PipeCAR, ASTM C76 is utilized to determine which standard pipe has reinforcement areas ***larger*** than those gathered from DD. Therefore, the final and limiting design criterion is ASTM C76. This situation also causes the designer to ignore the structurally designed outer reinforcement and results in A_{so} values that are strictly 60% of the inner reinforcement areas. *Based on our analyses, this is the methodology that is utilized by the Nebraska Department of Roads (NDOR), with the goals of utilizing the most up-to-date design method (DD) while making it easier for the pipe manufacturers to communicate pipe specifications based on the ASTM terms (e.g. pipe classes, reinforcement areas from ASTM C76).*
The fill heights vary from one end of a pipe segment to the other (Figure 4), thus, to be conservative the highest fill height that each pipe segment sees is utilized to gather the reinforcement areas (Table 10).

Method 3: Method 3 solely and strictly utilizes the Direct Design Method and thus the reinforcement area values (inner and outer) are directly taken from the PipeCAR software results, with the parameter inputs listed in Table 4. Crack control criterion is obeyed. The fill heights vary from one end of a pipe segment to the other (Figure 4), thus, to be conservative the highest fill height that each pipe segment sees is utilized to gather the reinforcement areas (Table 10).

Method 4: UNL Research team – Experimentation Final Design: The final design for the experimentation, also Method 4, is created by the UNL

research team such that direct design method (through PipeCAR) is used to its full potential, i.e. allowing use of material properties that truly reflect the manufacturer's (In this case, Concrete Industries, Inc.) standard concrete mixture (f'_c = 8,000 psi- Please see the cylinder test results in the Appendix). Furthermore, to test the *authors' hypothesis* that 0.01 inch crack limit state might be creating additionally conservative designs, this criterion is neglected when it governs the design. This omission causes flexure limit state to govern all designs, given the other parameters in the experimental installation design. The outer reinforcement is designed structurally using DD (PipeCAR). As other designs, the actual fill heights vary from one end of a pipe segment to the other (Figure 3), however, this time in order to be conservative for some of the pipe segments and create slightly un-conservative pipe segments for the rest, the highest fill height for the first pipe segment of each pair is utilized to gather the reinforcement areas while the lowest fill height is used for the second pipe segment. Thus, in the final design every two segments with the same letter designation have the same design earth fill load (average of the range from the start of segment 1 to the end of segment 2), even though the actual earth fill loads they carry are different (Figure 4, Table 10). This implies that segments A2, B2, C2 and both D pipes are un-conservative, while the rest are intentionally conservative. Details and the progression of final design are listed in Table 11.

Table 9 Summary of Design Parameters for Methods 1-4

	Method 1 Indirect Design	Method 2 Direct Design (PipeCAR) + ASTM	Method 3 Direct Design (PipeCAR)	Method 4 UNL Research
Pipe Diameter (D_o)	**48 in**			
Wall type (thickness)	**B (5 in)**			
Standard Installation Type	**Type 3 bedding (embankment)**			
Concrete (f'_c)	**4,000 psi**	**4,000 - 6,000 psi**	**8,000 psi**	**8,000 psi**
Steel (f_y)	**Wire fabric conforming to A 185/A497 or f_y = 65, 000 psi**			
Design basis for (A_{so})	**60 % of inner reinforcement**		**Structurally designed**	
Spacing	**4 in**			
0.01 in crack control limit state considered?	**N/A**	**Yes**	**Yes**	**No**

Table 10 Test installation design options with different assumptions

Pipe Segment	Fill Height (ft)			Method 1			Method 2			Method 3		Method 4	
				Indirect Design[a]			Direct Design (PipeCAR) + ASTM[a, b]			Direct Design (PipeCAR)[c]		UNL Experimental Design[c]	
	Actual min-max	Design (Methods 1, 2, 3)	Design (Method 4)	ASTM C76 Class	A_{si}	A_{so}	ASTM C76 Class	A_{si}	A_{so}	A_{si}	A_{so}	A_{si}	A_{so}
A1	5.0 - 7.5	7.5	7.5	II	0.180[a]	0.110[a]	III	0.240[a]	0.140[a]	0.174[c]	0.081[c]	0.174[c]	0.081[c]
A2	7.5 - 10.0	10.0	7.5	II	0.180[a]	0.110[a]	III	0.240[a]	0.140[a]	0.215[c]	0.100[c]	0.174[c]	0.081[c]
B1	10.0-12.5	12.5	12.5	III	0.240[a]	0.140[a]	IV	0.420[a,d]	0.250[a]	0.257[c]	0.120[c]	0.257[c]	0.120[c]
B2	12.5-15.0	15.0	12.5	IV	0.420[a]	0.250[a]	IV	0.420[a,d]	0.250[a]	0.299[c]	0.141[c]	0.257[c]	0.120[c]
C1	15.0-17.5	17.5	17.5	IV	0.420[a]	0.250[a]	V	0.730[a,b,d]	0.440[a,b]	0.346[c,d]	0.161[c]	0.341[c,e]	0.161[c]
C2	17.5-20.0	20.0	17.5	IV	0.420[a]	0.250[a]	V	0.730[a,b,d]	0.440[a,b]	0.447[c,d]	0.182[c]	0.341[c,e]	0.161[c]
D1	20.0	20.0	20.0[f]	IV	0.420[a]	0.250[a]	V	0.730[a,b,d]	0.440[a,b]	0.447[c,d]	0.182[c]	0.384[c,e,f]	0.182[c,f]
D2	20.0	20.0	20.0[f]	IV	0.420[a]	0.250[a]	V	0.730[a,b,d]	0.440[a,b]	0.447[c,d]	0.182[c]	0.384[c,e,f]	0.182[c,f]

[a] f'_c = 4, 000 psi per ASTM C76 standards
[b] Initial f'_c = 4, 000 in PipeCAR, Final f'_c = 6, 000 psi per ASTM C76 standards for Class V pipe with 48inch diameter and 5 inch wall thickness
[c] f'_c = 8,000 psi
[d] Designs where 0.01inch crack control limit state governs
[e] Adjusted designs ignoring 0.01 inch crack control limit state, therefore flexure governs.
[f] In the final designs (See Table 5) these designs are adjusted to match C1 and C2 designs, thus designed for 17.5 ft

Table 11 Details and Progression of the UNL Research Team Design (Method 4 in Table 9)

Pipe Segment	Design Fill Height (ft)	Reinforcement Areas*					
		Considering 0.01inch crack limit state		Ignoring 0.01inch crack limit state		Actual (as built)	
		A_{si}	A_{so}	A_{si}	A_{so}	A_{si}	A_{so}
A1	**7.5**	**0.174**	**0.081**	**0.174**	**0.081**	**0.175**	**0.081**
A2	**7.5**	**0.174**	**0.081**	**0.174**	**0.081**	**0.175**	**0.081**
B1	**12.5**	**0.257**	**0.120**	**0.257**	**0.120**	**0.259**	**0.121**
B2	**12.5**	**0.257**	**0.120**	**0.257**	**0.120**	**0.259**	**0.121**
C1	**17.5**	**0.346**[a]	**0.161**	**0.341**[b]	**0.161**	**0.344**	**0.161**
C2	**17.5**	**0.346**[a]	**0.161**	**0.341**[b]	**0.161**	**0.344**	**0.161**
D1	**20.0**	**0.447**[a]	**0.182**	**0.384**[b]	**0.182**	**0.344c**	**0.161c**
D2	**20.0**	**0.447**[a]	**0.182**	**0.384**[b]	**0.182**	**0.344c**	**0.161c**

[a] 0.01inch crack control governs
[b] Adjusted for 0.01 inch crack control
[c] Adjusted to match design with C1 and C2, i.e. designed for 17.5ft fill height
***All design values are based on f'c= 8,000 psi, 5inch wall thickness, 4inch reinforcement spacing**

Table 12 Percent difference of all methods from Method 2 (*i.e.* method generally followed in NDOR specs) in terms of Reinforcement areas

Pipe Segment	Method 2	Method 1		Method 3		Method 4	
	Direct Design (PipeCAR) + ASTM	Indirect Design		Direct Design (PipeCAR)		UNL Research	
	A_{TOTAL}	A_{TOTAL}	% dif. From Method 2	A_{TOTAL}	% dif. From Method 2	A_{TOTAL}	% dif. From Method 2
A1	0.380	0.290	-23.68%	0.255	-32.89%	0.255	-32.89%
A2	0.380	0.290	-23.68%	0.315	-17.11%	0.255	-32.89%
B1	0.670	0.380	-43.28%	0.377	-43.73%	0.377	-43.73%
B2	0.670	0.670	0.00%	0.440	-34.33%	0.377	-43.73%
C1	1.170	0.670	-42.74%	0.507	-56.67%	0.502	-57.09%
C2	1.170	0.670	-42.74%	0.629	-46.24%	0.502	-57.09%
D1	1.170	0.670	-42.74%	0.629	-46.24%	0.566	-51.62%
D2	1.170	0.670	-42.74%	0.629	-46.24%	0.566	-51.62%
	Average		**-32.70 %**		**-40.43%**		**-46.34%**

Table 13 Percent difference of all methods from Method 4 (*i.e.* method followed by the UNL research team for the "daring" experimental design) in terms of Reinforcement areas

Pipe Segment	Method 4	Method 1		Method 2		Method 3	
	UNL Research Experimental Design	**Indirect Design**		**Direct Design (PipeCAR) + ASTM**		**Direct Design (PipeCAR)**	
	A_{TOTAL}	**A_{TOTAL}**	**% dif. From Method 4**	**A_{TOTAL}**	**% dif. From Method 4**	**A_{TOTAL}**	**% dif. From Method 4**
A1	0.255	0.290	13.73%	0.380	49.02%	0.255	0.00%
A2	0.255	0.290	13.73%	0.380	49.02%	0.315	23.53%
B1	0.377	0.380	0.80%	0.670	77.72%	0.377	0.00%
B2	0.377	0.670	77.72%	0.670	77.72%	0.440	16.71%
C1	0.502	0.670	33.47%	1.170	133.07%	0.507	1.00%
C2	0.502	0.670	33.47%	1.170	133.07%	0.629	25.30%
D1	0.566	0.670	18.37%	1.170	106.71%	0.629	11.13%
D2	0.566	0.670	18.37%	1.170	106.71%	0.629	11.13%
	Average		**26.21%**		**91.63%**		**11.10%**

Tables 12 and 13 compare the four possible design methodologies. Table 12 compares all of the methods to Method 2, which utilizes direct design through PipeCAR and then checks the results against ASTM C76 to establish the required reinforcement. Method 4, which is the method used by the UNL research team to design the "daring" experimental pipe at the COL landfill.
As anticipated, Method 4 and Method 3, both direct design methods, are the closest in percent difference with 11.10%. The difference comes from ignoring crack control limit state and using the least conservative fill height value for Method 4, as opposed to the average value for Method 3.
When Tables 12 and 13 are inspected together, it can be seen that Method 4 is closer to indirect design method (Method 1) results (26.21%) than Method 3 versus indirect design (32.70%), proving if certain alterations are made, direct design and indirect design values can be brought closer.

Of all the methods most conservative is Method 2, followed by Methods 1, 3, and 4. Method 4, which is the final design method used for the experimental pipe, is ***intentionally un-conservative to observe stresses in the pipe through the installed strain gages and therefore see the effects of the additional burden on the pipe's behavior with the design decisions made***. While pipe segment B1 is almost equivalent to indirect design result, pipe segment B2 seems the least conservative compared to indirect. Once again, this is due to the stepped distribution of designs for indirect design method versus the continuous distribution of designs for DD (Figure 1). It can

be expected for pipe segment B2 to show higher stresses than the other segments, however, it the pipe segment is still expected to be structurally safe, given that DD approach adopted incorporates the necessary load and resistance factors into the strength design for the 4 limit states (flexure, shear, radial tension, and diagonal tension), while ignoring the fifth limit state (crack control). Again, it is the *authors' hypothesis* that the 0.01 in crack width is an arbitrary limit; it does not cause structural problems, and thus will not affect the behavior of the pipe. This hypothesis is put to test through the monitoring of the pipe, as the results will be discussed later in this section.

Joint Design

One issue that was brought to the research team's attention was that City of Lincoln is worried about the integrity of RCP joints and consistently requests additional reinforcement to be added to the standard R4 joint (Figure 5, Table 14).

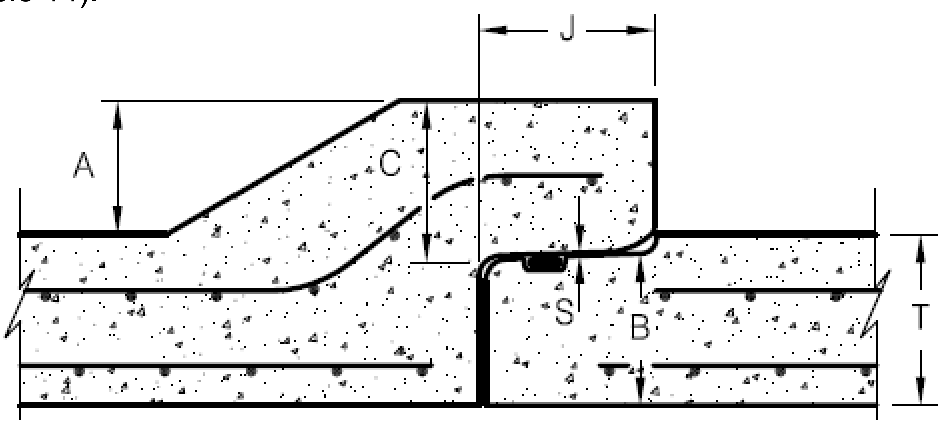

Figure 5 Standard R4 joint

Table 14 Details of the Standard R4 joint (figure 5)

Joint length; J (in.)	4 ¾
B (in.)	4.60
C (in.)	4.61
S (in.)	0.07
Wall thickness; T (in.)	5
A (in.)	4 1/8

For the testing pipe installation, regular R4 joints are used for all of the pipe segments. This way any major distress, displacement or failure at the joints can be observed with the fill height as a variable, and the question of whether or not standard R4 joints are safe in installed conditions can be answered.

4.2. Instrumentation for data collection and long term monitoring

Figure 6 illustrates the location of the pressure cells and the strain gages located on instrumented pipe segments, which are A2, B2, C2 and D2, i.e. segments those that are “under designed”. Four pressure cells with a diameter of 9.06 in. were mounted at the mid-length of each instrumented segments corresponding to following: 1) vertical pressure at the crown, 2) vertical pressure at the invert, 3) horizontal pressure at the spring-line, and 4) lateral pressure at the spring-line. To determine the relationship between the vertical and horizontal earth pressure at spring-line level, both vertical and horizontal earth pressure cells are placed.

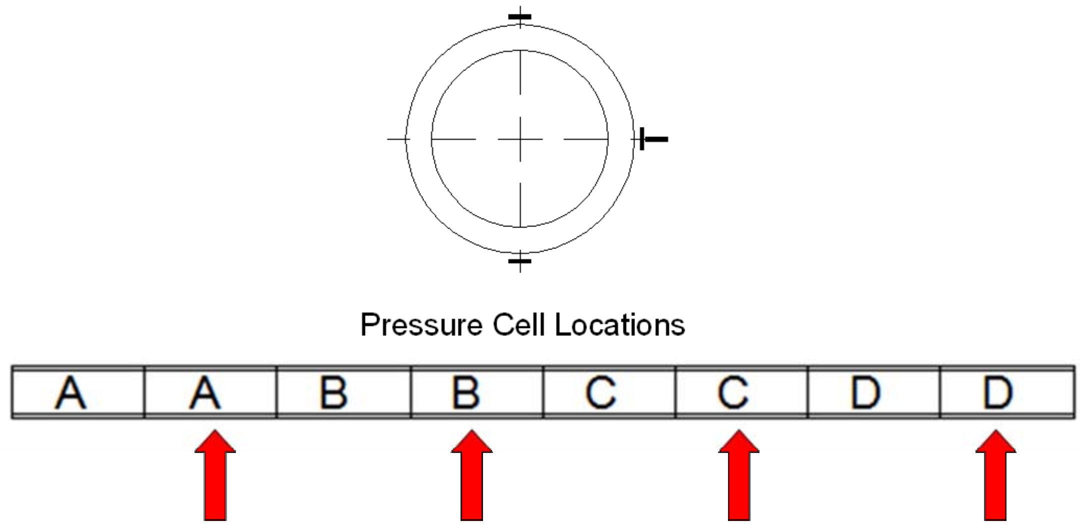

Figure 6 Pressure cell locations around a typical pipe segment

Figure 7 Pressure cells applied at the construction site to avoid damage during transportation

Each of the eight segments was instrumented with ten vibrating wire strain gages at the crown, negative 45˚from the crown, spring line, negative 135˚ from the crown, and invert (Figures 8 and 9). Five strain gages were mounted on the inner reinforcement cage and five were mounted on the outer reinforcement cage. While three locations both on the inner and outer reinforcements coincide with the pressure cells location, the other two locations were chosen as intermediate points (one at 45˚from the crown and another at 135˚from the crown) between those three locations to better observe the strain distribution within the pipe wall.

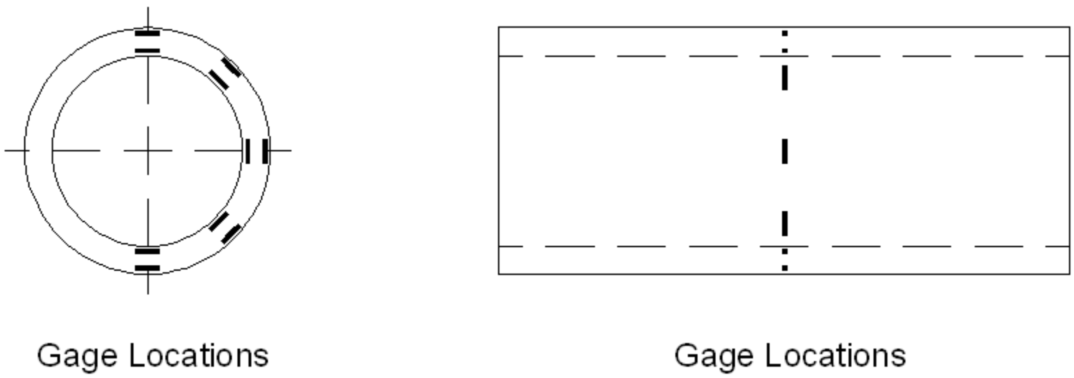

Figure 8 Strain gage locations on a typical pipe segment

Figure 9 Strain gages were applied on the inner and outer reinforcement gages at the pipe manufacturing plant

Vibrating wire strain gages operate on the theory the frequency of the vibration of a tensioned wire is proportionate to the tension in it. Strains are measured using the vibrating wire principle: a length of steel wire is tensioned between two end blocks that are firmly in contact with concrete. Deformations in the concrete will cause the two end blocks to move relative to one another,

altering the tension in the steel wire. This change in tension is measured as a change in the resonant frequency of vibration of the wire. Electromagnetic coils that are located close to the wire accomplish excitation and readout of the gage frequency.

4.3. Construction of the experimental pipe installation

The construction of the pipe installation started in October 2007 and was completed on December 12th, 2007. The instrumented test installation is constructed as positive projecting embankment type, in sub-trench (Conc. Tech Handbook, pg. 4-2, 1993). Figure 10 shows the cross-section of the installation.

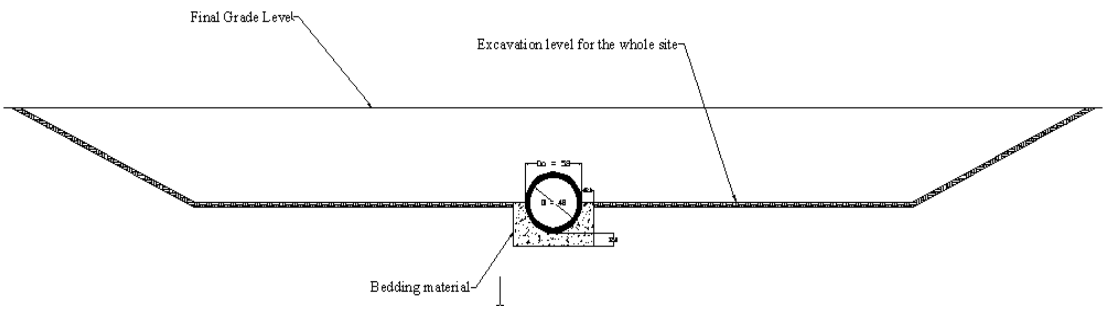

Figure 10 Cross section showing the excavation for installation

Selected photos from construction in Figures 11- 15 illustrate views from the construction of the test installation.

Figure 11 Handling of pipe segments

Figure 12 Pipe segments are placed in the sub-trench

Figure 13 Inside of the pipe illustrating the strain gage cables. Pipe is not lined to allow monitoring for the cracks

Figure 14 All eight of the pipe segments are placed in the sub-trench

Figure 15 Pipe Installation: Earth Fill compaction

4.4. Results and Discussion on the Full Scale Pipe Installation

This section presents results of the field monitoring of the installed pipe as well as the results of the TEB test of the identically designed pipe to compare to the installed conditions. The results are discussed with respect to the goals of the project and suggestions for RCP design are developed.

Pipe installation is monitored between the end of construction in January, 2008 and June, 2009; covering a period of 18 months. Pressure cell readings were recorded during construction at several lifts of the backfill. Because of the grade profile illustrated in Figure 4, backfilling was leveled for the whole site until the minimum height of the slope was reached (5 ft. above the pipe crown). Since gathering strain gage readings during construction would interrupt the construction process; construction-period strain gage readings were not collected. Furthermore, the intermediate strain readings before the earth fill is fully placed would not relate neither to the design of the pipe, nor the objectives of the study.

Table 15 Data Collection Schedule*

No	Data Collection Dates
1	1/25/2008
2	1/31/2008
3	2/7/2008
4	2/15/2008
5	3/4/2008
6	4/11/2008
7	4/22/2008
8	5/12/2008
9	7/8/2008
10	10/10/2008
11	6/12/2009

*Data was collected a few more times, however, since the data presented anomaly compared to other collected data, these data sets were discarded

4.4.1. Pressure Gage Readings

The soil-structure interactions and re-establishment of the Heger pressure distributions were out of the scope of this project, however, the team used pressure cells to monitor the pressure values to make sure the applied loads are within the range of design values and the bedding type assumed in design is correct. It must be noted here that pressure cells are flat instruments mounted on the circular face of the pipe. Furthermore, the soil pressure is

distributed around the pipe as estimated by Heger distribution, however, the pressure cells would only read the pressure distributed over the cell's surface area. As a result, the values should only be treated as estimates, and not exact comparisons. Table 16 presents the comparison of expected pressures according type 3 standard installation and Heger distribution versus the measured pressures.

Table 16 Measured vs. Theoretical Pressures

Type 1 Installation: Installation type assumed in design

		Springline Pressure (psi)			Invert Pressure (psi)			Crown Pressure (psi)		
Pipe	**h(ft)**	**Heger**	**Exp.**	**%DIFF**	**Heger**	**Exp.**	**%DIFF**	**Heger**	**Exp.**	**%DIFF**
A2	8.75	3.38	0.7	-79.2899	24.26	30.74	26.71063	11.83	16.84	42.34996
B2	13.75	5.2	1.64	-68.4615	37.35	35.86	-3.98929	18.22	15.18	-16.685
C2	18.75	7.03	4.87	-30.7255	50.44	38.95	-22.7795	24.6	14.17	-42.3984
D2	20	7.48	4.1	-45.1872	53.71	5.49	-89.7784	26.2	9.41	-64.084

Type 2 Installation: Installation type assumed in design

		Springline Pressure (psi)			Invert Pressure (psi)			Crown Pressure (psi)		
Pipe	**h(ft)**	**Heger**	**Exp.**	**%DIFF**	**Heger**	**Exp.**	**%DIFF**	**Heger**	**Exp.**	**%DIFF**
A2	8.75	3.38	0.7	-79.2899	31.16	30.74	-1.34788	12.25	16.84	37.46939
B2	13.75	5.2	1.64	-68.4615	47.98	35.86	-25.2605	18.87	15.18	-19.5548
C2	18.75	7.03	4.87	-30.7255	64.79	38.95	-39.8827	25.48	14.17	-44.3878
D2	20	7.48	4.1	-45.1872	68.99	5.49	-92.0423	27.13	9.41	-65.3151

Type 3 Installation: Installation type assumed in design

		Springline Pressure (psi)			Invert Pressure (psi)			Crown Pressure (psi)		
Pipe	**h(ft)**	**Heger**	**Exp.**	**%DIFF**	**Heger**	**Exp.**	**%DIFF**	**Heger**	**Exp.**	**%DIFF**
A2	8.75	3.04	0.7	-76.9737	35.98	30.74	-14.5636	12.25	16.84	37.46939
B2	13.75	4.68	1.64	-64.9573	55.39	35.86	-35.2591	18.87	15.18	-19.5548
C2	18.75	6.32	4.87	-22.943	74.8	38.95	-47.9278	25.48	14.17	-44.3878
D2	20	6.73	4.1	-39.0788	79.65	5.49	-93.1073	27.13	9.41	-65.3151

Type 4 Installation: Installation type assumed in design

		Springline Pressure (psi)			Invert Pressure (psi)			Crown Pressure (psi)		
Pipe	**h(ft)**	**Heger**	**Exp.**	**%DIFF**	**Heger**	**Exp.**	**%DIFF**	**Heger**	**Exp.**	**%DIFF**
A2	8.75	2.53	0.7	-72.332	38.7	30.74	-20.5685	12.25	16.84	37.46939
B2	13.75	3.9	1.64	-57.9487	59.58	35.86	-39.812	18.87	15.18	-19.5548
C2	18.75	5.27	4.87	-7.59013	80.46	38.95	-51.5909	25.48	14.17	-44.3878
D2	20	5.61	4.1	-26.9162	85.68	5.49	-93.5924	27.13	9.41	-65.3151

Discussion had emerged in TAC meetings that the actual installation type may not be type 3 but better, such as the stronger type 2 or 1. Upon reviewing the numbers, indeed, this seems to be the case. It seems, the contractors have compacted the bedding more than asked for, thus providing stronger bedding than specified. While this is a slight impediment to the experiment's goals, it also presents validity to the former suggestion that Type 3 bedding can be easily *exceeded*, and therefore type 3 bedding can be safely specified and the pipe can be designed for Type 3 bedding support.

4.4.2. Strain Gage Readings

Strain gage readings are taken over 18 months. Figures 16- 23 present the strain data versus data collection dates. It can be seen that over 18 months, the steel has been stressed, however, yielding of steel have not been observed in any of the segments. Highest stresses have been observed in segment B2, where strains are at 22.5% of steel's yield stress are observed in the outer reinforcement for the crown. It must be noted that while higher than others, the strains on this reinforcement cage is still very low compared to the capacity of the material, and is not a cause for structural failure. Higher values for strain on segment B2 were anticipated as discussed earlier in the report.

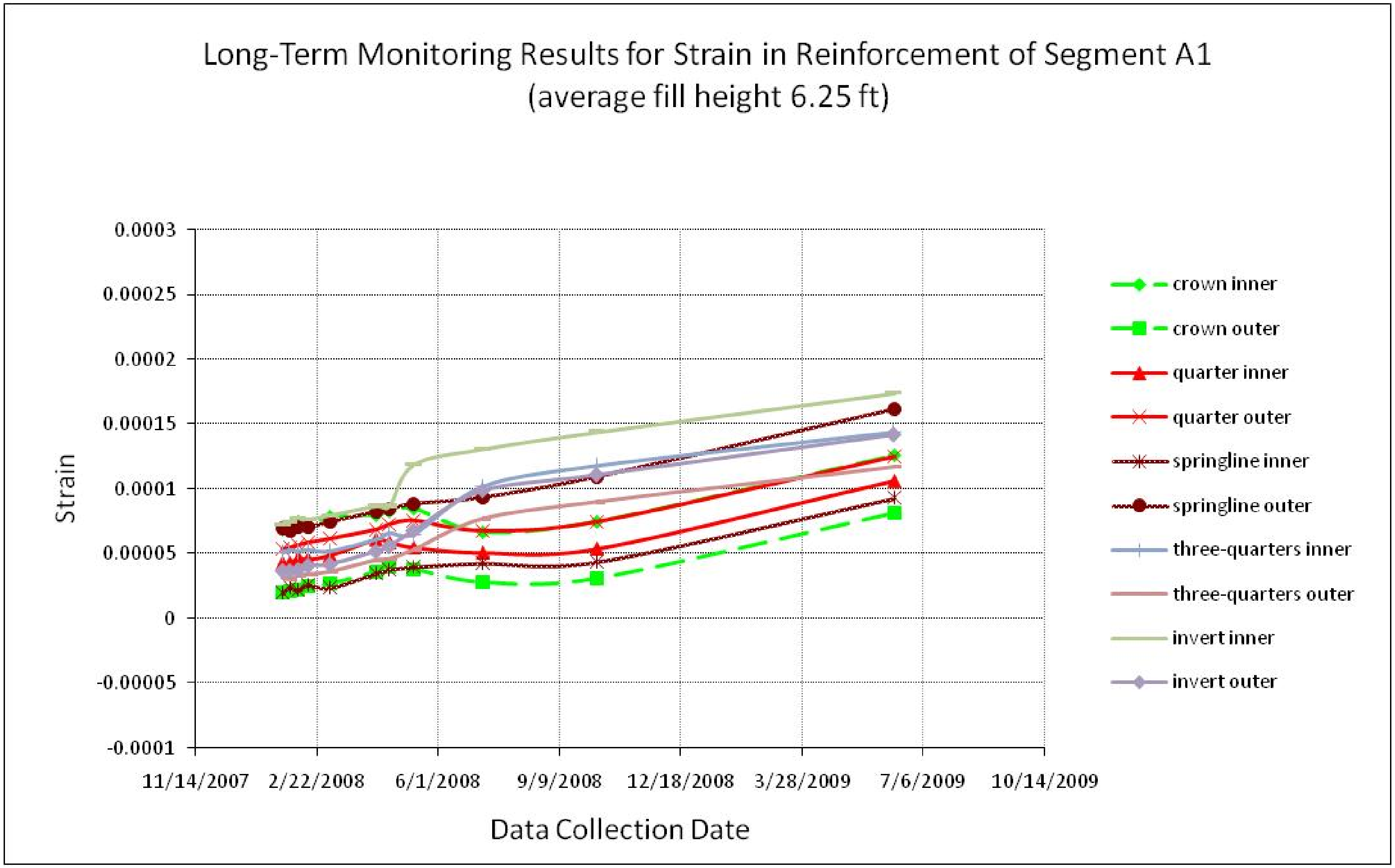

Figure 16 Strain Gage Results for Segment A1

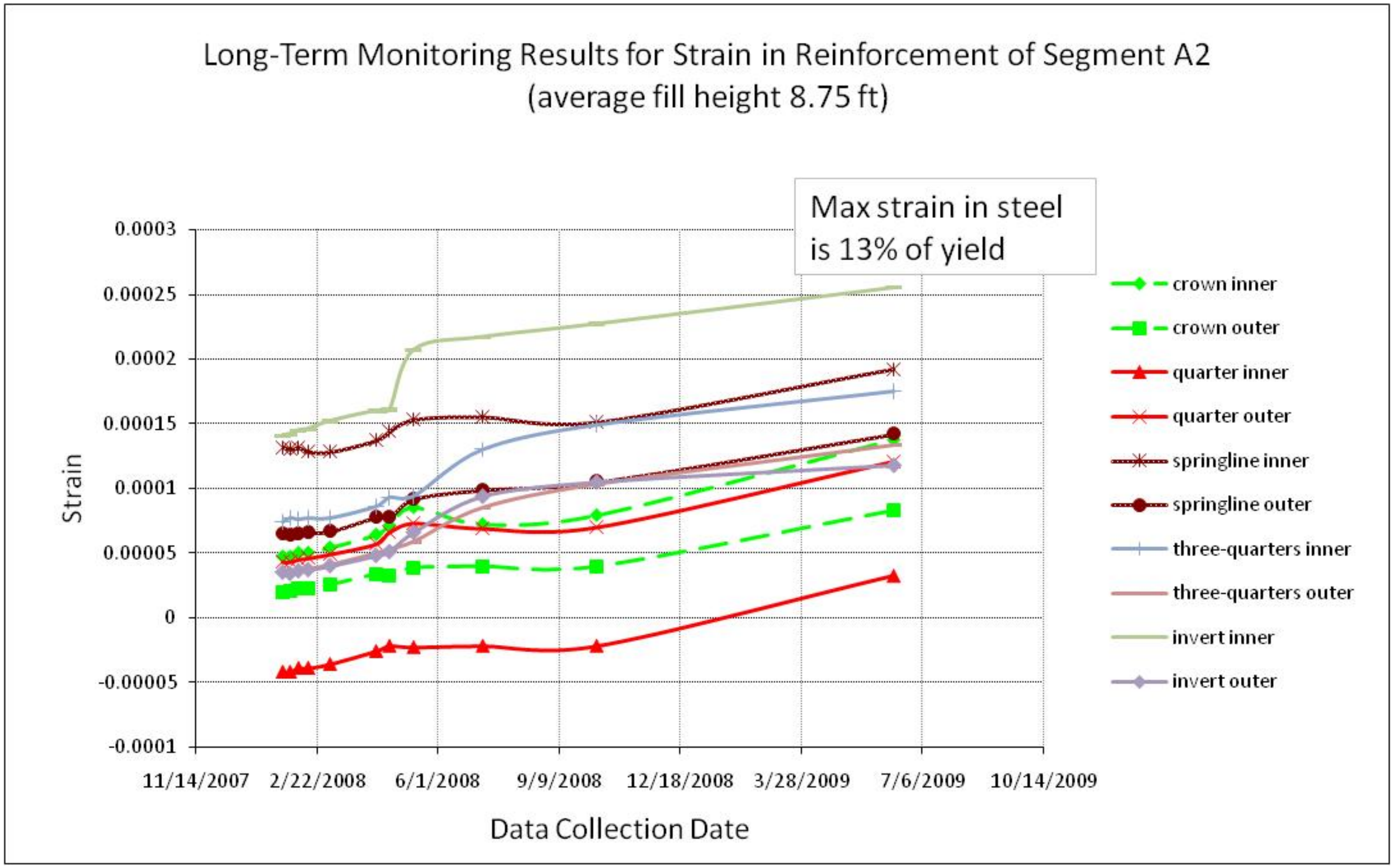

Figure 17 Strain Gage Results for Segment A2

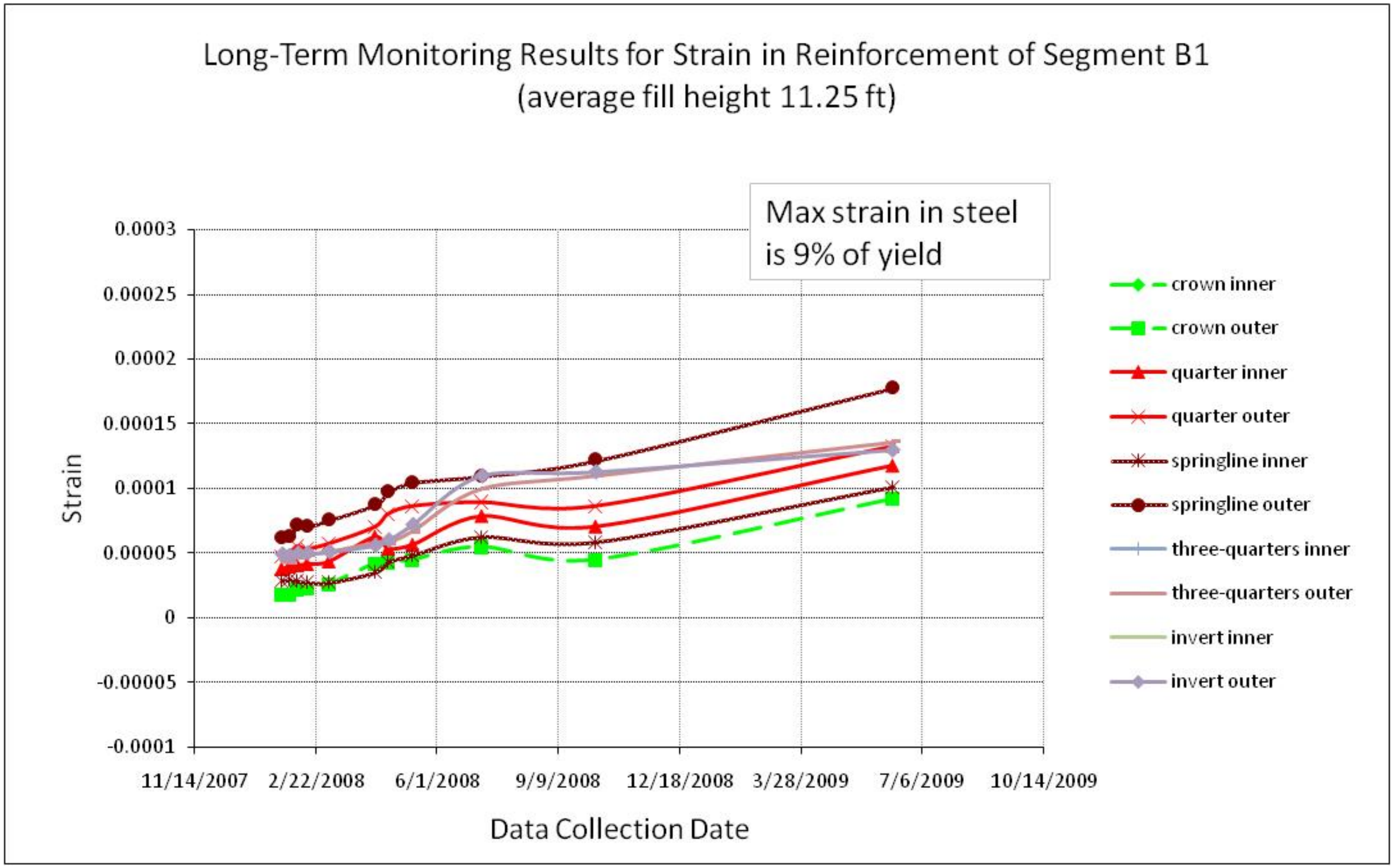

Figure 18 Strain Gage Results for Segment B1

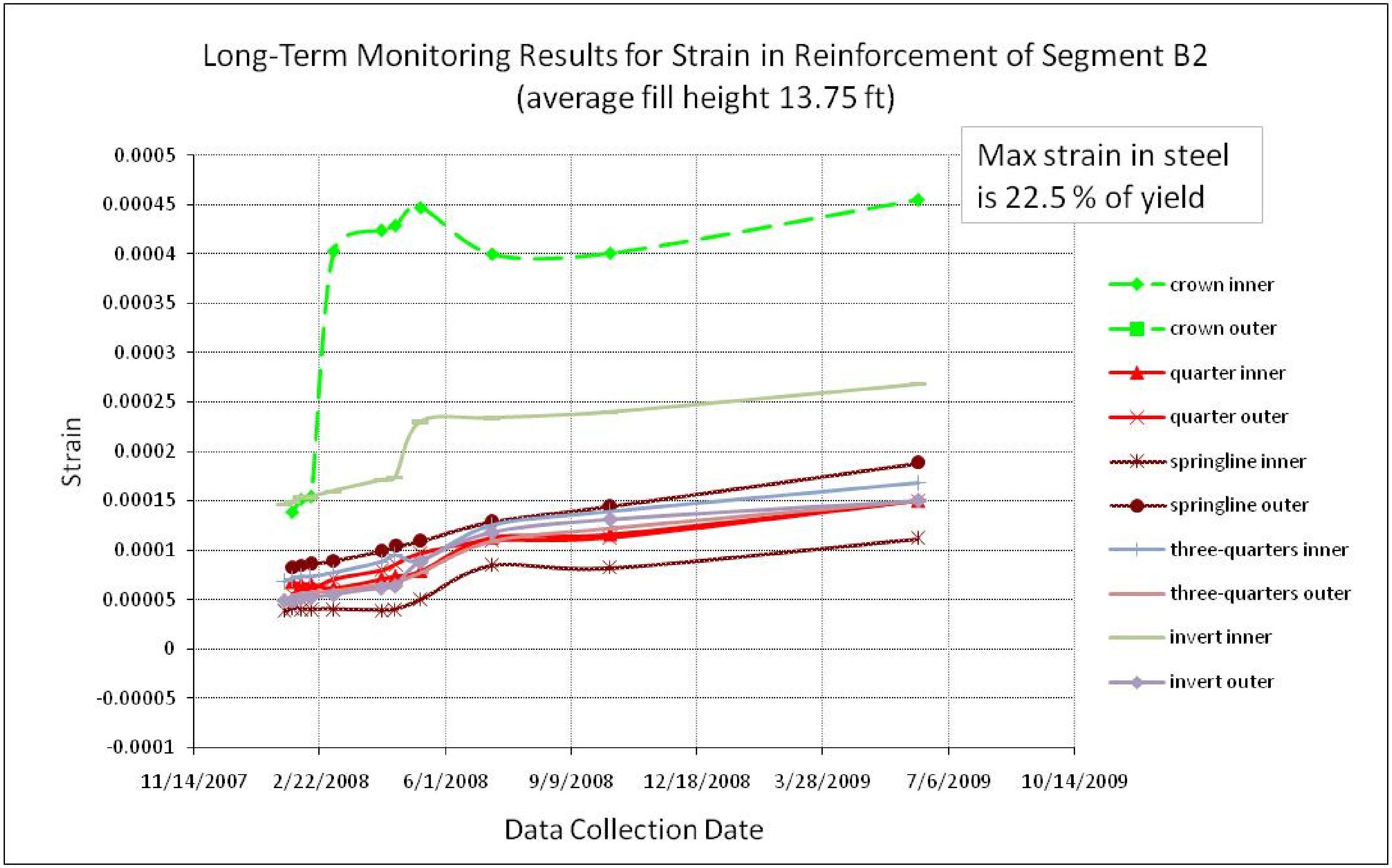

Figure 19 Strain Gage Results for Segment B2

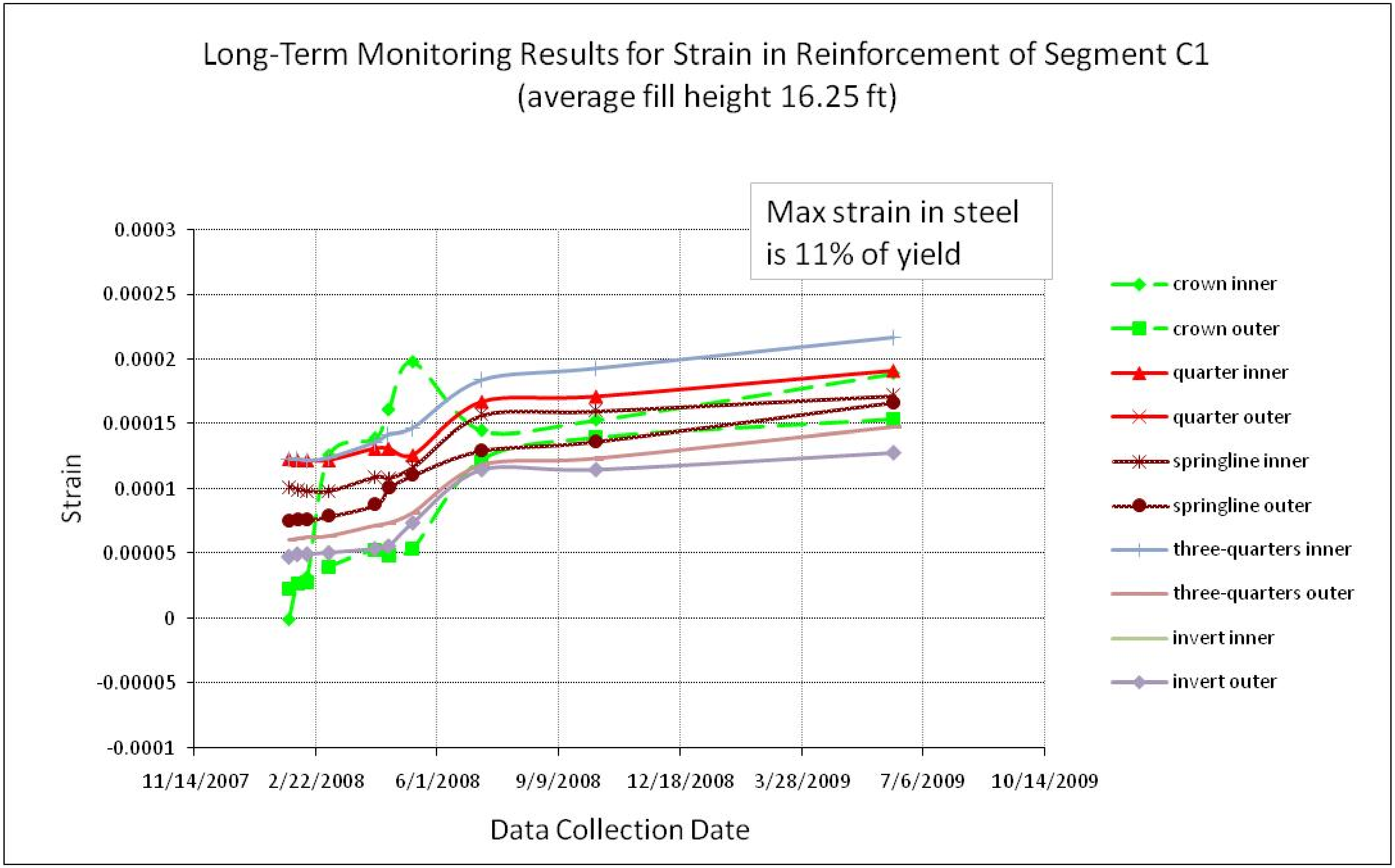

Figure 20 Strain Gage Results for Segment C1

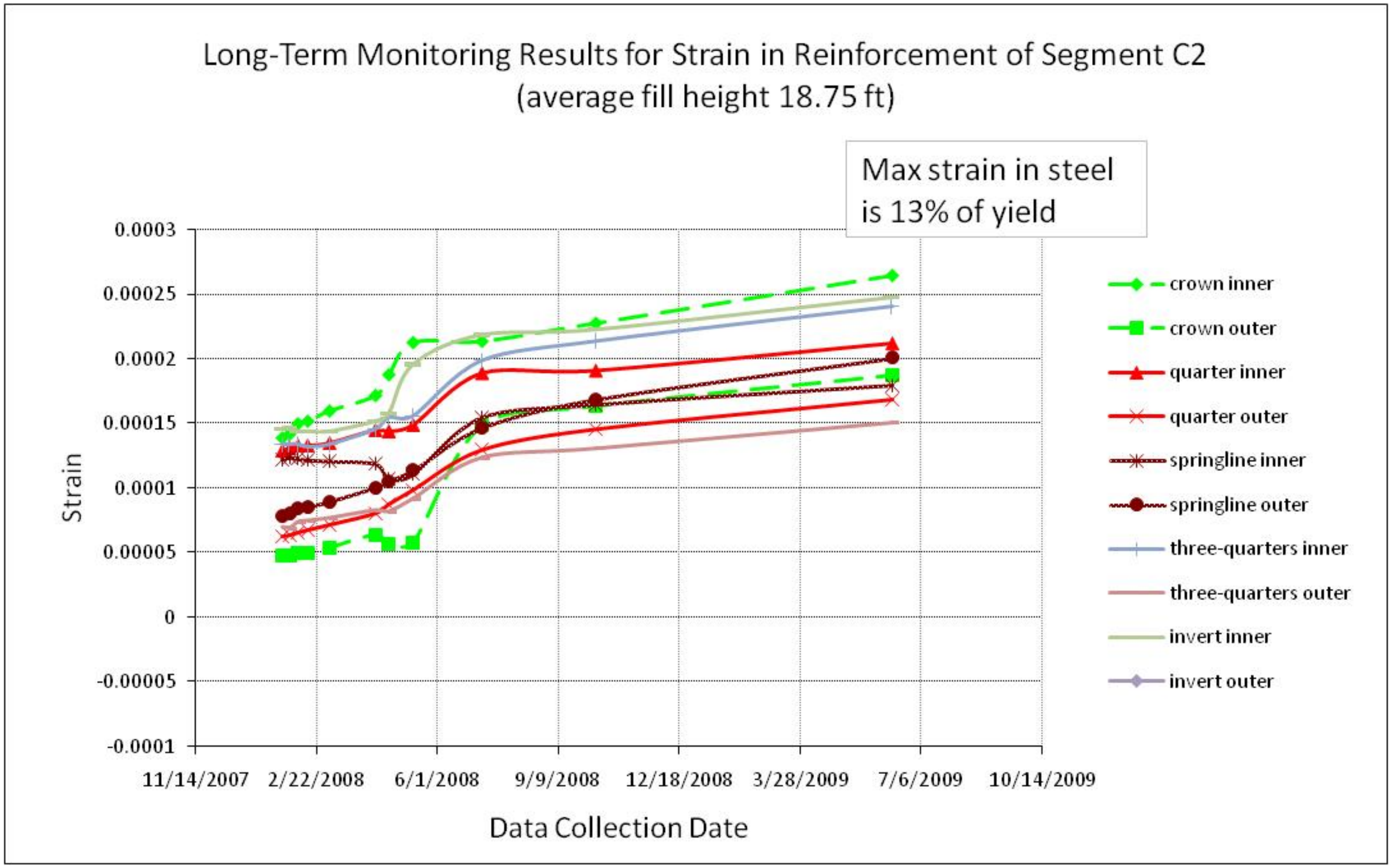

Figure 21 Strain Gage Results for Segment C2

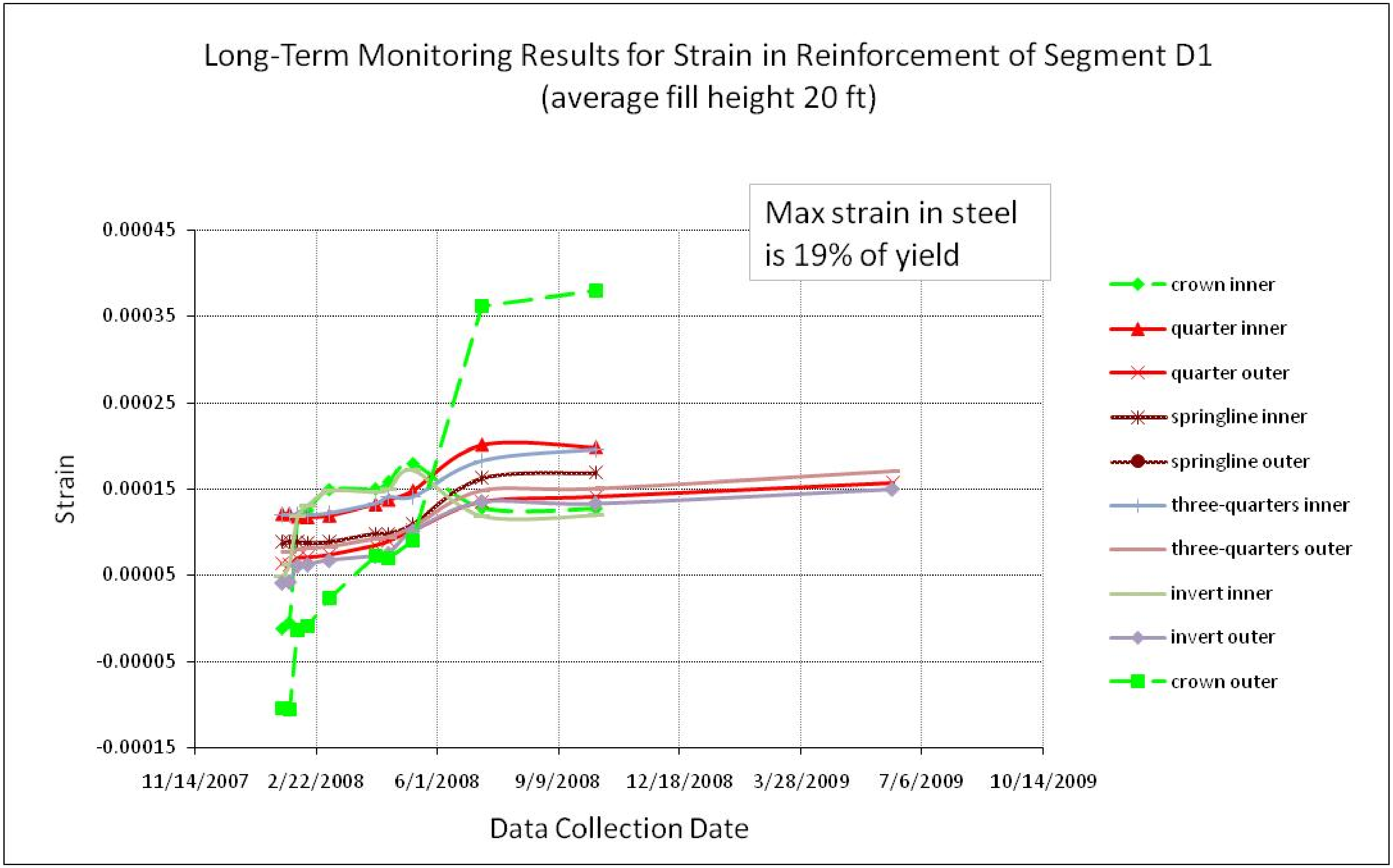

Figure 22 Strain Gage Results for Segment D1

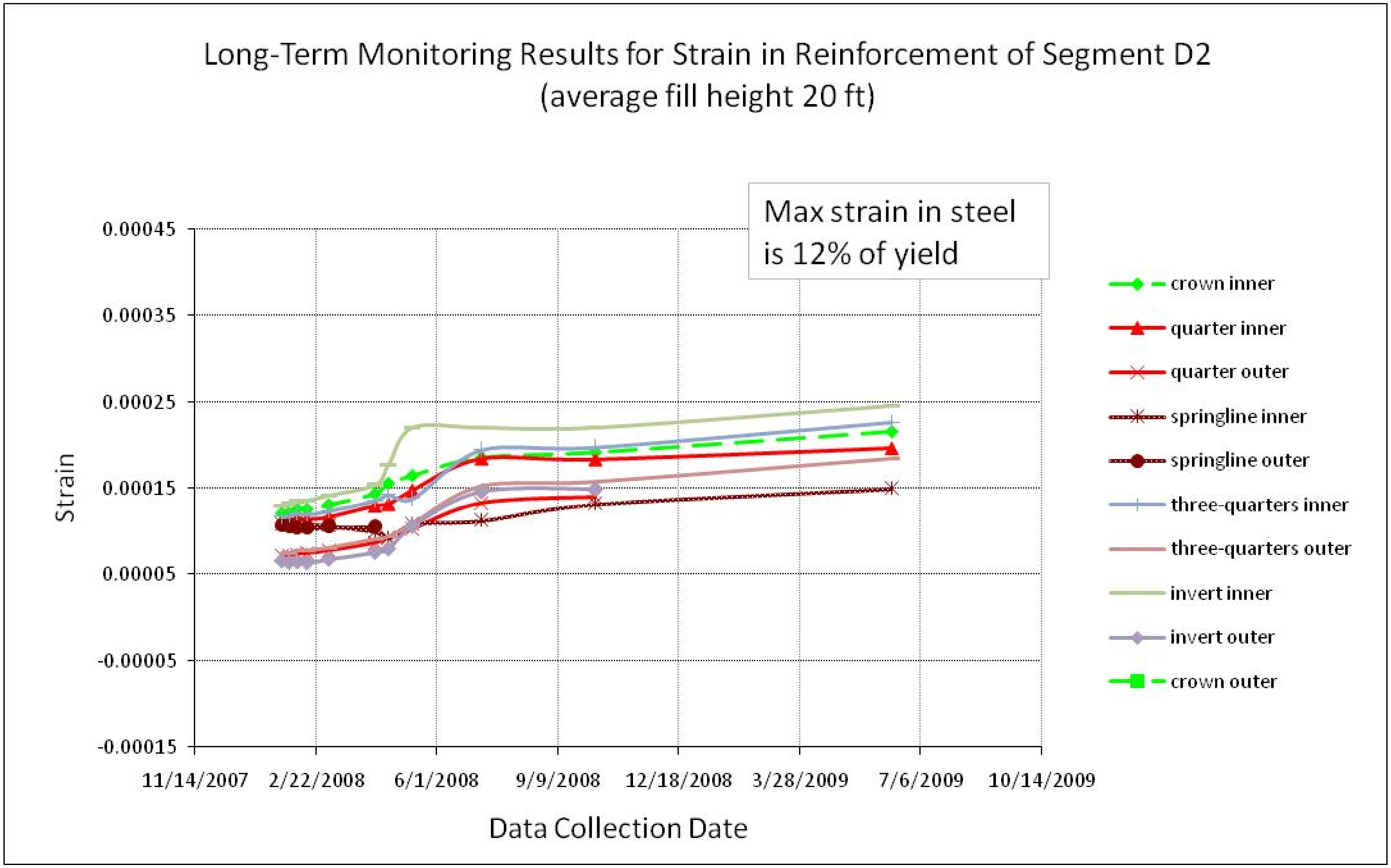

Figure 23 Strain Gage Results for Segment D2

4.4.3. Observations on Crack Development

Some cracking was observed on the pipe, as expected for any reinforced concrete structure should crack for the reinforcement to be engaged; however, none of the cracks exceeded the 0.01 in width during our observation period. Some images from the inside of the pipe segments documenting the cracks are presented in Figures 24-28, and a summary of cracking is presented in Figure 29.

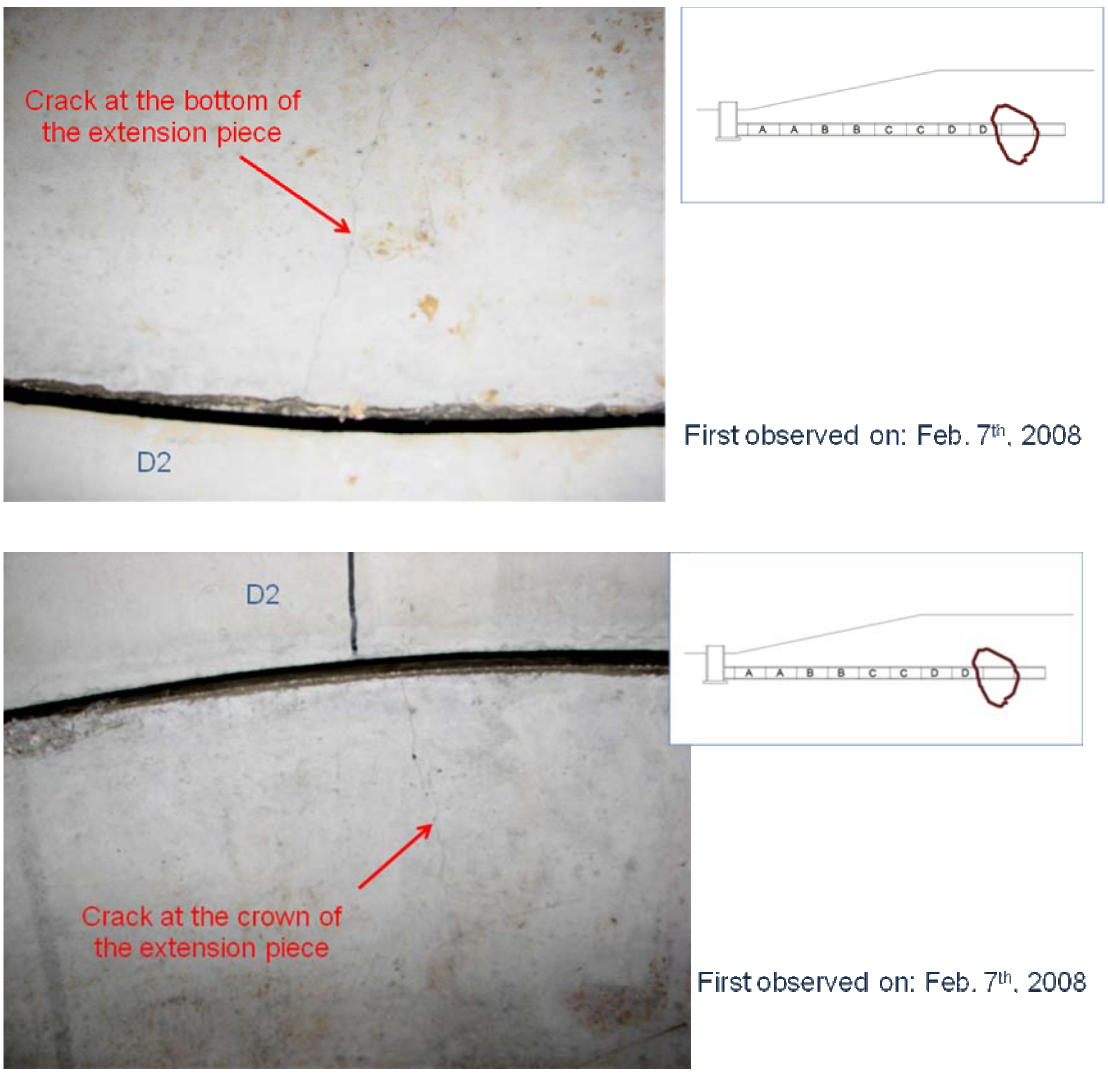

Figure 24 Crack observed on the extension piece

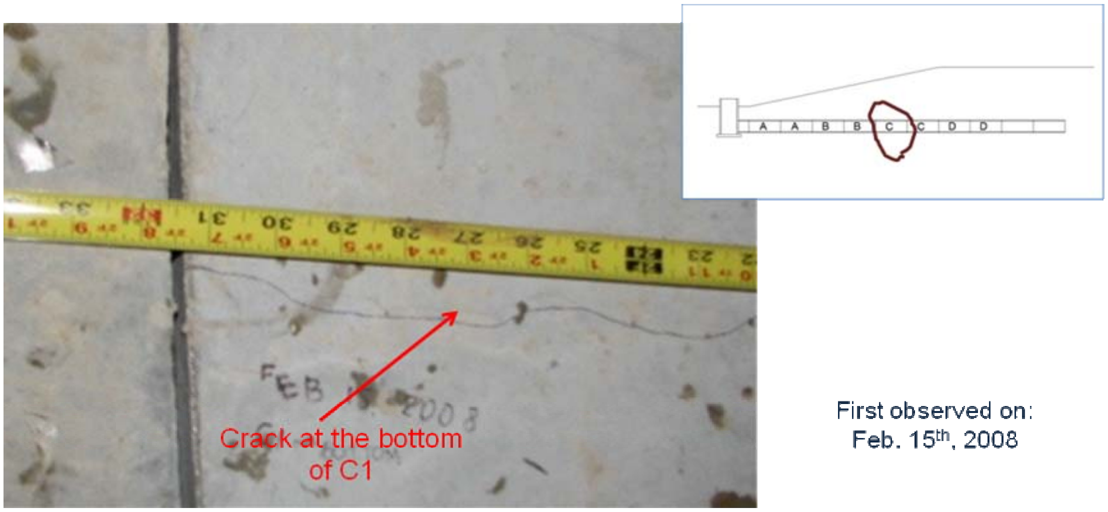

Figure 25 Crack observed on C1

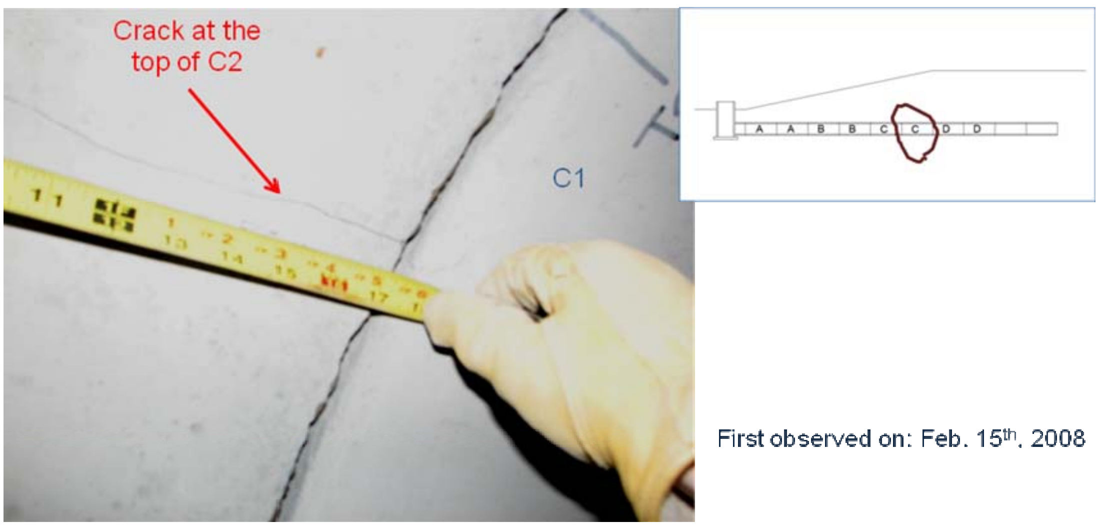

Figure 26 Crack observed on C2

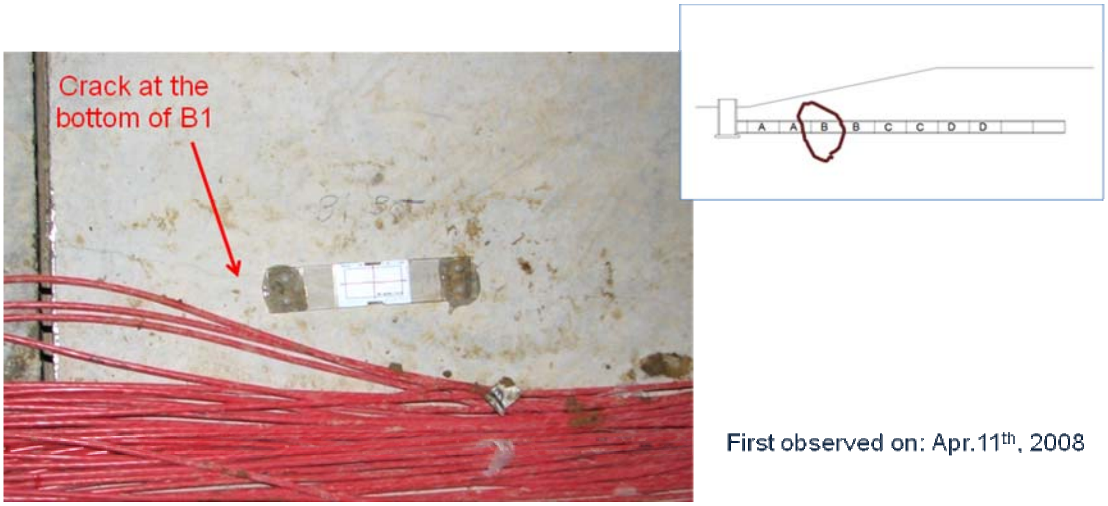

Figure 27 Crack observed on B1

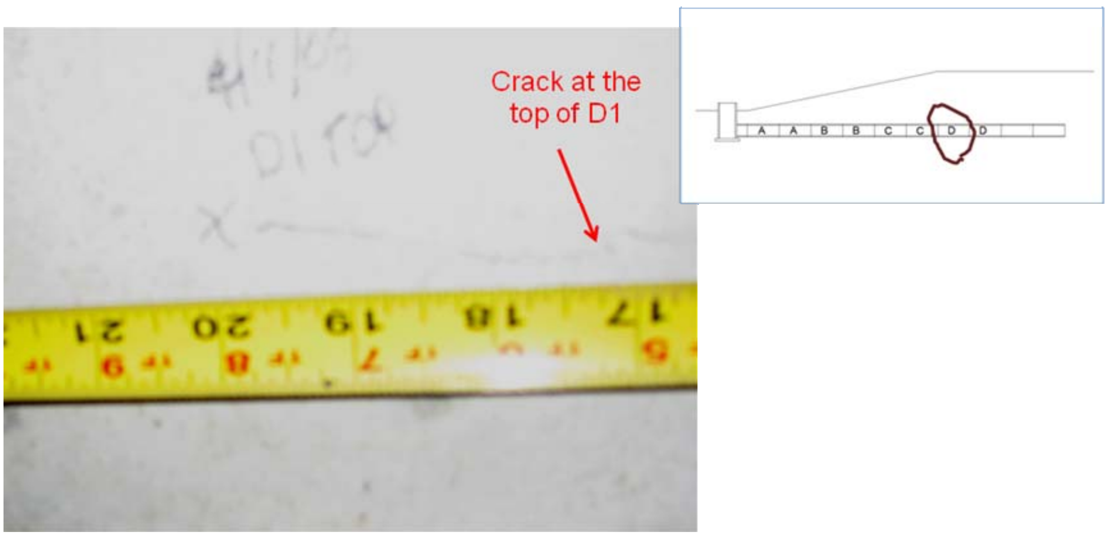

Figure 28 Crack observed on D1

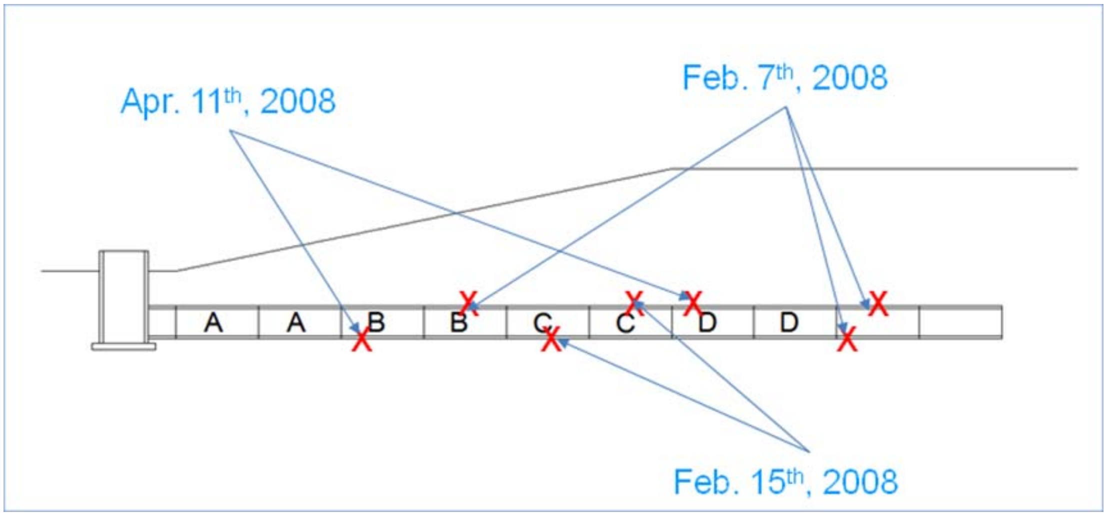

Figure 29 Summary of Cracking on the experimental pipe installation

4.4.4. Observations on Joint Behavior

As discussed in section 5.1, the joints were designed as standard R4 joints. According to our observations, no noticeable cracking, failure, dislocation, or displacement have occurred at the joints of the pipe installation.

4.5. Laboratory test of the proposed pipe design

One pipe segment designed identically as the C and D pipe segments (Figure 4, Table 10) was instrumented with surface-mounted strain gages and a displacement transducer and tested in TEB in order to compare the behavior of the pipe in TEB and in installed conditions (Figures 30 and 31).

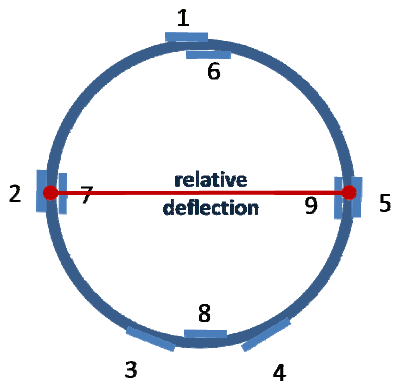

Figure 30 Instrumentation scheme for the laboratory test segment

Figure 31 TEB test setup for the laboratory test segment

Figure 32 Photos from various stages of specimen C and D TEB testing

During the test data is continuously recorded. Table 16 presents the strain gage data and the lateral deflection readings from the milestone stages of 0.01inch crack, ultimate load, and failure. Figure 33 presents the strain distribution through the pipe's wall at the crown, at 0.01inch crack load level.

Table 17 Strain Gage and Lateral Deflection Readings for the TEB Test Specimen

Test Milestone	D-load (lb/ft/ft)	ASTM C76 Class	Relative Deflection (in)	Strain Gage Readings (Strain*)								
				1	2	3	4	5	6	7	8	9
0.01in crack	1235	class III	0.2045	-0.0004	0.0044[a,b]	-0.0004	-0.0001	0.0015[b]	0.0403[a,b,c]	-0.0007	0.0064[a,b]	-0.0009
Ult. Load	1630	class III	0.5362	-0.0003	0.0069[a,b]	-0.0006	-0.0002	0.0015[b]	0.0403[a,b,c]	-0.0011	0.0103[a,b]	-0.0013
Failure	1698	class III	0.7054	-0.0003	0.0081[a,b]	-0.0007	-0.0002	0.0015[b]	0.0403[a,b,c]	-0.0013	0.0120[a,b]	-0.0016

* Negative denotes compressive strain and positive denotes tensile strain
[a] Strains above yield strain of steel reinforcement
[b] Strains above the cracking strain of the concrete (f'_c= 8,000psi)
[c] Strain gage 6 disengaged after 0.01 in crack and did not detect increased strains after that point

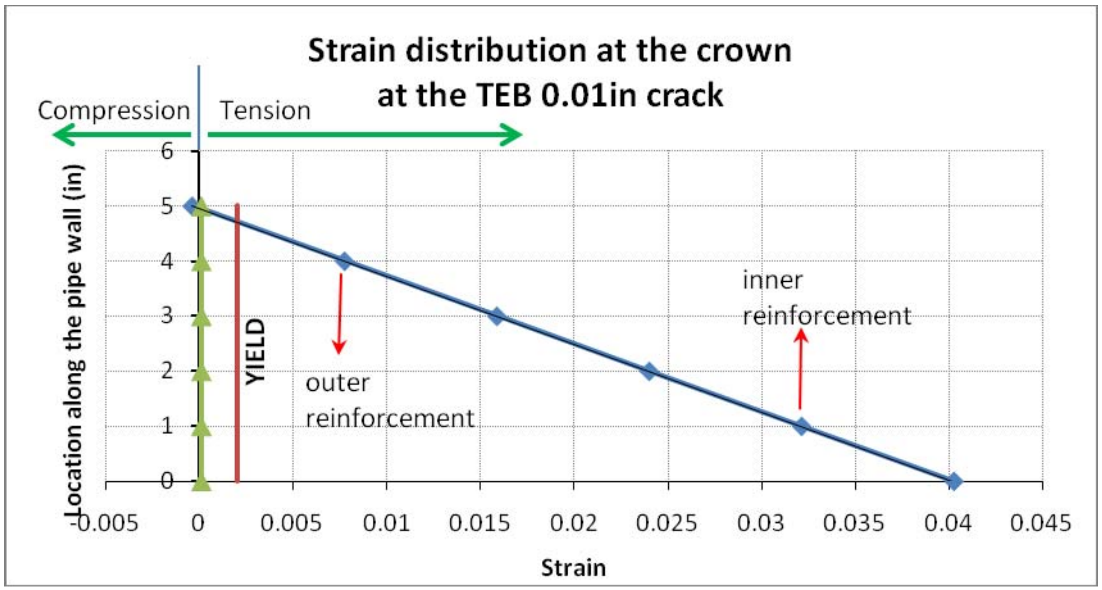

Figure 33 Strain distribution at the crown at 0.01 in crack load

Through the process illustrated in Figure 33, the strain levels at the inner and outer reinforcement can be extrapolated from the surface strain gages mounted on the concrete. As can be seen from the results above, the steel at locations 2 (spring-line outer), 6 (crown inner), and 8 (invert inner) have **yielded**. Concrete strains at locations 2 (left spring-line outer), 5 (right spring-line outer), 6 (crown inner), and 8 (invert inner) **are above cracking strains** according to equation (3).

$$\frac{7.5\sqrt{f_c^{'}}}{E_c} \qquad \text{(Eq. 3)}$$

Where, f'c= 8,000 psi, Ec= 57,000(F'c)^(1/2)*

Cracking of concrete is desired and anticipated, as this is necessary for the reinforcement to be engaged. Thus, such initial cracking does not indicate any structural failure; it is simply showing that reinforced concrete is behaving as it is designed to behave. Yielding of steel, however, denotes failure of the specimen. Therefore, this specimen has structurally failed at 0.01inch crack load level, due to above-yield level strains at three locations.

While the laboratory (TEB) test results for the specific design proposed in this study is interesting on its own, the comparison of the TEB results to the installed conditions provides the most valuable insights for the goals of the project.

1. In the installed conditions, some cracking –although mostly thinner than 0.01in- is observed; however, ***none*** of the strains on the steel are equal to or greater than yield strain. Even the most stressed reinforcement, those on segment B2, only present values at 22.5% of the yield strains, presenting 77.5% more capacity until steel yields. Structural strength design of reinforced concrete is always provided such that the steel yields before concrete crushes, thus providing a ductile failure. Direct design method for reinforced concrete pipe obeys strength design theory and follows this rule. Therefore, beyond the 77.5% more capacity of steel, there is more capacity until a potential collapse of the pipe may occur. Furthermore, as a structural system, an arch is indeterminate to the third degree, i.e. has 3 levels of redundancy. It would only collapse after 4 hinges (i.e. cracks developed through the entire thickness and length of the pipe) are developed. It can be concluded then, that the design method utilized by the UNL Research Team is structurally safe with a 77.5% margin at service loads, while saving in average, in terms of overall reinforcement values, 26.21 % over the indirect design (Method 1),

11.10 % over DD -only (Method 2) and 90.63 % over DD+ASTM C76 method (Method 2). These percent differences can be found in Table 13.

2. TEB test specimen has steel yielding at 3 locations (i.e. 100+% of yield strain), therefore fails, at the 0.01 inch crack load level. The D-load recorded at this level is 1235 lb/ft/ft, which according to Indirect design, corresponds to Class II pipe that can carry 10 ft of fill in Type 3 bedding conditions. However, the experimental results of the full scale installation proves that this design performs safely (i.e. with only 11-19% of yield strain in the installed condition as opposed to 100+% of yield in TEB), under 20 ft of fill in the installed condition. This proves the authors' assertion that TEB is not an accurate measure of the pipe performance in the installed condition. TEB test **ignores** the drastic difference between point load vs. distributed loading on the structural behavior of a circular (arch) element **and** the beneficial effects of the lateral thrust in the installed conditions.
3. Discussion item 2 above becomes further valid when the design method is DD as opposed to ID. ID is a methodology that was developed concurrently with the TEB and the two methods complement each other relatively better. DD, on the other hand, adopts AASHTO LRFD load and resistance factors; therefore, further factors of safety do not need to be added by using TEB and then selecting one class higher pipe using ASTM standards. This would be analogous to using strength design designing a reinforced concrete beam using all of the load and resistance factors, and then checking the design against a test method that is developed for Allowable Stress Design (ASD) and using a second set of safety factors to satisfy the test results for ASD. Once DD is used, the results should be treated as ***the final structural design such that neither TEB nor ASTM C76 is further consulted***. Alternatively, the designer can choose to strictly use ID in conjunction with ASTM C76 standards and TEB for quality control testing.

4.6. Conclusions from the monitoring of the full scale installation design

Following conclusions are withdrawn from this study.

1. Design method. Engineering standpoint: Use direct design. Manufacturers' standpoint: Use indirect design until new ASTM standards are established. Method 4 (least conservative), or Method 3, or Method 1 can be used by designers, with care to the design conditions and assumptions with their use. Method 2 is not recommended.

2. TEB: should not be observed any longer, especially if the design is by DD. TEB results compared to installed condition: At 3 locations, steel yielded at 0.01 inch crack load level. Installed condition, at a load level close to 0.01 inch crack load level, however, it is observed that all steel is at less than 25% of yield strength.

3. Even when in TEB the steel yielded, i.e. structural failure; the deflection is only 7/32 of an inch, which would not be enough to dislocate a joint. A hinge is not formed, thus the structural collapse does not happen. A concrete arch is an inherently stable, indeterminate structure with 3 degrees of indeterminacy. For it to fail and collapse it needs to form 4 hinges. Even in the not-related load conditions of TEB, we only get one crack- not enough for a total collapse.

4. After intensive literature review, the authors still are not aware of the technical origins of the 0.01 inch crack as an indicator for allowance for water ingress to cause corrosion. Thus the authors maintain their position that this limit is arbitrary and should be eliminated both as acceptance criteria for TEB for Indirect design, and as a limit state in direct design. At the very least, it should be eliminated as a strength limit state if the pipe is **lined**, because when the pipe is lined, corrosion is no longer a concern.

5. Standard R4 joints presented no visible problems, thus, the authors do not see any problems with the continued use of these joints.

5. Survey of Practice Results

In response to a request from City of Lincoln, an additional task is added to the scope with no additional cost. The survey is prepared in 4 different formats to limit the questions asked to different parties involved in the pipe design-specification- manufacturing process. The four surveys posted online are as follows:

Group (A): Designers With installation involvement
http://www.zoomerang.com/Survey/survey-intro.zgi?p=WEB227M6W6567W

Group (B): Designers WithOUT installation involvement
http://www.zoomerang.com/Survey/survey-intro.zgi?p=WEB227M6WL56GG

Group (C): Owners, Manufacturers and Contractors With Design involvement
http://www.zoomerang.com/Survey/survey-intro.zgi?p=WEB227M6XJ572S

Group (D): Contractors WithOUT Design involvement
http://www.zoomerang.com/Survey/survey-intro.zgi?p=WEB227M6XM574M

The questionnaires for each survey can be retrieved by visiting the linked websites.

The low number of responses (5 for Group A, 5 for Group C, and none for Group B and D), unfortunately do not allow accurate statistical analysis nor let concrete conclusions to be drawn due to the small size of the pool. However, a few important observations can be made:

- *Indirect design method is preferred to the direct design method:* Authors think this is due to the convenience of using ASTM standards and ACPA fill height tables.
- *Historical bedding classes are still used instead of standard installations:* All designers should use Standard Installations as suggested by ACPA regardless of the design method. Historical bedding classes are difficult to communicate with the contractors and thus are difficult to keep standard. Furthermore, use of historical bedding classes result in more expensive pipe segments.
- *The reasons listed for the question "32.Please give reasons for not using RCP" are as follows:*
    1. *Hydrogen sulfide gas deteriorates concrete pipe reducing design life.*

2. *We used RCP for years. But, we will no longer use it in sanitary sewer applications. It cannot hold up to Microbial Induced Corrosion due to hydrogen sulfide.*
3. *Good for small diameters, but past experience with larger diameter has not been positive*
4. *Feel PVC pipe is better product and usually more cost effective*
5. *We sometimes spec with a tee loc liner competitively against PVC and/or Hobas (CCFGRP). Usually Hobas is cheaper. Prefer the quality and ease of installation of the HOBAS*
6. *[We] feel PVC products are better and usually more cost effective*

These comments show that the concerns about RCP do not really lie with the safety of the pipe. The concerns are either related to cost (3 out of 6 responses exclude RCP for not being cost effective), or deterioration. Cost effectiveness is not a surprising result given the several layers of conservatism, which frequently factor into the design of pipe. For instance, use of bedding classes, as shown in the design evaluation for the City (Section 4), causes the resulting design to be double the capacity than necessary. Another example is the use of DD along with ASTM standards and TEB, and again resulting in excessive capacity than needed. It is the authors' view, therefore, that if the designers follow well defined design procedures with carefully set design criteria; RCP need not be less cost effective. The issues regarding hydrogen sulfide deteriorating the pipe, however, are out of the scope of this study, where only structural considerations of pipe are considered.

6. Proposed NDOR RCP Design Procedures and Tables

Based on the extensive literature review, analyses, comparative designs and most importantly experimental work done in this project, the following conclusions are drawn:

For reinforced concrete pipe with double reinforcement cage, i.e. larger than 36 inch- diameter, a careful application of direct design procedures can produce both safe and economical solutions as demonstrated in this project.
Direct design method needs to be further studied to be applied effectively to pipe smaller than 36in in diameter, i.e. using single cage. The structural behavior of the single caged small diameter pipe is more complex than the larger diameter pipe, for which DD has been proven as an effective design method.

Therefore, the authors suggest that **direct design** is used for pipe larger than 36in (double cage) and indirect design is used for pipe that is smaller than 36 in and/or has single cage of reinforcement.

Using these procedures, tables for diameters 42 – 108 inch are prepared. These tables can be found in Appendix B. It should be noted that since approval on ignoring crack control limit state is not received from the NDOR or City of Lincoln, these tables consider crack control as a limit state. Whenever this limit state controls, however, it is stated on the table.

7. Conclusions

Currently, RCP can be designed according to two methods: Direct Design Method and Indirect Design method. These two methods generally give different answers for design of pipe that is carrying the same load. Furthermore, while the design methods and the resulting designs for the same loads are completely different, there is only one commonly used standard available for specification of pipe (ASTM C76) and only one commonly used test for the quality control and acceptance of manufactured pipe (three edge bearing test, *i.e.* TEB). These manufacturing standards and quality control measures align better with the indirect design method; however, they limit the effective use of the more modern direct design method to less than its full potential. As a result, some of the reinforced concrete pipe constructed, especially according to the newer direct design method – yet subjected to the limits of ASTM C76 and TEB which are better suited with indirect design- is overly conservative, which in turn causes reinforced concrete pipe to lose its competitiveness against flexible pipe. This situation causes confusion and frustration among related parties, such as owners, designers, manufacturers, and contractors.

To address and resolve these problems, Nebraska Department of Roads and City of Lincoln administration hired the University of Nebraska researchers, the authors, to perform experimental and analytical research.

Authors designed a full scale reinforced concrete pipe (RCP) installation, according to the direct design method (DD) with specific criteria explained in this paper, which is installed at the City of Lincoln Landfill in order to monitor the behavior of pipe in installed conditions and over time. Applied soil pressures are measured to make sure they are within Heger pressure distribution limits. Strains in the outer and inner reinforcement are monitored to study the behavior of the pipe over time. Crack development and joint displacement, if applicable, are also monitored.

Results show that the measured soil pressures are generally lower than the predicted values according to Heger distribution. Strains in the reinforcement are in the elastic range, *i.e.* the steel has not yielded. The highest steel strain measured is only 22.5% of the yield strain. Concrete has cracked at several locations, as expected for any reinforced concrete structural element that engages steel in tension; however, cracks are smaller than 0.01 in wide. The authors' extensive literature review revealed that the 0.01 in crack limitation is arbitrary and the omission of crack control criteria does not affect the safety of the pipe, yet it is important to note that the pipe in installed condition still has cracks smaller than 0.01 in. TEB testing was employed on an identical specimen to one of the installation pipe segments. Results of this test showed that despite the identical design, the steel of the pipe experiences strains higher than the yield strain (0.002) at loads as

low as the 0.01 in crack load. Yielding of steel in reinforced concrete denote overstress, while the full scale pipe monitored in the landfill proves that this level of structural distress is not easily reached in installed conditions.

Conclusions drawn from the study are as follows:

1. The pipe in the test installation, designed according to DD with unique and daring criteria has reserve steel capacity of 77.5% in installed conditions. This is due to a combination of factors: a) There is indeed room in DD method for improvement such that the material behaviors are better represented, limit state criteria is re-visited, and as a result the designs are closer to those from ID. b) The actual bedding in the field is stronger than that of the specified, thus he pipe is stronger than expected against the loads. c) Installed conditions are more favorable for the pipe than the TEB conditions, and even some of the field handling conditions. Thus some additional capacity is necessary -and available from the nature of the method- if the quality assurance and handling procedures are not changed.
2. Based on our discussions with our sponsors (and typically the owners of the pipe installation projects in the State of Nebraska), our experience with the contractors does not reflect the general situation. The actual conditions were superior to those requested by the designers, yet, the owners worry that the opposite may be true more often. Therefore, they (especially City of Lincoln), in an attempt to err on the conservative side, tend to specify pipe for a poor bedding (ex: Type 3 or 4) but request that the bedding is superior (ex: Type 1). The authors suggest this may be an inefficient way of design and construction. If NDOR or City come up with one standard bedding (we suggest Standard Installation Type 3, relatively poorer) and communicate to the contractors that this is the minimum requirement and will be monitored; the contractors –without too much trouble- would achieve Type 3 bedding, because compaction requirements are not very stringent. If the design is also carried out for Type 3 then, it would be an efficient system. The owners should rest assured that there are enough safety factors to account for the potential minor deviations in design criteria in both design methods, and this process would not cause failure, especially because they require a relatively easy-to-achieve installation type.
3. In installed conditions, both the inner and outer reinforcement of most segments are in tension; however, the DD method does not account for this. Even in TEB, where the loading condition is more critical causing higher bending stresses in the pipe wall, in most locations that were monitored, the strain distribution is such that both reinforcements are in tension. This is one of the reasons why, *sometimes*, the DD method results are more conservative

than the ID[6]. The differences between ID and DD become further pronounced for pipe with diameters smaller than 36inch (i.e. single cage pipe); because the behavior is more complex. Thus, if the "true" material behavior of steel is incorporated into the DD results, the results gathered for small diameter pipe would more accurately represent the true capacity of these structures, and the results would be closer to those gathered from ID[7].

4. TEB is not a good representation of the pipe's behavior in installed conditions and may cause unnecessary conservatism, especially if the pipe is designed according to DD.
5. Crack control criteria in DD can be eliminated, especially if the pipe is lined: Crack control criteria is one of the limit states in the strength design based DD method along with flexure, shear, diagonal, and radial tension. While all of the other limit states follow, in general, the criteria used for the design of other structural concrete elements, the stringent 0.01 in criteria seems arbitrary (no evidence in literature for why it is set at this limit), especially when checked through an experiment (TEB) that does not reflect the pipe's actual behavior in installed conditions
6. Designers should either use DD with ASTM C1417, or ID with ASTM C76 and TEB to specify safe, economical, and practical reinforced concrete pipe. Using DD along with ASTM C76 and TEB is not an appropriate design procedure.
7. A new ASTM standard (as user friendly as ASTM C76), and a new acceptance test (as practical as TEB) may facilitate the adoption of DD by more practitioners and owners; as well as eliminate misunderstandings or misuse of methods. It is recommended by the authors of this report that NDOR and City of Lincoln team up with ACPA and DOTs in order to lead the nation, approach ASTM/ NCHRP for a national project, and perform work towards resolving these issues.
8. An online survey on pipe design practice is prepared and pipe designers, manufacturers, and contractors were invited to participate. The small pool of responses to the RCP survey of practice does not allow detailed statistical analysis; however, some insights are gathered and summarized in the report.

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[6] It must be noted that the conservatism in DD and ID switches depending on the loads, i.e. fill height. DD presents a continuous function where there is an answer for every set of selected design parameters, while the ID results form a discrete function defined by classes and ASTM standards.

[7] A case study is carried out to show-case this point and added to the appendices of the report.

One important finding is a confirmation that there is mix-and-match approach in using DD, ID, TEB, and ASTM C76.

9. Direct design method is the rational method to choose for the design of the pipe, thus should be continued to be used by NDOR and should be adopted by COL designers for all pipe – except small diameter (smaller than 36inch diameter), single cage pipe. The behavior of small diameter pipe needs to be further studied and DD should be updated to reflect the results of such research. The structural behavior of the single caged small diameter pipe is more complex than the larger diameter pipe, for which DD has been proven as an effective design method. Therefore, at this time, the authors propose that NDOR and COL design and specify reinforced concrete pipe as follows: *Direct design* is used for all pipe larger than 36 in (double cage); and *indirect design* is used for pipe that is smaller than 36 in and/or has single cage of reinforcement.

10. Based on the experimental and analytical research, and extensive study of the relevant literature, the authors have developed expanded tables for reinforced concrete pipe larger than 36 inch (42- 108 inch) for NDOR to adopt in their specifications as they see fit. These tables are prepared using direct design method, obeying all limit states – including the 0.01inch crack control criterion. Concrete strengths of 4, 5, 6, 7, and 8 ksi; standard installation types 1,2,3; and fill heights of 5-20 ft with 2.5 ft increments are included in the tables.

8. Implementation Plan

The Nebraska Department of Roads would like to thank the efforts of Dr Tadros and Dr Erdogmus regarding their pipe research submitted for our review. To give a historical perspective, back in the year 1997, NDOR established a pipe policy that included updated design procedures for reinforced concrete pipe. Following the recommendations of industry experts to use Direct Design methods for pipe design, NDOR developed new standards for reinforced concrete pipe. During the 1990's, this was considered a radical shift from the status quo with respect to pipe design and installation requirements. Since this time, other agencies such as AASHTO and ASTM have also incorporated these design standards (and the much improved Standard Installations for Direct Design). We are pleased that the UNL research team has recommended that NDOR continue to use the Direct Design approach and has validated the methodology through their research and experimentation.

UNL has made the recommendation that NDOR use Direct Design to design pipe larger than 36 inch diameter and Indirect Design for pipe 36 inch and smaller. It has also been suggested that since the Indirect Design method is more closely aligned with loads established and confirmed through 3-edge bearing testing, that NDOR discontinue the use of this TEB test if pipe are designed using Direct Design. We concur with this rationale, and as a result, next year we will be modifying our specifications to no longer require manufacturers to qualify their product using the TEB test (unless a special design is submitted to NDOR for approval that has been designed using Indirect Design methodology). To be consistent, we believe it is counter productive to mix and match two design methods (Indirect for smaller pipe, Direct Design for larger pipe), since NDOR will no longer require the TEB test to be conducted. We also believe it is somewhat arbitrary to select smaller pipe to employ the Indirect design approach, especially since the Indirect Design method does not adequately deal with certain failure mechanisms (as resulting from diagonal shear and radial tension forces within the pipe wall section), which are addressed by the fundamentally superior Direct Design method. Since Standard Installations are required by NDOR for pipe installation, it is also logical to use the Direct Design approach since it was specifically developed for use with these Standard Installations (contrary to the modified Indirect Design method which results in questionable safety factors resulting from assumed bedding factors).

NDOR will continue to study and review the much-appreciated UNL research findings and will look forward to working with manufacturers to establish new guidelines for testing and approval of reinforced concrete pipe in Nebraska. In addition to our thanking the UNL research team, we also appreciate the City of Lincoln for their efforts, as well as the generous contributions of Concrete Industries and the expertise of the Concrete Pipe Association in this research endeavor.

9. References

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10. Appendices

APPENDIX A

NDOR TABLES [diameters 42 in – 108 in]

NDOR Tables

Pipe diameters: 42in- 108 inch. Pipe smaller than 42inch and/or with single reinforcement cage should be designed using indirect design method.

Direct Design Method Variables:

- Tool/software: ACPA's PipeCAR
- Concrete Strength: Variable between 4,000- 8,000 psi with 1,000psi increments
- Steel Strength: 65,000 psi
- AASHTO LRFD Load and resistance factors
- Fill heights 5- 20 ft with 2.5 ft increments
- Wall thickness: Depends on the pipe diameter, manufacturing standards, for the relationship of pipe diameter and pipe wall thickness, are followed.
- D-load equivalents are calculated and presented only for comparison.

Summary of tables

Pipe Diameter (in)	Wall thickness (in)		
42	3.5	4.5	5.25
48	4	5	5.75
54	4.5	5.5	6.25
60	5	6	6.75
66	5.5	6.5	7.25
72	6	7	7.75
78	6.5	7.5	8.25
102	8.5	9.5	10.25
108	9	10	10.75

42 inch Tables

42" Pipe Diameter

			Fill Height (feet)																	
			5			**7.5**			**10**			**12.5**			**15**			**20**		
		fc' (kips)	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**
3.5" Wall Thickness	4	**Ai** (sq. in/ft)	0.096	0.127	0.153	0.124	0.170	0.207	0.154	0.215	0.303	0.184	0.293	0.413	0.216	0.381	0.523	0.320	0.566*	-
	4	**Ao** (sq. in/ft)	0.070	0.070	0.075	0.070	0.087	0.103	0.087	0.111	0.133	0.106	0.137	0.164	0.126	0.163	0.196	0.169	0.221	-
	4	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack	flexure	0.01" crack	0.01" crack	flexure	0.01" crack	0.01" crack	0.01" crack	rad. Ten. & 0.01	-
	4	**D-Load** (lb/ft/ft)	759.77	1004.1	1195.2	981.25	1313.3	1551.9	1202.3	1600.1	2052.4	1406.6	2008.2	2444.9	1606.1	2333.0	-	2123.2	-	-
	5	**Ai** (sq. in/ft)	0.095	0.126	0.151	0.123	0.167	0.204	0.152	0.211	0.273	0.181	0.262	0.383	0.211	0.350	0.493	0.290	0.526	0.713*
	5	**Ao** (sq. in/ft)	0.070	0.070	0.074	0.070	0.086	0.102	0.086	0.109	0.130	0.104	0.134	0.159	0.123	0.159	0.190	0.163	0.212	0.255
	5	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack	flexure	0.01" crack	0.01" crack	flexure	0.01" crack	0.01" crack	0.01" crack	0.01" crack	. Ten. & 0.01" cr
	5	**D-Load** (lb/ft/ft)	767.26	1024.1	1220.6	999.91	1341.5	1606.2	1228.3	1654.0	2044.9	1444.1	1979.8	2596.8	1654.0	2450.3	2967.3	2142.1	3104.9	-
	6	**Ai** (sq. in/ft)	0.094	0.125	0.150	0.122	0.166	0.201	0.150	0.208	0.255	0.179	0.251	0.356	0.208	0.232	0.466	0.269	0.499	0.686*
	6	**Ao** (sq. in/ft)	0.070	0.070	0.074	0.070	0.085	0.101	0.085	0.108	0.128	0.103	0.131	0.157	0.121	0.156	0.186	0.159	0.206	0.247
	6	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack	flexure	0.01" crack	0.01" crack	flexure	0.01" crack	rad. Ten. & 0.01
	6	**D-Load** (lb/ft/ft)	768.97	1034.2	1239.1	1009.0	1366.1	1632.6	1239.1	1684.0	2013.3	1466.9	1986.3	2626.7	1684.0	2440.4	3148.6	2106.0	3275.5	-
	7	**Ai** (sq. in/ft)	0.094	0.124	0.149	0.122	0.165	0.200	0.149	0.206	0.252	0.178	0.248	0.331	0.206	0.298	0.441	0.265	0.474	0.661
	7	**Ao** (sq. in/ft)	0.070	0.070	0.074	0.070	0.085	0.100	0.084	0.107	0.127	0.102	0.130	0.155	0.119	0.154	0.183	0.157	0.203	0.243
	7	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack	flexure	0.01" crack	0.01" crack	flexure	0.01" crack	0.01" crack
	7	**D-Load** (lb/ft/ft)	776.28	1038.5	1249.5	1021.4	1380.9	1658.4	1249.5	1704.7	2046.0	1485.5	2017.3	2578.4	1704.7	2364.3	3206.6	2138.3	3369.5	4068.2
	8	**Ai** (sq. in/ft)	0.094	0.124	0.148	0.121	0.164	0.199	0.149	0.205	0.250	0.176	0.246	0.307	0.205	0.289	0.417	0.263	0.451	0.638
	8	**Ao** (sq. in/ft)	0.070	0.070	0.073	0.070	0.084	0.099	0.084	0.106	0.126	0.101	0.129	0.153	0.118	0.152	0.181	0.155	0.200	0.239
	8	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack	flexure	flexure	0.01" crack	flexure	0.01" crack	0.01" crack
	8	**D-Load** (lb/ft/ft)	781.76	1048.1	1254.8	1021.9	1389.5	1675.4	1263.3	1723.2	2070.8	1488.9	2040.7	2483.0	1723.2	2356.2	3190.2	2167.5	3385.3	4260.6

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 3" maximum spacing and 36" reinforcing diameter

42" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
		fc' (kips)	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**
4.5" Wall Thickness		**Ai** (sq. in/ft)	0.074	0.097	0.115	0.094	0.127	0.153	0.114	0.157	0.192	0.156	0.220	0.289	0.177	0.253	0.370	0.199	0.310	0.488
		Ao (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.074	0.089	0.080	0.105	0.128	0.092	0.122	0.148	0.105	0.139	0.169
		Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack	flexure	flexure	0.01" crack	flexure	0.01" crack	shear
	4	**D-Load** (lb/ft/ft)	771.54	1035.9	1235.9	1002.0	1365.9	1638.3	1224.9	1679.1	2023.4	1668.9	2282.6	2895.5	1878.6	2569.5	3425.0	2089.6	3017.7	4281.2
		Ai (sq. in/ft)	0.074	0.096	0.115	0.093	0.126	0.152	0.113	0.156	0.190	0.154	0.217	0.268	0.175	0.248	0.335	0.196	0.280	0.416
		Ao (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.073	0.088	0.079	0.104	0.125	0.090	0.119	0.145	0.102	0.135	0.165
		Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack	flexure	flexure	0.01" crack
	5	**D-Load** (lb/ft/ft)	781.02	1040.6	1258.8	1005.6	1382.7	1668.2	1236.1	1711.2	2067.2	1689.7	2337.5	2818.5	1912.3	2634.5	3391.6	2128.2	2926.1	3995.3
		Ai (sq. in/ft)	0.074	0.096	0.114	0.093	0.125	0.151	0.113	0.155	0.188	0.153	0.215	0.265	0.173	0.245	0.304	0.194	0.277	0.385
		Ao (sq. in/ft)	0.070	0.070	0.07	0.070	0.070	0.070	0.070	0.072	0.087	0.078	0.105	0.124	0.089	0.118	0.143	0.101	0.133	0.162
		Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
	6	**D-Load** (lb/ft/ft)	787.35	1051.2	1262.5	1015.6	1389.6	1683.8	1250.9	1728.3	2087.7	1706.1	2371.6	2873.0	1926.1	2676.2	3242.3	2151.6	2988.6	3948.6
		Ai (sq. in/ft)	0.073	0.096	0.114	0.093	0.125	0.150	0.112	0.154	0.187	0.152	0.213	0.263	0.172	0.244	0.301	0.192	0.274	0.355
		Ao (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.072	0.087	0.077	0.101	0.123	0.088	0.116	0.141	0.100	0.132	0.160
		Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
	7	**D-Load** (lb/ft/ft)	779.60	1058.8	1273.3	1022.8	1402.5	1691.3	1249.6	1736.8	2106.0	1741.1	2388.5	2911.0	1939.7	2715.6	3289.9	2160.9	3022.3	3801.5
		Ai (sq. in/ft)	0.073	0.096	0.113	0.093	0.124	0.150	0.112	0.153	0.186	0.151	0.212	0.261	0.171	0.242	0.299	0.191	0.272	0.337
		Ao (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.072	0.086	0.077	0.101	0.122	0.088	0.116	0.140	0.099	0.131	0.159
		Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
	8	**D-Load** (lb/ft/ft)	782.89	1064.5	1269.4	1028.1	1400.4	1705.2	1257.4	1740.0	2116.5	1716.8	2405.7	2933.0	1946.7	2731.3	3326.1	2172.6	3048.2	3705.3

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 3" maximum spacing and 44" reinforcing diameter

42" Pipe Diameter

Fill Height (feet)

			5			7.5			10			15			17.5			20		
		fc' (kips)	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**
5.25" Wall Thickness		**Ai** (sq. in/ft)	0.070	0.084	0.099	0.081	0.108	0.130	0.097	0.133	0.162	0.131	0.184	0.227	0.148	0.210	0.260	0.165	0.237	0.357
		Ao (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.081	0.100	0.070	0.093	0.115	0.078	0.106	0.130
		Governing	minimum rei	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	shear
	4	**D-Load** (lb/ft/ft)	727.75	903.74	1090.7	866.15	1202.1	1471.9	1065.8	1508.5	1471.9	1484.1	2120.0	2621.7	1690.2	2424.8	2621.7	1894.3	2736.5	4062.7
		Ai (sq. in/ft)	0.070	0.084	0.099	0.081	0.108	0.130	0.097	0.132	0.161	0.130	0.182	0.224	0.147	0.208	0.224	0.163	0.233	0.290
		Ao (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.080	0.098	0.070	0.092	0.098	0.076	0.104	0.128
		Governing	minimum rei	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
	5	**D-Load** (lb/ft/ft)	730.58	907.81	1096.3	869.93	1208.8	1481.7	1071.3	1506.4	1861.4	1481.7	2115.5	2616.2	1690.6	2426.6	3002.6	1885.7	2722.2	3382.9
		Ai (sq. in/ft)	0.070	0.083	0.099	0.080	0.107	0.129	0.096	0.132	0.160	0.129	0.181	0.222	0.146	0.206	0.254	0.162	0.231	0.286
		Ao (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.079	0.097	0.070	0.091	0.112	0.075	0.102	0.126
		Governing	minimum rei	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
	6	**D-Load** (lb/ft/ft)	732.46	897.84	1100.1	859.8	1200.7	1475.8	1062.3	1513.1	1859.2	1475.8	2116.1	2611.6	1686.6	2419.2	2992.7	1883.7	2719.3	3368.8
		Ai (sq. in/ft)	0.070	0.083	0.098	0.080	0.107	0.129	0.096	0.131	0.159	0.129	0.180	0.221	0.145	0.205	0.253	0.161	0.230	0.284
		Ao (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.079	0.096	0.070	0.090	0.111	0.075	0.101	0.125
		Governing	minimum rei	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
	7	**D-Load** (lb/ft/ft)	733.81	899.73	1090.1	861.52	1203.9	1480.4	1064.8	1505.4	1853.8	1480.4	2112.9	2613.1	1680.0	2418.8	2998.5	1878.6	2721.9	3367.7
		Ai (sq. in/ft)	0.070	0.083	0.098	0.080	0.107	0.128	0.096	0.131	0.159	0.128	0.180	0.220	0.145	0.204	0.251	0.161	0.229	0.283
		Ao (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.078	0.096	0.070	0.089	0.110	0.074	0.101	0.124
		Governing	minimum rei	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
	8	**D-Load** (lb/ft/ft)	734.82	901.15	1092.1	862.84	1206.2	1471.2	1066.7	1508.9	1859.1	1471.2	2119.6	2611.0	1684.4	2415.2	2987.6	1883.9	2720.7	3372.5

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 3" maximum spacing and 44" reinforcing diameter

48 inch Tables

48" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			12.5			15			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
4" Wall Thickness	4	**Ai** (sq. in/	0.108	0.142	0.170	0.139	0.187	0.247	0.170	0.259	0.376	0.202	0.362	0.505	0.252	0.466	0.635	0.392	0.672*	0.893*
	4	**Ao** (sq. in/	0.070	0.071	0.094	0.076	0.096	0.113	0.096	0.121	0.144	0.115	0.148	0.176	0.136	0.176	0.210	0.181	0.235	0.287
	4	**Governin**	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens. & c	ns. & 0.01'
	4	**D-Load** (lb	740.27	978.36	1161.9	958.03	1267.8	1608.7	1161.9	1670.7	2167.1	1357.9	2118.0	2724.5	1634.8	2552.4	-	2219.8	-	-
	5	**Ai** (sq. in/	0.107	0.141	0.168	0.137	0.185	0.224	0.167	0.230	0.341	0.198	0.327	0.470	0.230	0.430	0.599	0.357	0.637	0.858*
	5	**Ao** (sq. in/	0.070	0.071	0.083	0.075	0.095	0.112	0.094	0.119	0.141	0.113	0.145	0.172	0.133	0.171	0.204	0.175	0.227	0.272
	5	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	ens. & 0.01" c
	5	**D-Load** (lb	748.26	998.12	1186.9	969.43	1301.4	1551.3	1180.0	1588.2	2195.6	1386.6	2126.8	2722.4	1588.2	2579.6	3269.0	2271.3	3432.1	-
	6	**Ai** (sq. in/	0.107	0.140	0.167	0.136	0.183	0.222	0.166	0.228	0.309	0.196	0.295	0.438	0.227	0.398	0.567	0.325	0.605	0.826*
	6	**Ao** (sq. in/	0.070	0.070	0.082	0.075	0.094	0.111	0.093	0.118	0.140	0.112	0.143	0.170	0.131	0.168	0.200	0.171	0.221	0.265
	6	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens. & 0
	6	**D-Load** (lb	758.42	1008.4	1204.9	978.67	1317.9	1582.9	1197.7	1622.4	2120.6	1407.9	2039.1	2782.3	1615.8	2594.4	3282.2	2211.5	3405.5	-
	7	**Ai** (sq. in/	0.107	0.139	0.166	0.136	0.182	0.220	0.165	0.226	0.279	0.195	0.271	0.409	0.225	0.369	0.538	0.296	0.576	0.797
	7	**Ao** (sq. in/	0.070	0.070	0.082	0.074	0.093	0.110	0.092	0.117	0.139	0.111	0.141	0.168	0.130	0.166	0.198	0.169	0.218	0.260
	7	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crack
	7	**D-Load** (lb	765.68	1013.2	1215.2	990.42	1332.0	1600.6	1207.9	1641.9	1993.3	1425.3	1941.8	1635.0	2535.8	2535.8	3370.5	2101.0	3525.1	4381.8
	8	**Ai** (sq. in/	0.106	0.139	0.165	0.135	0.182	0.219	0.164	0.225	0.274	0.194	0.269	0.381	0.224	0.342	0.511	0.285	0.548	0.769
	8	**Ao** (sq. in/	0.070	0.070	0.082	0.074	0.093	0.109	0.092	0.116	0.138	0.110	0.140	0.167	0.129	0.165	0.196	0.167	0.215	0.257
	8	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
	8	**D-Load** (lb	763.14	1022.4	1220.8	991.47	1347.8	1616.6	1213.3	1659.2	1997.1	1436.1	1963.5	2672.8	1652.1	2436.4	3379.3	2070.5	3557.6	4411.0

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.32" reinforcing diameter

48" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
5" Wall Thickness	4	Ai (sq. in/	0.088	0.114	0.135	0.110	0.148	0.178	0.133	0.182	0.221	0.180	0.257	0.391	0.204	0.337	0.491	0.228	0.417	0.638
	4	Ao (sq. in/	0.070	0.070	0.070	0.070	0.070	0.082	0.070	0.086	0.104	0.093	0.122	0.148	0.107	0.141	0.171	0.122	0.160	0.194
	4	Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crack	diag. tens.
	4	D-Load (lb	767.85	1021.2	1218.6	982.86	1337.7	1603.3	1200.1	1637.7	1961.5	1620.5	2241.1	3120.0	1823.0	2796.5	3808.2	2017.3	3291.2	4752.3
	5	Ai (sq. in/	0.088	0.114	0.135	0.110	0.147	0.176	0.132	0.180	0.219	0.178	0.249	0.350	0.201	0.296	0.450	0.225	0.375	0.550
	5	Ao (sq. in/	0.070	0.070	0.070	0.070	0.070	0.082	0.070	0.085	0.102	0.092	0.120	0.145	0.105	0.138	0.167	0.119	0.156	0.189
	5	Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crack	0.01" crack
	5	D-Load (lb	778.13	1038.4	1242.9	998.94	1357.4	1627.3	1214.0	1663.7	2009.4	1645.5	2263.3	3042.2	1852.0	2640.4	3698.1	2061.0	3216.9	4336.0
	6	Ai (sq. in/	0.087	0.113	0.134	0.109	0.146	0.175	0.132	0.179	0.217	0.177	0.246	0.312	0.199	0.281	0.413	0.222	0.338	0.513
	6	Ao (sq. in/	0.070	0.070	0.070	0.070	0.070	0.081	0.070	0.085	0.101	0.091	0.119	0.143	0.104	0.136	0.164	0.117	0.154	0.186
	6	Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crack
	6	D-Load (lb	774.66	1039.9	1249.2	999.56	1366.9	1645.3	1229.5	1683.1	2034.0	1664.2	2292.3	2849.8	1869.5	2593.2	3621.3	2079.1	3057.8	4288.3
	7	Ai (sq. in/	0.087	0.113	0.134	0.109	0.145	0.174	0.131	0.178	0.216	0.176	0.245	0.300	0.198	0.279	0.378	0.221	0.313	0.479
	7	Ao (sq. in/	0.070	0.070	0.070	0.070	0.070	0.081	0.070	0.084	0.101	0.090	0.118	0.142	0.103	0.135	0.163	0.116	0.152	0.184
	7	Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crack
	7	D-Load (lb	779.45	1048.0	1260.6	1007.0	1370.4	1655.1	1230.4	1693.8	2054.6	1674.4	2321.7	2808.9	1885.2	2625.9	3456.3	2101.1	2920.3	4219.1
	8	Ai (sq. in/	0.087	0.113	0.133	0.109	0.145	0.174	0.131	0.178	0.215	0.175	0.244	0.299	0.197	0.277	0.346	0.220	0.311	0.447
	8	Ao (sq. in/	0.070	0.070	0.070	0.070	0.070	0.081	0.070	0.084	0.100	0.089	0.117	0.141	0.102	0.134	0.161	0.115	0.151	0.182
	8	Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crack
	8	D-Load (lb	783.04	1054.0	1259.0	1012.7	1380.4	1669.5	1238.6	1708.8	2067.3	1679.3	2341.0	2842.9	1894.2	2644.9	3254.1	2114.9	2949.5	4082.4

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.40" reinforcing diameter

48" Pipe Diameter

	fc' (kips)		Fill Height (feet): 5			7.5			10			15			17.5			20		
			type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
5.75" Wall Thickness	4	**Ai** (sq. in/	0.079	0.102	0.120	0.098	0.130	0.156	0.117	0.159	0.192	0.156	0.218	0.268	0.176	0.248	0.357	0.196	0.281	0.505
		Ao (sq. in/	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.085	0.074	0.098	0.120	0.084	0.113	0.138	0.095	0.128	0.156
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	diag. tens	flexure	0.01" crack	diag. tens.
		D-Load (lb	680.11	926.57	1117.3	883.92	1222.5	1493.5	1085.6	1524.5	1862.5	1493.5	2124.8	2619.0	1699.4	2422.9	3466.3	1903.1	2745.3	4784.9
	5	**Ai** (sq. in/	0.079	0.101	0.119	0.098	0.129	0.155	0.116	0.158	0.191	0.155	0.216	0.264	0.174	0.245	0.302	0.194	0.275	0.389
		Ao (sq. in/	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.084	0.073	0.097	0.118	0.083	0.111	0.135	0.093	0.125	0.153
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
		D-Load (lb	682.87	920.43	1113.0	888.17	1219.4	1493.8	1081.0	1525.2	1868.6	1493.8	2125.4	2610.9	1692.3	2420.0	2988.1	1899.5	2720.7	3828.4
	6	**Ai** (sq. in/	0.079	0.101	0.119	0.097	0.129	0.154	0.116	0.157	0.190	0.154	0.214	0.262	0.173	0.243	0.299	0.192	0.272	0.347
		Ao (sq. in/	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.084	0.072	0.096	0.117	0.082	0.109	0.134	0.092	0.123	0.151
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
		D-Load (lb	684.71	923.44	1117.2	880.19	1224.3	1490.3	1085.0	1522.0	1868.9	1490.3	2118.6	2611.2	1690.7	2417.3	2985.1	1889.8	2712.8	3462.5
	7	**Ai** (sq. in/	0.078	0.101	0.119	0.097	0.129	0.154	0.116	0.156	0.189	0.153	0.213	0.261	0.172	0.242	0.297	0.191	0.271	0.334
		Ao (sq. in/	0.079	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.083	0.071	0.095	0.116	0.081	0.109	0.133	0.091	0.122	0.150
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
		D-Load (lb	675.09	925.59	1120.2	882.17	1227.8	1495.3	1087.8	1516.6	1866.0	1484.6	2117.8	2615.5	1686.5	2419.4	2983.7	1887.1	2718.2	3357.7
	8	**Ai** (sq. in/	0.078	0.101	0.119	0.097	0.128	0.153	0.115	0.156	0.189	0.153	0.212	0.260	0.172	0.241	0.296	0.191	0.269	0.332
		Ao (sq. in/	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.083	0.071	0.095	0.115	0.081	0.108	0.132	0.090	0.121	0.149
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
		D-Load (lb	676.05	927.20	1122.4	883.66	1219.7	1488.3	1079.1	1520.4	1871.7	1488.3	2177.5	2615.9	1691.2	2418.3	2987.5	1892.9	2709.2	3355.1

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.46" reinforcing diameter

54 inch Tables

54" Pipe Diameter

Wall Thickness	fc' (kips)		5 type 1	5 type 2	5 type 3	7.5 type 1	7.5 type 2	7.5 type 3	10 type 1	10 type 2	10 type 3	12.5 type 1	12.5 type 2	12.5 type 3	15 type 1	15 type 2	15 type 3	20 type 1	20 type 2	20 type 3
			Fill Height (feet)																	
4.5" Wall Thickness	4	**Ai** (sq. in/ft)	0.124	0.162	0.192	0.157	0.210	0.262	0.19	0.272	0.389	0.225	0.374	0.517	0.264	0.476	0.644	0.402	0.680*	0.899*
	4	**Ao** (sq. in/ft)	0.070	0.080	0.094	0.086	0.107	0.126	0.106	0.135	0.160	0.128	0.163	0.194	0.150	0.193	0.230	0.198	0.257	0.308
	4	**Governing**	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	Rad. Tens	0.01" crac	rad. Tens. & (	ens & 0.01'
	4	**D-Load** (lb/ft/ft)	751.51	991.09	1168.8	960.49	1270.6	1544.3	1157.2	1593.5	2086.2	1352.6	2031.6	2663.2	1554.2	2480.3	3187.5	2133.2	3324.5	-
	5	**Ai** (sq. in/ft)	0.123	0.160	0.190	0.155	0.208	0.251	0.188	0.256	0.355	0.221	0.339	0.482	0.255	0.441	0.609	0.368	0.645	0.864*
	5	**Ao** (sq. in/ft)	0.070	0.080	0.093	0.085	0.106	0.125	0.105	0.132	0.157	0.125	0.160	0.190	0.147	0.188	0.224	0.192	0.248	0.296
	5	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	Tens & 0.01" c
	5	**D-Load** (lb/ft/ft)	760.87	1005.8	1195.2	973.44	1305	1555.4	1182.9	1583.4	2092.1	1382.4	2015.8	2615.6	1577.8	2462.4	3180.8	2152.3	3338.9	-
	6	**Ai** (sq. in/ft)	0.123	0.159	0.189	0.154	0.206	0.248	0.186	0.254	0.323	0.219	0.308	0.451	0.252	0.41	0.578	0.336	0.613	0.832*
	6	**Ao** (sq. in/ft)	0.070	0.079	0.093	0.084	0.105	0.123	0.104	0.131	0.155	0.124	0.158	0.187	0.144	0.185	0.220	0.188	0.242	0.296
	6	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	Rad. Tens & 0
	6	**D-Load** (lb/ft/ft)	771.46	1017	1214.1	983.6	1322.7	1581.7	1194.7	1617.6	2010.8	1404.3	1928.4	2644.9	1605.6	2455.3	3152	2080.8	3287.4	4257.0
	7	**Ai** (sq. in/ft)	0.122	0.159	0.188	0.154	0.205	0.246	0.185	0.252	0.306	0.218	0.300	0.422	0.250	0.381	0.549	0.317	0.585	0.803
	7	**Ao** (sq. in/ft)	0.070	0.079	0.092	0.084	0.104	0.123	0.103	0.130	0.154	0.123	0.156	0.185	0.143	0.183	0.218	0.185	0.238	0.285
	7	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
	7	**D-Load** (lb/ft/ft)	771.94	1029.7	1225.4	995.43	1337.5	1600.0	1205.4	1637.5	1964.3	1421.9	1929.0	2601.9	1625.1	2386.6	3199.4	2028.6	3349.7	4245.4
	8	**Ai** (sq. in/ft)	0.122	0.158	0.187	0.153	0.204	0.245	0.185	0.251	0.304	0.217	0.298	0.395	0.249	0.354	0.522	0.315	0.558	0.777
	8	**Ao** (sq. in/ft)	0.070	0.079	0.092	0.083	0.104	0.122	0.102	0.129	0.153	0.122	0.155	0.184	0.142	0.181	0.216	0.183	0.236	0.281
	8	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
	8	**D-Load** (lb/ft/ft)	777.52	1032.2	1231.9	997.34	1346.6	1616.4	1218.3	1655.0	1987.4	1433.2	1950.6	2520.3	1642.2	2286.2	3184.5	2054.4	3355.9	4238.8

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 3" maximum spacing and 0.36" reinforcing diameter

54" Pipe Diameter

Fill Height (feet) — 5.5" Wall Thickness

fc' (kips)		5			7.5			10			15			17.5			20		
		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
4	**Ai** (sq. in/ft)	0.104	0.134	0.158	0.129	0.172	0.206	0.155	0.210	0.255	0.207	0.290	0.439	0.234	0.371	0.628	0.261	0.495	0.632*
	Ao (sq. in/ft)	0.070	0.070	0.073	0.070	0.081	0.096	0.079	0.100	0.120	0.108	0.141	0.170	0.124	0.162	0.196	0.14	0.184	0.223
	Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	shear	flexure	0.01" crac	shear	flexure	0.01" crack	ns. & 0.01'
	D-Load (lb/ft/ft)	672.65	909.49	1096.2	870.28	1203.9	1462.3	1072.9	1492.4	1826.4	1469.9	2080.4	3106.7	1671.6	2649.4	4281.9	1870.3	3469.6	4305.3
5	**Ai** (sq. in/ft)	0.104	0.133	0.157	0.129	0.170	0.204	0.154	0.208	0.252	0.205	0.285	0.387	0.231	0.331	0.489	0.257	0.413	0.622
	Ao (sq. in/ft)	0.070	0.070	0.072	0.070	0.080	0.095	0.078	0.099	0.118	0.078	0.139	0.167	0.121	0.159	0.191	0.137	0.18	0.217
	Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crack	shear
	D-Load (lb/ft/ft)	676.43	907.84	1097.0	876.10	1198.7	1461.9	1073.5	1492.6	1826.6	1469.5	2072.9	2811.3	1668.0	2410.2	3515.6	1864.2	2994.1	4383.4
6	**Ai** (sq. in/ft)	0.103	0.133	0.157	0.128	0.170	0.203	0.153	0.207	0.250	0.203	0.282	0.351	0.229	0.321	0.453	0.255	0.376	0.555
	Ao (sq. in/ft)	0.070	0.070	0.072	0.070	0.080	0.095	0.077	0.098	0.117	0.105	0.137	0.164	0.120	0.157	0.189	0.135	0.177	0.213
	Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crack	0.01" crack
	D-Load (lb/ft/ft)	670.87	911.96	1102.8	872.0	1205.5	1463.8	1071.1	1494.9	1826.2	1463.8	2069.3	2583.5	1665.1	2361.6	3319.1	1864.4	2766.5	4025.8
7	**Ai** (sq. in/ft)	0.103	0.133	0.156	0.128	0.169	0.202	0.152	0.206	0.248	0.202	0.280	0.343	0.228	0.318	0.419	0.253	0.357	0.521
	Ao (sq. in/ft)	0.070	0.070	0.072	0.070	0.079	0.094	0.077	0.098	0.117	0.104	0.136	0.163	0.119	0.155	0.187	0.134	0.175	0.211
	Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crack
	D-Load (lb/ft/ft)	672.63	914.91	1098.9	874.7	1202.3	1462.8	1067.0	1494.2	1821.2	1462.8	2067.3	2544.3	1666.1	2356.2	3106.5	1859.8	2648.9	3838.9
8	**Ai** (sq. in/ft)	0.103	0.132	0.156	0.127	0.168	0.156	0.152	0.205	0.201	0.202	0.279	0.341	0.227	0.316	0.389	0.252	0.354	0.490
	Ao (sq. in/ft)	0.070	0.070	0.072	0.070	0.079	0.072	0.076	0.097	0.094	0.104	0.135	0.162	0.118	0.154	0.185	0.133	0.173	0.209
	Governing	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
	D-Load (lb/ft/ft)	673.96	909.05	1102.0	868.67	1197.9	1460	1069.9	1491.6	1821.1	1467.9	2069.4	2543.9	1664.7	2353.6	2905.3	1860.1	2642.3	3649.2

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 3" maximum spacing and 44" reinforcing diameter

54" Pipe Diameter

Wall Thickness	fc' (kips)		5			7.5			10			15			17.5			20		
			Fill Height (feet)																	
			type 1	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**
6.25" Wall Thickness	4	**Ai** (sq. in/ft)	0.094	0.120	0.142	0.116	0.153	0.182	0.137	0.185	0.224	0.182	0.252	0.309	0.204	0.286	0.477	0.227	0.358	0.647
	4	**Ao** (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.081	0.070	0.083	0.100	0.088	0.116	0.140	0.100	0.132	0.161	0.112	0.150	0.182
	4	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	shear	flexure	0.01" crack	shear
	4	**D-Load** (lb/ft/ft)	699.23	942.76	1146.5	905.48	1247.6	1511.8	1100.4	1539.0	1888.3	1511.8	2135.3	2628.2	1709.9	2430.8	4005.4	1914.9	3041.4	5285.6
	5	**Ai** (sq. in/ft)	0.094	0.120	0.141	0.115	0.152	0.181	0.136	0.184	0.222	0.180	0.249	0.305	0.202	0.283	0.350	0.224	0.317	0.468
	5	**Ao** (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.080	0.070	0.082	0.099	0.086	0.114	0.138	0.098	0.130	0.158	0.110	0.146	0.179
	5	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	shear
	5	**D-Load** (lb/ft/ft)	702.31	947.79	1144.2	900.77	1246.6	1514.3	1097.6	1541.8	1887.8	1505.1	2130.7	2626.6	1706.3	2433	3017.6	1905.9	2731.5	4011.4
	6	**Ai** (sq. in/ft)	0.094	0.120	0.140	0.115	0.151	0.180	0.136	0.183	0.220	0.179	0.248	0.302	0.201	0.280	0.344	0.223	0.314	0.4
	6	**Ao** (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.080	0.070	0.082	0.099	0.085	0.113	0.137	0.097	0.128	0.156	0.109	0.144	0.176
	6	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
	6	**D-Load** (lb/ft/ft)	704.37	951.14	1139.5	903.85	1242.6	1512.6	1101.9	1540.4	1881.0	1503.4	2136.1	2621.6	1706.6	2424.8	2993.6	1908.4	2728.4	3481.7
	7	**Ai** (sq. in/ft)	0.094	0.119	0.14	0.115	0.151	0.180	0.136	0.182	0.219	0.178	0.246	0.301	0.200	0.279	0.342	0.222	0.311	0.383
	7	**Ao** (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.079	0.070	0.081	0.098	0.085	0.112	0.136	0.096	0.127	0.155	0.108	0.143	0.174
	7	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
	7	**D-Load** (lb/ft/ft)	705.84	944.05	1142.8	906.05	1246.4	1518.0	1105.0	1536.7	1879.9	1499.4	2128	2627.9	1704.1	2428.8	2995.5	1907.5	2728.4	3359.0
	8	**Ai** (sq. in/ft)	0.093	0.119	0.14	0.114	0.150	0.179	0.135	0.182	0.219	0.178	0.245	0.299	0.199	0.277	0.340	0.221	0.310	0.381
	8	**Ao** (sq. in/ft)	0.070	0.070	0.070	0.070	0.070	0.079	0.070	0.081	0.098	0.084	0.111	0.135	0.095	0.127	0.154	0.107	0.142	0.173
	8	**Governing**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
	8	**D-Load** (lb/ft/ft)	697.35	945.81	1145.2	898.17	1239.8	1512.7	1097.8	1540.8	1885.8	1503.3	2126.4	2621.0	1699.7	2420.3	2992.2	1904.4	2721.0	3359.6

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 3" maximum spacing and 44" reinforcing diameter

60 inch Tables

60" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
5" Wall Thickness	4	**Ai** (sq. in/	0.141	0.183	0.217	0.176	0.235	0.335	0.212	0.345	0.486	0.250	0.466	0.637	0.332	0.587	0.788*	0.497	0.828*	1.090*
		Ao (sq. in/	0.074	0.091	0.106	0.096	0.119	0.140	0.118	0.149	0.176	0.141	0.180	0.213	0.165	0.212	0.252	0.216	0.280	0.359
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens	0.01" crac	rad. Tens. & c	ns. & 0.01'
		D-Load (lb	759.39	997.71	1178.8	959.12	1270.4	1725.6	1152.8	1766.1	2359.5	1344.5	2271.5	2981.7	1713.3	2783.9	3526.7	2407.4	-	-
	5	**Ai** (sq. in/	0.140	0.181	0.214	0.175	0.232	0.293	0.210	0.303	0.444	0.246	0.424	0.596	0.291	0.545	0.747	0.456	0.787	1.049*
		Ao (sq. in/	0.074	0.090	0.105	0.095	0.118	0.138	0.116	0.146	0.173	0.139	0.176	0.209	0.161	0.206	0.246	0.210	0.270	0.323
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	Tens. & 0.01" c
		D-Load (lb	770.22	1014.6	1202.3	979.68	1301.3	1619.0	1180	1668.4	2287.7	1376.6	2208.7	2922.1	1609.0	2696.7	3549.0	2333.7	3704.9	-
	6	**Ai** (sq. in/	0.139	0.180	0.213	0.174	0.230	0.276	0.208	0.282	0.407	0.243	0.387	0.558	0.279	0.508	0.709	0.418	0.750	1.012*
		Ao (sq. in/	0.073	0.089	0.104	0.094	0.117	0.137	0.115	0.145	0.171	0.137	0.174	0.206	0.159	0.203	0.241	0.205	0.264	0.315
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens. & 0
		D-Load (lb	775.07	1027.8	1222.6	991.04	1320.6	1320.6	1193.4	1609.1	2234.1	1394.3	2140.6	2860.6	1592.9	2668.7	3493.4	2284.5	3668.9	-
	7	**Ai** (sq. in/	0.139	0.179	0.212	0.173	0.229	0.229	0.207	0.280	0.373	0.242	0.353	0.524	0.277	0.474	0.675	0.384	0.715	0.977
		Ao (sq. in/	0.073	0.089	0.104	0.094	0.116	0.116	0.114	0.144	0.170	0.136	0.172	0.204	0.157	0.201	0.238	0.203	0.260	0.310
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crack
		D-Load (lb	782.91	1040.4	1235.0	997.13	1336.2	1336.2	1205.0	1630.2	2130.5	1412.5	2026.8	2844.3	1613.3	2621.4	3436.8	2186.6	3589.4	4703.4
	8	**Ai** (sq. in/	0.139	0.179	0.211	0.172	0.228	0.228	0.206	0.278	0.341	0.241	0.329	0.492	0.275	0.442	0.643	0.352	0.684	0.945
		Ao (sq. in/	0.073	0.089	0.103	0.093	0.116	0.116	0.114	0.143	0.169	0.135	0.171	0.202	0.156	0.199	0.236	0.201	0.257	0.307
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crack
		D-Load (lb	788.78	1044.0	1242.6	999.93	1346.1	1346.1	1211.9	1642.6	1999.2	1424.4	1932.7	2777.5	1625.1	2531.7	3448.8	2059.5	3612.6	4666.7

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 3" maximum spacing and 44" reinforcing diameter

60" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
6" Wall Thickness	4	**Ai** (sq. in/	0.121	0.155	0.183	0.149	0.197	0.236	0.178	0.240	0.305	0.236	0.385	0.562	0.266	0.484	0.678	0.306	0.623	0.802*
		Ao (sq. in/	0.070	0.072	0.085	0.074	0.093	0.110	0.091	0.115	0.137	0.124	0.161	0.193	0.141	0.184	0.222	0.222	0.209	0.252
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	diag. tens	flexure	0.01" crac	diag. tens	0.01" crac	diag. tens.	ens & 0.01"
		D-Load (lb	694.62	935.03	1129.9	892.9	1226.4	1491.6	1095.3	1518.5	1948.2	1491.6	2457.7	3510.5	1692.0	3059.1	4145.4	1954.7	3849.8	4776.1
	5	**Ai** (sq. in/	0.121	0.155	0.182	0.149	0.196	0.234	0.176	0.237	0.286	0.233	0.337	0.506	0.262	0.437	0.630	0.292	0.536	0.755
		Ao (sq. in/	0.070	0.072	0.084	0.074	0.092	0.109	0.089	0.114	0.135	0.122	0.158	0.189	0.139	0.180	0.217	0.156	0.204	0.245
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crack	0.01" crack
		D-Load (lb	698.77	941.84	1132.4	899.19	1230.4	1493.7	1090.2	1514.3	1847.3	1486.8	2186.9	3261.6	1685.0	2832.1	4001.6	1887.6	3444.4	4706.4
	6	**Ai** (sq. in/	0.121	0.154	0.181	0.148	0.195	0.232	0.175	0.236	0.284	0.232	0.319	0.463	0.260	0.384	0.587	0.289	0.493	0.712
		Ao (sq. in/	0.070	0.071	0.084	0.073	0.092	0.109	0.089	0.113	0.134	0.120	0.156	0.187	0.137	0.178	0.214	0.154	0.200	0.241
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
		D-Load (lb	701.53	939.23	1131.6	896.22	1230.6	1490.1	1089.0	1518.0	1849.1	1490.1	2087.2	3036.2	1684.2	2587.5	3815.3	1883.3	3227.9	4565.4
	7	**Ai** (sq. in/	0.120	0.154	0.180	0.147	0.194	0.231	0.175	0.234	0.282	0.230	0.317	0.424	0.258	0.359	0.548	0.287	0.453	0.672
		Ao (sq. in/	0.070	0.071	0.083	0.073	0.091	0.108	0.088	0.112	0.133	0.119	0.154	0.185	0.135	0.176	0.211	0.152	0.198	0.238
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crack
		D-Load (lb	696.23	942.43	1128.9	891.96	1228.7	1490.4	1093.1	1511.4	1846.2	1483.3	2087.3	2808.4	1679.4	2373.1	3614.9	1880.8	2999.8	4390.8
	8	**Ai** (sq. in/	0.120	0.153	0.180	0.147	0.193	0.230	0.174	0.234	0.281	0.229	0.316	0.387	0.257	0.357	0.511	0.285	0.417	0.636
		Ao (sq. in/	0.070	0.071	0.083	0.073	0.091	0.108	0.088	0.112	0.133	0.119	0.153	0.184	0.134	0.175	0.210	0.151	0.196	0.236
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	flexure	flexure	0.01" crac	0.01" crack
		D-Load (lb	697.69	937.60	1132.2	894.15	1225.3	1488.7	1089	1517.0	1847.3	1481.6	2090.6	2576.9	1679.2	2372.6	3404.2	1875.2	2779.6	4210.1

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.48" reinforcing diameter

60" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
6.75" Wall Thickness	4	**Ai** (sq. in/	0.112	0.120	0.141	0.136	0.156	0.187	0.161	0.193	0.233	0.211	0.268	0.354	0.236	0.307	0.518	0.262	0.398	0.733
	4	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.070	0.082	0.076	0.086	0.104	0.103	0.123	0.149	0.117	0.142	0.173	0.131	0.162	0.197
	4	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	diag. tens	flexure	diag. tens.	diag. tens.
	4	**D-Load** (lb	732.14	798.53	971.74	930.64	1094.5	1345.7	1135.2	1394.0	1712.5	1538	1986.7	2643.2	1736.1	2287.5	3827.9	1940.0	2969.7	5249.2
	5	**Ai** (sq. in/	0.111	0.119	0.140	0.135	0.155	0.185	0.141	0.191	0.231	0.190	0.265	0.325	0.215	0.303	0.412	0.240	0.341	0.523
	5	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.070	0.081	0.070	0.085	0.103	0.091	0.121	0.147	0.105	0.139	0.170	0.119	0.158	0.193
	5	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crack
	5	**D-Load** (lb	727.31	794.26	969.08	927.57	1093.1	1339.3	977.37	1388.2	1711.8	1380.1	1983.3	2454.6	1582.9	2283	3120.6	1784.0	2578.6	3940.7
	6	**Ai** (sq. in/	0.093	0.119	0.140	0.154	0.154	0.184	0.14	0.190	0.230	0.189	0.263	0.322	0.214	0.300	0.369	0.238	0.338	0.476
	6	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.070	0.081	0.070	0.084	0.102	0.090	0.120	0.145	0.138	0.138	0.168	0.117	0.156	0.190
	6	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
	6	**D-Load** (lb	577.60	769.93	972.78	771.71	1089.3	1337.5	972.78	1386.9	1713.8	1378.7	1980.5	2451.0	1583.5	2276.5	2819.8	1778.7	2577.1	3640.5
	7	**Ai** (sq. in/	0.092	0.119	0.139	0.116	0.154	0.184	0.140	0.190	0.229	0.188	0.262	0.320	0.213	0.278	0.367	0.237	0.335	0.432
	7	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.070	0.080	0.070	0.084	0.101	0.090	0.119	0.144	0.103	0.137	0.166	0.116	0.155	0.188
	7	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
	7	**D-Load** (lb	570.27	789.84	967.04	773.53	1092.5	1342.1	975.43	1391.8	1712.8	1375.2	1981.8	2449.0	1581.5	2111.4	2822.5	1778.2	2568.7	3331.5
	8	**Ai** (sq. in/	0.092	0.118	0.139	0.116	0.154	0.183	0.140	0.189	0.228	0.188	0.261	0.319	0.212	0.297	0.365	0.236	0.334	0.411
	8	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.070	0.080	0.070	0.084	0.101	0.089	0.118	0.144	0.102	0.136	0.165	0.115	0.153	0.187
	8	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure
	8	**D-Load** (lb	571.13	791.8	969.00	774.89	1094.9	1337.2	977.41	1387.1	1709.8	1378.8	1980.6	2451.4	1577.8	2273.5	2820.2	1775.7	2572.1	3185.2

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.54" reinforcing diameter

66 inch Tables

66" Pipe Diameter

Fill Height (feet)

Wall	fc' (kips)		5			7.5			10			12.5			15			20		
			type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
5.5" Wall Thickness	4	**Ai** (sq. in/	0.160	0.205	0.242	0.197	0.263	0.384	0.236	0.393	0.547	0.289	0.523	0.709	0.377	0.563	0.872*	0.554	0.913*	1.196*
	4	**Ao** (sq. in/	0.084	0.101	0.118	0.107	0.132	0.155	0.131	0.164	0.194	0.155	0.197	0.233	0.181	0.231	0.275	0.235	0.304	0.398
	4	**Governin**	flexure	flexure	flexure	flexure	0.01" crac	0.01"crack	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens. &0	ns. & 0.01'
	4	**D-Load** (lb	685.29	913.95	1097.6	873.72	1200.2	1767.4	1068.1	1808.0	2468.5	1325.5	2369.8	3694.6	1735.7	2886.1	3653.9	2497	-	-
	5	**Ai** (sq. in/	0.158	0.203	0.240	0.196	0.258	0.340	0.233	0.349	0.502	0.272	0.497	0.665	0.333	0.609	0.827	0.510	0.869*	1.152*
	5	**Ao** (sq. in/	0.083	0.101	0.117	0.105	0.130	0.153	0.129	0.161	0.190	0.152	0.193	0.228	0.177	0.226	0.268	0.228	0.294	0.354
	5	**Governin**	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	ens. & 0.01" c
	5	**D-Load** (lb	680.85	913.59	1101.3	877.71	1191.5	1593.1	1066.1	1636.2	2341.7	1261.2	2319.5	3036.4	1559.4	2804.3	3669.2	2377.2	3823.9	-
	6	**Ai** (sq. in/	0.158	0.202	0.238	0.194	0.256	0.307	0.232	0.312	0.462	0.269	0.439	0.625	0.308	0.569	0.787	0.470	0.828	1.112
	6	**Ao** (sq. in/	0.082	0.100	0.116	0.105	0.129	0.152	0.127	0.160	0.188	0.151	0.190	0.225	0.174	0.222	0.268	0.224	0.288	0.343
	6	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens. & 0
	6	**D-Load** (lb	684.76	914.86	1100.1	873.32	1191.8	1448.1	1069.4	1473.0	2196.0	1257.7	2087.9	2933.0	1453.1	2685.4	3616.3	2233.3	3781.6	4841.1
	7	**Ai** (sq. in/	0.157	0.201	0.237	0.194	0.255	0.305	0.230	0.309	0.425	0.268	0.402	0.588	0.305	0.532	0.750	0.433	0.792	1.075*
	7	**Ao** (sq. in/	0.082	0.100	0.116	0.104	0.129	0.151	0.127	0.158	0.187	0.149	0.189	0.233	0.173	0.220	0.260	0.221	0.283	0.337
	7	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.
	7	**D-Load** (lb	682.23	914.20	1101.3	877.53	1194	1448.6	1065.1	1468.8	2041.9	1260.6	1930.1	2809.1	1448.6	2550.5	3528.2	2080.6	3707.6	4842.8
	8	**Ai** (sq. in/	0.157	0.201	0.236	0.193	0.254	0.303	0.230	0.308	0.391	0.266	0.368	0.554	0.304	0.497	0.716	0.399	0.757	1.041
	8	**Ao** (sq. in/	0.082	0.099	0.115	0.128	0.128	0.126	0.126	0.157	0.186	0.148	0.187	0.222	0.171	0.218	0.258	0.219	0.280	0.333
	8	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crack
	8	**D-Load** (lb	684.30	917.59	1100.8	875.41	1194.3	1446.2	1069.6	1471.7	1889.2	1256.4	1774.6	2678.7	1451.3	2407.1	3424.3	1928.9	3606.9	4805.5

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and .44" reinforcing diameter

66" Pipe Diameter

Wall	fc' (kips)		Fill Height (feet) 5			7.5			10			15			17.5			20		
			type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
6.5" Wall Thickness	4	**Ai** (sq. in/	0.140	0.178	0.209	0.171	0.224	0.267	0.202	0.271	0.367	0.266	0.453	0.695	0.299	0.582	0.776*	0.365	0.761	0.912*
		Ao (sq. in/	0.070	0.083	0.097	0.085	0.106	0.125	0.103	0.130	0.155	0.140	0.181	0.216	0.160	0.207	0.249	0.179	0.234	0.282
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	duag. Ten	flexure	diag. tens	rad. Tens.	0.01" crac	diag.tens.	ens. * 0.01'
		D-Load (lb	724.19	968.03	1163.9	923.43	1257.7	1523.1	1119.9	1547.5	2120.6	1517	2612.7	3891.1	1717.3	3313.6	4284.2	2108.9	4212.7	4905.4
	5	**Ai** (sq. in/	0.139	0.177	0.208	0.170	0.222	0.230	0.200	0.268	0.287	0.263	0.403	0.502	0.295	0.512	0.638	0.327	0.620	0.791
		Ao (sq. in/	0.070	0.082	0.096	0.085	0.105	0.106	0.102	0.129	0.134	0.138	0.177	0.193	0.156	0.203	0.224	0.175	0.228	0.255
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	Tens. * 0.01" c
		D-Load (lb	722.24	969.01	1167.7	923.82	1256.8	1307.4	1116.7	1546.1	1664.1	1514.9	2367.3	2943.6	1731.6	3000.7	3700.2	1910	3602.4	4503.3
	6	**Ai** (sq. in/	0.139	0.176	0.172	0.169	0.221	0.228	0.199	0.266	0.285	0.261	0.358	0.456	0.292	0.466	0.592	0.324	0.575	0.729
		Ao (sq. in/	0.070	0.082	0.078	0.084	0.104	0.105	0.101	0.128	0.133	0.136	0.175	0.191	0.156	0.200	0.220	0.173	0.225	0.251
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
		D-Load (lb	725.26	967.41	941.36	921.81	1258.1	1302.9	1116.5	1544.7	1664.5	1513.0	2118.2	2711.2	1708.4	2770.7	3504	1908.2	3406.8	4267.8
	7	**Ai** (sq. in/	0.139	0.176	0.172	0.168	0.220	0.227	0.199	0.265	0.283	0.259	0.356	0.414	0.290	0.424	0.550	0.321	0.533	0.687
		Ao (sq. in/	0.070	0.082	0.077	0.084	0.104	0.105	0.101	0.127	0.132	0.135	0.174	0.189	0.153	0.198	0.218	0.171	0.222	0.248
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
		D-Load (lb	727.41	970.86	944.67	918.44	1257.1	1302.3	1120.9	1546.2	1660.9	1507.9	2120.1	2478.5	1705.3	2539.8	3269.9	1901.1	3196.3	4090.5
	8	**Ai** (sq. in/	0.138	0.175	0.171	0.168	0.219	0.227	0.198	0.264	0.282	0.258	0.354	0.396	0.289	0.400	0.511	0.320	0.493	0.647
		Ao (sq. in/	0.070	0.081	0.077	0.083	0.104	0.104	0.100	0.126	0.132	0.134	0.173	0.188	0.152	0.196	0.217	0.169	0.220	0.246
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crack
		D-Load (lb	722.39	966.88	940.56	920.80	1254.6	1306.6	1117.7	1545.7	1661.2	1507.0	2118.2	2381.1	1706.0	2406.0	3087.3	1903.4	2978.1	3897.3

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.52" reinforcing diameter

66" Pipe Diameter

	fc' (kips)		5			7.5			10			12.5			15			20		
			Fill Height (feet)																	
			type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
7.25" Wall Thickness	4	**Ai** (sq. in/	0.107	0.136	0.160	0.134	0.176	0.211	0.161	0.217	0.262	0.216	0.300	0.422	0.244	0.361	0.636	0.273	0.500	0.876
	4	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.078	0.093	0.075	0.098	0.117	0.105	0.139	0.168	0.121	0.160	0.195	0.137	0.182	0.222
	4	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	diag. tens	flexure	diag. tens.	diag. tens.
	4	**D-Load** (lb	534.02	732.47	894.84	718.86	1002.1	1234.4	901.57	1273.8	1566.6	1267.3	1809.5	2562.6	1450.2	2191.1	3786.7	1637.3	3022.9	5015.1
	5	**Ai** (sq. in/	0.106	0.136	0.159	0.133	0.175	0.209	0.16	0.215	0.26	0.214	0.297	0.367	0.242	0.338	0.489	0.269	0.403	0.651
	5	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.077	0.092	0.074	0.096	0.116	0.103	0.137	0.166	0.119	0.157	0.191	0.134	0.179	0.271
	5	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crack	diag. tens.
	5	**D-Load** (lb	529.76	736.8	894.03	716.19	1002.6	1231.4	900.84	1271.5	1569.6	1264.9	1811.2	2259.8	1450.9	2075.3	3015.4	1628.7	2486.2	3968.1
	6	**Ai** (sq. in/	0.106	0.135	0.159	0.132	0.175	0.208	0.159	0.214	0.258	0.213	0.295	0.360	0.240	0.335	0.439	0.267	0.377	0.561
	6	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.077	0.074	0.074	0.096	0.115	0.102	0.135	0.164	0.117	0.155	0.189	0.133	0.176	0.214
	6	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crack
	6	**D-Load** (lb	531.52	732.98	897.98	712.04	1007.4	1231.5	897.98	1272.0	1566.9	1265.3	1811.8	2235.7	1446.7	2073.7	2739.9	1626.7	2345.2	3495.4
	7	**Ai** (sq. in/	0.106	0.158	0.158	0.132	0.174	0.207	0.158	0.213	0.257	0.212	0.293	0.358	0.239	0.333	0.409	0.266	0.374	0.516
	7	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.076	0.091	0.073	0.095	0.115	0.101	0.134	0.163	0.116	0.154	0.187	0.131	0.174	0.212
	7	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
	7	**D-Load** (lb	532.77	734.81	893.91	713.98	1004.0	1229.5	893.9	1270.3	1567.6	1263.5	1508.3	2237.2	1446.4	2073.1	2568.6	1628.0	2341.6	3249.9
	8	**Ai** (sq. in/	0.106	0.135	0.158	0.132	0.174	0.207	0.158	0.213	0.256	0.211	0.292	0.332	0.238	0.332	0.407	0.265	0.372	0.473
	8	**Ao** (sq. in/	0.070	0.070	0.070	0.070	0.076	0.091	0.073	0.095	0.114	0.101	0.133	0.153	0.116	0.153	0.186	0.130	0.173	0.210
	8	**Governin**	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
	8	**D-Load** (lb	533.71	736.33	895.99	715.44	1006.5	1233.1	895.99	1274.1	1566.4	1260.5	1808.8	2234.7	1444.4	2075.7	2569.6	1627.2	2340.2	2997.2

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and .56" reinforcing diameter

72 inch Tables

72" Pipe Diameter

Fill Height (feet)

Wall	fc' (kips)		5 type 1	5 type 2	5 type 3	7.5 type 1	7.5 type 2	7.5 type 3	10 type 1	10 type 2	10 type 3
6" Wall Thickness	4	**Ai** (sq. in/	0.179	0.229	0.270	0.220	0.306	0.438	0.261	0.445	0.612
		Ao (sq. in/	0.093	0.113	0.131	0.118	0.146	0.171	0.144	0.180	0.212
		Governin	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	flexure	0.01" crac
		D-Load (lb	708.55	946.13	1136.5	903.80	1300.5	1876.2	1095.0	1905.6	2574.6
	5	**Ai** (sq. in/	0.178	0.227	0.267	0.218	0.286	0.390	0.258	0.398	0.564
		Ao (sq. in/	0.093	0.112	0.130	0.117	0.144	0.169	0.147	0.177	0.208
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac
		D-Load (lb	709.99	946.91	1136.8	903.75	1225.9	1701.5	1094.3	1737.3	2451.9
	6	**Ai** (sq. in/	0.177	0.226	0.266	0.217	0.284	0.348	0.256	0.355	0.521
		Ao (sq. in/	0.092	0.111	0.129	0.116	0.143	0.167	0.140	0.175	0.206
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac
		D-Load (lb	709.22	948.84	1141.4	905.14	1227.2	1527.9	1093.5	1560.4	2307.6
	7	**Ai** (sq. in/	0.177	0.225	0.264	0.216	0.282	0.336	0.255	0.34	0.482
		Ao (sq. in/	0.092	0.111	0.129	0.115	0.142	0.166	0.139	0.174	0.204
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac
		D-Load (lb	712.16	948.75	1138.4	904.65	1225.2	1482.7	1094.8	1501.6	2158.0
	8	**Ai** (sq. in/	0.176	0.224	0.263	0.215	0.281	0.335	0.254	0.339	0.445
		Ao (sq. in/	0.091	0.111	0.128	0.115	0.141	0.165	0.139	0.173	0.203
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac
		D-Load (lb	709.37	947.39	1138.4	903.00	1225.9	1485.9	1094.5	1505.0	2003.7

Wall	fc' (kips)		12.5 type 1	12.5 type 2	12.5 type 3	15 type 1	15 type 2	15 type 3	20 type 1	20 type 2	20 type 3
6" Wall Thickness	4	**Ai** (sq. in/	0.331	0.584	0.785	0.426	0.723	0.959*	0.615	1.061*	1.307*
		Ao (sq. in/	0.170	0.215	0.255	0.197	0.251	0.299	0.255	0.329	0.439
		Governin	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	flexure	rad tens. & 0	ns. & 0.01"
		D-Load (lb	1412.6	2466.8	3201.8	1825.5	2984.7	3765.4	2586.1	-	-
	5	**Ai** (sq. in/	0.299	0.537	0.738	0.378	0.676	0.912*	0.568	0.954*	1.260*
		Ao (sq. in/	0.167	0.211	0.249	0.193	0.245	0.291	0.247	0.318	0.391
		Governin	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad tens. &	Tens. & 0.01" c
		D-Load (lb	1286.5	2339.2	3146.5	1647.7	2905.4	3785.8	2468.5	3931.3	-
	6	**Ai** (sq. in/	0.297	0.494	0.695	0.338	0.633	0.869	0.525	0.911	1.217*
		Ao (sq. in/	0.165	0.208	0.246	0.190	0.242	0.287	0.243	0.312	0.371
		Governin	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens. & 0
		D-Load (lb	1288.8	2189.1	3044.1	1481.4	2787.1	3733.3	2325.1	3892.7	4972.1
	7	**Ai** (sq. in/	0.295	0.454	0.656	0.335	0.593	0.83	0.485	0.872	1.177*
		Ao (sq. in/	0.164	0.206	0.243	0.189	0.239	0.283	0.240	0.307	0.365
		Governin	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.
		D-Load (lb	1287.5	2030.8	2923.9	1477.9	2651.4	3648.3	2171.5	3817.0	4971.2
	8	**Ai** (sq. in/	0.293	0.418	0.619	0.333	0.557	0.793	0.449	0.835	1.141*
		Ao (sq. in/	0.163	0.205	0.242	0.187	0.237	0.281	0.237	0.304	0.361
		Governin	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.
		D-Load (lb	1284.0	1878.0	2791.7	1476.3	2515.3	3542.5	2022.3	3718.2	4934.5

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.48" reinforcing diameter

72" Pipe Diameter

			Fill Height (feet)																	
			5			**7.5**			**10**			**15**			**17.5**			**20**		
7" Wall Thickness	**fc' (kips)**		**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**
		Ai (sq. in/	0.160	0.167	0.195	0.193	0.216	0.258	0.227	0.267	0.329	0.297	0.435	0.668	0.347	0.553	0.774*	0.427	0.764	0.923*
		Ao (sq. in/	0.078	0.075	0.088	0.097	0.100	0.119	0.116	0.127	0.151	0.157	0.181	0.218	0.178	0.210	0.253	0.200	0.239	0.289
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	diag. tens	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	diag. tens.	ns. & 0.01'
	4	**D-Load** (lb	752.10	793.49	957.91	946.23	1079.9	1321.0	1143.5	1372.1	1719.2	1541.2	2292.2	3462.6	1818.3	2900.1	3955.1	2249.8	3909.7	4605.2
		Ai (sq. in/	0.159	0.165	0.194	0.192	0.214	0.256	0.225	0.264	0.318	0.294	0.381	0.572	0.328	0.499	0.720	0.374	0.617	0.869*
		Ao (sq. in/	0.077	0.074	0.087	0.096	0.099	0.118	0.115	0.125	0.149	0.154	0.178	0.214	0.175	0.205	0.247	0.195	0.233	0.281
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	Tens. & 0.01" c
	5	**D-Load** (lb	751.15	787.04	959.48	947.64	1077.4	1322.5	1141.9	1368.9	1678.2	1541.4	2032.2	3059.9	1734.9	2675.1	3810.2	1993.2	3292.3	4525.4
		Ai (sq. in/	0.158	0.165	0.193	0.191	0.213	0.254	0.224	0.262	0.316	0.291	0.362	0.523	0.325	0.451	0.672	0.360	0.569	0.820
		Ao (sq. in/	0.077	0.074	0.087	0.095	0.099	0.117	0.114	0.124	0.148	0.153	0.176	0.211	0.172	0.203	0.243	0.192	0.230	0.276
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
	6	**D-Load** (lb	748.44	790.61	958.45	946.51	1077.5	1319.4	1142.7	1366.3	1680.0	1535.4	1943.5	2838.8	1731.8	2443.5	3631.0	1932.1	3087.1	4383.7
		Ai (sq. in/	0.158	0.164	0.193	0.191	0.212	0.253	0.223	0.261	0.314	0.290	0.359	0.479	0.323	0.409	0.627	0.357	0.524	0.776
		Ao (sq. in/	0.076	0.074	0.087	0.095	0.098	0.117	0.113	0.123	0.147	0.151	0.174	0.209	0.171	0.200	0.241	0.190	0.227	0.273
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crack
	7	**D-Load** (lb	750.77	787.11	961.95	949.93	1075.8	1319.6	1141.4	1366.9	1677.7	1537.5	1938.5	2619.8	1730.1	2224.9	3432.5	1927.0	2870.1	4220.4
		Ai (sq. in/	0.158	0.164	0.192	0.190	0.212	0.252	0.223	0.260	0.313	0.289	0.358	0.437	0.322	0.407	0.586	0.326	0.483	0.734
		Ao (sq. in/	0.076	0.074	0.087	0.094	0.098	0.116	0.113	0.123	0.146	0.150	0.173	0.208	0.169	0.199	0.239	0.172	0.225	0.271
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crack
	8	**D-Load** (lb	752.53	789.00	958.53	946.46	1078.9	1318.1	1144.9	1365.7	1678.8	1537.5	1941.8	2397.2	1731.6	2225.2	3234.7	1755.1	2658.7	4039.6

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.56" reinforcing diameter

72" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
7.75" Wall Thickness	4	**Ai** (sq. in/	0.149	0.188	0.219	0.179	0.232	0.275	0.209	0.278	0.333	0.271	0.405	0.717	0.302	0.580	0.726*	0.334	0.777	0.860*
		Ao (sq. in/	0.070	0.084	0.098	0.085	0.105	0.125	0.101	0.128	0.153	0.135	0.175	0.210	0.153	0.199	0.240	0.171	0.224	0.270
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	diag. tens	flexure	diag. tens	rad. Tens	flexure	diag. tens.	ens. &0.01'
		D-Load (lb	779.01	1040.3	1245.4	980.36	1330.8	1610.3	1179.5	1629.7	1980.6	1584.5	2429.5	4240.1	1783.6	3471.8	4289.1	1986.9	4565.1	4997.8
	5	**Ai** (sq. in/	0.149	0.187	0.218	0.178	0.230	0.273	0.208	0.275	0.329	0.268	0.366	0.533	0.299	0.453	0.719	0.330	0.560	0.802*
		Ao (sq. in/	0.070	0.083	0.097	0.085	0.104	0.124	0.100	0.127	0.151	0.133	0.172	0.206	0.150	0.195	0.235	0.167	0.219	0.264
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	diag. tens	flexure	0.01" crac	Tens. &0.01" c
		D-Load (lb	783.37	1040.5	1248.2	979.92	1328.1	1612.1	1181.4	1625.2	1976.6	1579.3	2214.2	3254.8	1782.1	2762.8	4353.5	1983.1	3418.2	4823.5
	6	**Ai** (sq. in/	0.148	0.186	0.217	0.178	0.230	0.272	0.207	0.273	0.327	0.267	0.363	0.480	0.297	0.408	0.615	0.327	0.507	0.749
		Ao (sq. in/	0.070	0.083	0.097	0.084	0.104	0.123	0.099	0.126	0.150	0.132	0.170	0.204	0.148	0.193	0.232	0.165	0.216	0.26
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crack
		D-Load (lb	779.44	1038.3	1247.7	984.07	1335.1	1615.3	1180.4	1621.9	1977.8	1582.1	2212.4	2960.5	1780.7	2502.7	3796.8	1977.8	3130.1	4598.9
	7	**Ai** (sq. in/	0.148	0.186	0.216	0.177	0.229	0.271	0.206	0.272	0.326	0.265	0.361	0.437	0.295	0.406	0.566	0.325	0.459	0.700
		Ao (sq. in/	0.070	0.083	0.097	0.083	0.103	0.123	0.099	0.125	0.149	0.131	0.169	0.202	0.147	0.191	0.23	0.163	0.214	0.258
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crack
		D-Load (lb	781.49	1041.6	1245.4	980.21	1333.3	1615.5	1177.6	1622.2	1981.2	1575.4	2211.7	2706.1	1775.6	2505.4	3526.8	1974.6	2847.7	4355.1
	8	**Ai** (sq. in/	0.148	0.185	0.216	0.177	0.228	0.270	0.206	0.325	0.258	0.264	0.272	0.398	0.294	0.359	0.454	0.324	0.404	0.561
		Ao (sq. in/	0.070	0.083	0.096	0.083	0.103	0.122	0.099	0.148	0.129	0.130	0.125	0.182	0.146	0.168	0.209	0.162	0.190	0.236
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crack
		D-Load (lb	783.03	1037.2	1248.7	982.42	1330.2	1614.0	1180.6	1982.0	1533.1	1573.6	1627.4	2464.5	1775.1	2207.6	2830.1	1975.4	2503.9	3517.6

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.62" reinforcing diameter

78 inch Tables

78" Pipe Diameter																				
			Fill Height (feet)																	
			5			7.5			10			12.5			15			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
6.5" Wall Thickness	4	**Ai** (sq. in/	0.200	0.255	0.310	0.244	0.352	0.495	0.288	0.500	0.680	0.376	0.649	0.866*	0.477	0.797	1.051*	0.678	1.094*	1.422*
		Ao (sq. in/	0.104	0.125	0.145	0.130	0.160	0.187	0.157	0.196	0.231	0.186	0.234	0.279	0.215	0.273	0.324	0.275	0.355	0.482
		Governin	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens. & c	ns. & 0.01'
		D-Load (lb	735.51	980.56	1219.5	932.03	1398.1	1980.2	1124.6	1999.9	2675.1	1498.5	2435.6	3308.3	1909.1	3081.0	3873.3	2671.6	3995.4	-
	5	**Ai** (sq. in/	0.199	0.252	0.296	0.241	0.315	0.445	0.284	0.45	0.630	0.328	0.598	0.815	0.426	0.746	1.001*	0.629	1.043*	1.371*
		Ao (sq. in/	0.103	0.124	0.144	0.129	0.158	0.185	0.155	0.193	0.227	0.182	0.229	0.271	0.210	0.266	0.324	0.268	0.344	0.431
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	ens. & 0.01" c
		D-Load (lb	737.65	978.02	1174.0	928.52	1257.7	1814.6	1120.9	1835.5	2560.9	1314.6	2435.6	3253.8	1734.9	3001.6	3897.2	2557.0	4035.2	-
	6	**Ai** (sq. in/	0.198	0.251	0.294	0.240	0.313	0.399	0.282	0.404	0.584	0.325	0.552	0.770	0.381	0.701	0.955	0.583	0.997*	1.326*
		Ao (sq. in/	0.102	0.123	0.143	0.128	0.157	0.183	0.154	0.191	0.225	0.180	0.226	0.267	0.207	0.262	0.310	0.263	0.337	0.400
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	rad. Tens. & 0
		D-Load (lb	737.46	980.59	1174.9	930.46	1259.9	1638.5	1120.9	1660.2	2418.8	1313.3	2287.1	3157.1	1560.1	2888.6	3846.3	2414.7	3996.6	5094.1
	7	**Ai** (sq. in/	0.197	0.250	0.293	0.239	0.311	0.370	0.281	0.373	0.542	0.323	0.510	0.728	0.366	0.659	0.913	0.541	0.955	1.284*
		Ao (sq. in/	0.102	0.123	0.142	0.127	0.156	0.182	0.153	0.190	0.223	0.179	0.224	0.265	0.205	0.259	0.307	0.26	0.332	0.394
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.
		D-Load (lb	735.93	981.05	1177.3	930.47	1258.7	1523.0	1122.7	1536.3	2269.3	1312.8	2133.1	3037.2	1505.2	2757.0	3761.2	2265.1	3920.1	5095.6
	8	**Ai** (sq. in/	0.197	0.249	0.292	0.238	0.310	0.368	0.280	0.371	0.503	0.322	0.471	0.688	0.364	0.620	0.874	0.502	0.916	1.245*
		Ao (sq. in/	0.102	0.122	0.142	0.142	0.155	0.181	0.152	0.189	0.222	0.178	0.223	0.263	0.204	0.257	0.304	0.257	0.328	0.390
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.
		D-Load (lb	738.26	980.18	1177.8	1260.0	1260.0	1522.2	1122.9	1535.7	2118.4	1314.5	1978.9	2904.0	1504.3	2619.4	3658.1	2114.1	3823.5	5057.0

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.52" reinforcing diameter

78" Pipe Diameter

	fc' (kips)		5 type 1	5 type 2	5 type 3	7.5 type 1	7.5 type 2	7.5 type 3	10 type 1	10 type 2	10 type 3	15 type 1	15 type 2	15 type 3	17.5 type 1	17.5 type 2	17.5 type 3	20 type 1	20 type 2	20 type 3
7.5" Wall Thickness		**Ai** (sq. in/	0.181	0.228	0.266	0.217	0.282	0.341	0.254	0.344	0.502	0.330	0.605	0.823*	0.406	0.845	0.983*	0.492	0.856*	1.143*
		Ao (sq. in/	0.088	0.106	0.123	0.109	0.134	0.157	0.130	0.163	0.193	0.174	0.223	0.266	0.198	0.254	0.304	0.221	0.287	0.344
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	flexure	diag. tens	rad. Tens.	0.01" crac	diag. tens	rad. Tens.	0.01" crac	rad. Tens. & (	ns. & 0.01'
	4	**D-Load** (lb	778.70	1032.9	1235.3	973.85	1319.6	1626.6	1171.7	1641.7	2428.7	1569.6	2916.0	3881.1	1956.2	3973.5	4532.6	2380.3	4019.4	5136.3
		Ai (sq. in/	0.180	0.226	0.264	0.216	0.279	0.331	0.252	0.333	0.445	0.326	0.543	0.766	0.363	0.671	0.926*	0.435	0.815	1.087*
		Ao (sq. in/	0.087	0.106	0.122	0.108	0.132	0.156	0.128	0.161	0.190	0.171	0.219	0.261	0.194	0.249	0.297	0.216	0.280	0.335
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.	0.01" crac	diag. tens	ens. & 0.01" c
	5	**D-Load** (lb	778.68	1030.8	1236.4	976.30	1316.9	1593.2	1171.7	1603.7	2183.6	1566.8	2674.8	3736.6	1761.0	3293.7	4451.2	2132.7	3959.6	5130.8
		Ai (sq. in/	0.179	0.225	0.262	0.215	0.278	0.329	0.250	0.331	0.396	0.323	0.492	0.714	0.360	0.620	0.875	0.397	0.748	1.035*
		Ao (sq. in/	0.087	0.105	0.122	0.107	0.131	0.155	0.127	0.159	0.188	0.169	0.216	0.257	0.191	0.245	0.293	0.213	0.275	0.329
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens. & 0
	6	**D-Load** (lb	776.74	1031.0	1233.3	976.01	1320.2	1594.8	1167.9	1605.5	1950.0	1562.6	2448.3	3553.3	1759.9	3093.4	4314.1	1955.2	3716.8	5036.6
		Ai (sq. in/	0.179	0.224	0.262	0.214	0.276	0.327	0.249	0.329	0.394	0.321	0.444	0.667	0.358	0.572	0.827	0.395	0.700	0.988
		Ao (sq. in/	0.087	0.105	0.121	0.106	0.131	0.154	0.127	0.158	0.187	0.168	0.214	0.255	0.189	0.243	0.290	0.211	0.272	0.325
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
	7	**D-Load** (lb	779.30	1029.5	1238.8	974.16	1315.4	1592.6	1167.4	1603.4	1951.9	1560.2	2216.5	3360.6	1759.5	2880.3	4145.9	1957.2	3525.0	4906.6
		Ai (sq. in/	0.178	0.224	0.261	0.213	0.276	0.326	0.249	0.328	0.392	0.320	0.434	0.623	0.356	0.528	0.783	0.393	0.656	0.944
		Ao (sq. in/	0.086	0.104	0.121	0.106	0.130	0.153	0.126	0.158	0.186	0.167	0.213	0.253	0.188	0.241	0.287	0.209	0.269	0.322
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
	8	**D-Load** (lb	775.61	1032.5	1237.4	971.33	1320.0	1593.6	1171.1	1604.5	1950.5	1560.9	2175.1	3162.8	1756.4	2671.1	3969.9	1955.9	3331.5	4755.5

Fill Height (feet): 5, 7.5, 10, 15, 17.5, 20

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.60" reinforcing diameter

78" Pipe Diameter

8.25" Wall Thickness	fc' (kips)		Fill Height (feet): 5			7.5			10			15			17.5			20		
			type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
	4	**Ai** (sq. in/	0.170	0.213	0.248	0.203	0.261	0.309	0.236	0.311	0.391	0.303	0.479	0.862	0.337	0.707	0.830*	0.377	0.923	0.976*
		Ao (sq. in/	0.079	0.096	0.111	0.096	0.119	0.141	0.115	0.144	0.171	0.152	0.196	0.234	0.112	0.222	0.267	0.192	0.250	0.301
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	diag. tens	flexure	diag. tens	rad. Tens.	0.01" crac	diag. tens.	ns. & 0.01'
		D-Load (lb	807.51	1070.5	1281.8	1009.7	1359.7	1644.4	1209.7	1656.2	2120.3	1609.1	2616.6	4605.3	1808.4	3833.8	4449.7	2040.0	4896.6	5144.0
	5	**Ai** (sq. in/	0.169	0.212	0.246	0.201	0.259	0.306	0.234	0.308	0.368	0.300	0.417	0.622	0.333	0.533	0.858	0.367	0.672	0.914*
		Ao (sq. in/	0.078	0.095	0.110	0.096	0.118	0.140	0.113	0.142	0.169	0.150	0.192	0.230	0.168	0.218	0.262	0.187	0.244	0.294
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	diag. tens	flexure	diag. tens	ens. & 0.01" c
		D-Load (lb	806.13	1072.0	1280.0	1004.2	1359.0	1642.5	1206.8	1654.4	2010.9	1606.5	2297.7	3456.7	1803.7	2961.6	4710.3	2005.0	3729.5	4995.2
	6	**Ai** (sq. in/	0.169	0.211	0.245	0.201	0.258	0.305	0.233	0.306	0.365	0.298	0.404	0.566	0.331	0.478	0.712	0.364	0.594	0.876
		Ao (sq. in/	0.078	0.095	0.110	0.095	0.117	0.139	0.112	0.141	0.168	0.148	0.190	0.228	0.166	0.215	0.258	0.185	0.241	0.290
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	diag. tens.
		D-Load (lb	809.32	1070.8	1280.6	1008.80	1360.4	1646.9	1206.7	1652.9	2008.1	1604.4	2240.3	3182.6	1804.0	2675.1	4001.9	2002.2	3341.9	4888.8
	7	**Ai** (sq. in/	0.168	0.210	0.244	0.200	0.257	0.304	0.232	0.305	0.364	0.297	0.401	0.515	0.329	0.450	0.661	0.362	0.543	0.807
		Ao (sq. in/	0.078	0.094	0.110	0.095	0.117	0.138	0.112	0.141	0.167	0.147	0.189	0.226	0.165	0.213	0.256	0.183	0.238	0.287
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crack
		D-Load (lb	805.32	1068.1	1279.2	1005.7	1359.5	1648.2	1204.9	1654.3	2012.8	1605.4	2235.4	2911.0	1800.6	2527.7	3754.0	2000.7	3074.6	4572.3
	8	**Ai** (sq. in/	0.168	0.210	0.243	0.200	0.257	0.303	0.231	0.304	0.362	0.264	0.400	0.483	0.328	0.448	0.613	0.360	0.497	0.760
		Ao (sq. in/	0.078	0.094	0.109	0.094	0.117	0.138	0.111	0.140	0.166	0.128	0.188	0.225	0.164	0.212	0.254	0.182	0.236	0.284
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crack
		D-Load (lb	807.00	1070.7	1276.6	1008.1	1363.5	1647.6	1201.9	1653.7	2008.5	1406.9	2239.0	2736.9	1801.0	2527.9	3502.2	1996.4	2820.2	4346.4

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.66" reinforcing diameter

102 inch Tables

102" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			12.5			15			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
8.5" Wall Thickness		**Ai** (sq. in/	0.297	0.384	0.529	0.351	0.570	0.761	0.459	0.756	0.993*	0.586	0.942*	1.226*	0.713	1.127*	1.458*	0.966*	1.499*	1.922*
		Ao (sq. in/	0.151	0.181	0.208	0.184	0.224	0.261	0.219	0.269	0.316	0.254	0.316	0.373	0.290	0.365	0.435	0.367	0.481	0.670
		Governin	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	rad. Tens.	rad. Tens. & c	ns. & 0.01"
	4	**D-Load** (lb	844.62	1152.3	1646.3	1036.6	1781.7	2388.1	1410.8	2372.7	3070.8	1834.1	2924.7	3697.4	2239.4	3438.4	4262.9	2994.3	4356.8	-
		Ai (sq. in/	0.295	0.368	0.466	0.348	0.507	0.698	0.402	0.690	0.930	0.523	0.878	1.162*	0.649	1.064	1.394*	0.903	1.436*	1.859*
		Ao (sq. in/	0.150	0.179	0.206	0.182	0.221	0.257	0.215	0.265	0.310	0.250	0.310	0.365	0.284	0.357	0.421	0.357	0.453	0.606
		Governin	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	0.01" crac	rad. Tens.	ens. & 0.01" c
	5	**D-Load** (lb	845.99	1109.7	1455.9	1037.9	1598.2	2240.6	1230.8	2214.3	2976.7	1653.3	2815.8	3664.8	2078.9	3379.9	4305.4	2893.5	4416.3	-
		Ai (sq. in/	0.293	0.366	0.425	0.346	0.450	0.641	0.399	0.635	0.873	0.466	0.821	1.105	0.592	1.007	1.337*	0.846	1.378*	1.802*
		Ao (sq. in/	0.149	0.178	0.204	0.181	0.219	0.255	0.213	0.262	0.307	0.247	0.306	0.360	0.281	0.351	0.414	0.350	0.444	0.549
		Governin	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens. & 0
	6	**D-Load** (lb	844.31	1111.3	1234.0	1038.6	1413.3	2079.3	1230.6	2058.8	2850.4	1470.2	2681.2	3580.7	1911.2	3277.2	4270.5	2762.8	4388.2	5532.4
		Ai (sq. in/	0.292	0.364	0.423	0.344	0.441	0.588	0.397	0.583	0.820	0.450	0.769	1.052	0.540	0.954	1.285*	0.793	1.326*	1.749*
		Ao (sq. in/	0.148	0.177	0.203	0.180	0.218	0.254	0.212	0.260	0.305	0.245	0.304	0.357	0.278	0.348	0.410	0.346	0.438	0.519
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.
	7	**D-Load** (lb	844.61	1110.2	1325.2	1036.8	1390.3	1913.6	1230.8	1896.0	2709.5	1422.8	2537.6	3469.6	1744.3	3152.8	4197.3	2618.7	4321.7	5541.5
		Ai (sq. in/	0.292	0.363	0.421	0.343	0.439	0.539	0.396	0.534	0.771	0.448	0.720	1.004	0.501	0.905	1.236*	0.744	1.277	1.700*
		Ao (sq. in/	0.148	0.177	0.203	0.179	0.217	0.252	0.211	0.259	0.303	0.243	0.302	0.354	0.276	0.345	0.406	0.343	0.434	0.513
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.	0.01" crac	0.01" crac	rad. Tens.
	8	**D-Load** (lb	847.60	1111.2	1324.2	1037.3	1389.9	1751.0	1232.6	1733.1	2565.4	1422.6	2389.1	3350.8	1614.5	3021.0	4101.2	2472.3	4230.6	5508.6

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.68" reinforcing diameter

102" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
9.5" Wall Thickness		**Ai** (sq. in/	0.217	0.270	0.313	0.264	0.340	0.402	0.311	0.418	0.607	0.409	0.824	1.021*	0.516	0.915*	1.229*	0.628	1.081*	1.436*
		Ao (sq. in/	0.115	0.121	0.141	0.126	0.157	0.185	0.154	0.195	0.231	0.213	0.273	0.326	0.243	0.314	0.376	0.274	0.356	0.427
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	diag. tens	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	0.01" crac	rad. Tens. & (	ns. & 0.01'
	4	**D-Load** (lb	634.20	855.73	1033.0	830.82	1143.3	1393.4	1024.8	1457.3	2189.7	1421.4	2982.1	3657.0	1842.0	3299.1	4323.8	2268.7	3854.1	4941.0
		Ai (sq. in/	0.215	0.269	0.311	0.262	0.337	0.397	0.309	0.407	0.537	0.404	0.680	0.984	0.453	0.846	1.160*	0.559	1.011*	1.367*
		Ao (sq. in/	0.115	0.120	0.140	0.125	0.156	0.183	0.152	0.192	0.227	0.209	0.268	0.319	0.238	0.307	0.367	0.268	0.347	0.416
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01"crack	diag. tens	flexure	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	ens. & 0.01" (
	5	**D-Load** (lb	630.31	858.68	1034.3	829.23	1142.2	1388.9	1026.0	1429.7	1951.4	1417.4	2507.6	3629.0	1868.2	3130.2	4240.7	2038.2	3724.6	4925.3
		Ai (sq. in/	0.215	0.267	0.309	0.260	0.335	0.395	0.307	0.404	0.481	0.401	0.617	0.889	0.449	0.783	1.097*	0.497	0.949	1.304*
		Ao (sq. in/	0.115	0.119	0.139	0.124	0.155	0.182	0.151	0.191	0.225	0.206	0.265	0.315	0.235	0.303	0.361	0.263	0.342	0.409
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.	flexure	0.01" crac	rad. Tens. & 0
	6	**D-Load** (lb	633.33	854.93	1032.2	825.2	1141.3	1390.9	1023.8	1428.1	1743.7	1415.7	2289.8	3339.4	1613.1	2937.1	4104.1	1808.7	3563.3	4833.0
		Ai (sq. in/	0.214	0.267	0.308	0.260	0.334	0.393	0.306	0.402	0.479	0.399	0.560	0.832	0.446	0.725	1.039	0.493	0.891	1.247*
		Ao (sq. in/	0.115	0.119	0.138	0.124	0.154	0.181	0.150	0.189	0.224	0.205	0.262	0.312	0.232	0.300	0.358	0.261	0.338	0.404
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.
	7	**D-Load** (lb	631.18	858.26	1032.5	828.39	1142.3	1389.9	1024.0	1427.4	1746.3	1414.9	2077.4	3156.6	1610.2	2738.0	3944.9	1803.9	3384.2	4708.7
		Ai (sq. in/	0.214	0.266	0.308	0.259	0.333	0.392	0.305	0.400	0.477	0.397	0.537	0.778	0.444	0.672	0.985	0.491	0.837	1.193
		Ao (sq. in/	0.115	0.118	0.138	0.123	0.153	0.180	0.150	0.189	0.223	0.203	0.261	0.310	0.231	0.298	0.355	0.258	0.335	0.400
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
	8	**D-Load** (lb	632.79	856.47	1035.8	826.47	1142.0	1391.1	1023.0	1424.7	1746.1	1412.1	1994.0	2967.6	1608.8	2543.7	3776.2	1804.1	3200.6	4563.4

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.80" reinforcing diameter

102" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
10.25" Wall Thickness		**Ai** (sq. in/	0.217	0.270	0.313	0.264	0.340	0.402	0.311	0.418	0.607	0.409	0.824*	1.021*	0.516	0.915*	1.229*	0.628	1.081*	1.436*
		Ao (sq. in/	0.115	0.121	0.141	0.126	0.157	0.185	0.154	0.195	0.231	0.213	0.273	0.326	0.243	0.314	0.376	0.274	0.356	0.427
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	rad. Tens.	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	0.01" crac	rad. Tens. & (	ns. & 0.01'
	4	**D-Load** (lb	694.00	936.63	1131.1	909.33	1526.9	1526.9	1122.1	1597.1	2404.9	1557.6	3283.8	4037.3	2020.9	3637.1	4787.2	2492.2	4258.4	5487.3
		Ai (sq. in/	0.215	0.269	0.311	0.262	0.337	0.397	0.309	0.407	0.537	0.404	0.680	0.984	0.453	0.846	1.160*	0.559	1.011*	1.367*
		Ao (sq. in/	0.115	0.120	0.140	0.125	0.156	0.183	0.152	0.192	0.227	0.209	0.268	0.319	0.238	0.307	0.367	0.268	0.347	0.416
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	diag. tens	flexure	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	ens. & 0.01" c
	5	**D-Load** (lb	689.31	939.18	1131.5	906.94	1249.8	1520.4	1122.4	1565.1	2138.7	1551.7	2751.8	3994.4	1769.8	3440.6	4676.4	2234.2	4100.8	5443.7
		Ai (sq. in/	0.215	0.267	0.309	0.260	0.335	0.395	0.307	0.404	0.481	0.401	0.617	0.889	0.449	0.783	1.097*	0.497	0.949	1.304*
		Ao (sq. in/	0.115	0.119	0.139	0.124	0.155	0.182	0.151	0.191	0.225	0.206	0.265	0.315	0.235	0.303	0.361	0.263	0.342	0.409
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.	flexure	0.01" crac	rad. Tens. & 0
	6	**D-Load** (lb	692.33	934.63	1128.7	902.14	1248.1	1521.6	1119.5	1562.4	1908.7	1548.8	2508.9	3666.9	1765.3	3222.3	4514.6	1980.0	3914.8	5326.1
		Ai (sq. in/	0.214	0.267	0.308	0.260	0.334	0.393	0.306	0.402	0.479	0.399	0.560	0.832	0.446	0.725	1.039	0.493	0.891	1.247*
		Ao (sq. in/	0.115	0.119	0.138	0.124	0.154	0.181	0.150	0.189	0.224	0.205	0.262	0.312	0.232	0.300	0.358	0.261	0.338	0.404
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.
	7	**D-Load** (lb	689.78	937.96	1128.5	905.30	1248.7	1519.8	1119.2	1560.9	1910.5	1547.2	2273.8	3461.3	1761.1	3000.1	4332.2	1973.6	3712.4	5179.0
		Ai (sq. in/	0.214	0.266	0.308	0.259	0.333	0.392	0.305	0.400	0.477	0.397	0.537	0.778	0.444	0.672	0.985	0.491	0.837	1.196
		Ao (sq. in/	0.115	0.118	0.138	0.123	0.153	0.180	0.150	0.189	0.223	0.203	0.261	0.310	0.231	0.298	0.355	0.258	0.335	0.400
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crack
	8	**D-Load** (lb	691.38	935.77	1131.8	902.98	1248.0	1520.6	1117.8	1557.4	1909.4	1543.6	2181.2	3250.8	1759.0	2784.7	4141.9	1973.0	3507.4	5024.4

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.76" reinforcing diameter

108 inch Tables

108" Pipe Diameter																				
			Fill Height (feet)																	
			5			**7.5**			**10**			**12.5**			**15**			**20**		
	fc' (kips)		**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**	**type 1**	**type 2**	**type 3**
9" Wall Thickness		**Ai** (sq. in/	0.324	0.438	0.593	0.381	0.633	0.837	0.513	0.828	1.081*	0.646	1.023*	1.325*	0.779	1.219*	1.569*	1.045*	1.609*	2.057*
		Ao (sq. in/	0.164	0.196	0.225	0.199	0.242	0.281	0.235	0.288	0.339	0.273	0.339	0.399	0.311	0.390	0.474	0.391	0.391	0.721
		Governing	flexure	0.01" crac	0.01" crac	flexure	flexure	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	rad. Tens.	rad. Tens. & 0	ns. & 0.01"
	4	**D-Load** (lb	870.48	1252.5	1451.1	1063.1	1875.9	2488.1	1496.7	2461.9	3167.0	1916.1	3010.9	3788.4	2318.2	3525.5	4352.4	3070.5	4439.4	-
		Ai (sq. in/	0.322	0.400	0.527	0.378	0.566	0.771	0.446	0.762	1.014	0.580	0.957	1.258*	0.713	1.152*	1.502*	0.979	1.543*	1.990*
		Ao (sq. in/	0.163	0.194	0.223	0.197	0.239	0.277	0.232	0.284	0.333	0.268	0.332	0.390	0.305	0.381	0.449	0.381	0.482	0.654
		Governing	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	0.01" crac	rad. Tens.	ens. & 0.01" c
	5	**D-Load** (lb	872.73	1140.6	1566.1	1065.6	1694.1	2346.8	1296.2	2318.8	3077.0	1739.7	2909.9	3763.2	2165.5	3470.8	4402.7	2974.7	4505.5	-
		Ai (sq. in/	0.320	0.398	0.466	0.376	0.506	0.710	0.432	0.702	0.954	0.520	0.897	1.198*	0.653	1.092	1.442*	0.919	1.482*	1.930*
		Ao (sq. in/	0.162	0.193	0.221	0.374	0.237	0.275	0.230	0.281	0.329	0.265	0.328	0.385	0.300	0.375	0.442	0.374	0.473	0.594
		Governing	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens. & 0
	6	**D-Load** (lb	871.78	1143.1	1376.1	1067.0	1511.6	2185.6	1260.0	2159.7	2954.5	1558.8	2778.5	3683.2	2000.2	3371.5	4372.2	2846.6	4481.4	5632.2
		Ai (sq. in/	0.319	0.396	0.459	0.374	0.477	0.655	0.429	0.646	0.899	0.485	0.841	1.143	0.597	1.037	1.387*	0.864	1.427*	1.875*
		Ao (sq. in/	0.161	0.192	0.220	0.194	0.235	0.273	0.228	0.279	0.327	0.263	0.325	0.382	0.298	0.371	0.437	0.369	0.467	0.552
		Governing	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.
	7	**D-Load** (lb	872.51	1142.7	1361.0	1065.9	1423.0	2024.7	1257.4	1994.7	2818.6	1450.4	2633.1	3577.3	1830.7	3252.0	4301.3	2706.8	4416.7	5646.3
		Ai (sq. in/	0.318	0.395	0.457	0.373	0.475	0.604	0.428	0.595	0.848	0.483	0.790	1.092	0.546	0.985	1.336	0.812	1.376*	1.823*
		Ao (sq. in/	0.192	0.192	0.219	0.194	0.234	0.272	0.227	0.277	0.325	0.261	0.323	0.379	0.295	0.369	0.434	0.366	0.462	0.546
		Governing	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	0.01" crac	rad. Tens.	rad. Tens.
	8	**D-Load** (lb	872.14	1144.1	1360.7	1066.7	1423.1	1865.7	1259.6	1835.1	2678.1	1450.9	2487.9	3459.1	1667.8	3120.5	4209.1	2560.3	4302.2	5614.6

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.72" reinforcing diameter

108" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
10" Wall Thickness	4	**Ai** (sq. in/	0.303	0.375	0.461	0.354	0.495	0.681	0.406	0.671	0.902*	0.622	1.023*	1.342*	0.786	1.199*	1.563*	1.007	1.375*	1.783*
		Ao (sq. in/	0.147	0.176	0.202	0.177	0.215	0.250	0.207	0.254	0.299	0.270	0.340	0.403	0.303	0.384	0.457	0.337	0.430	0.516
		Governin	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	diag. tens	rad. Tens.	rad. Tens.	diag. tens	rad. Tens. & (	ns. & 0.01"
		D-Load (lb	907.20	1185.6	1511.4	1104.6	1638.1	2311.3	1303.9	2276.0	3067.1	2101.5	3460.9	4431.2	2676.3	4008.4	5046.2	3409.6	4526.0	5611.9
	5	**Ai** (sq. in/	0.302	0.372	0.430	0.351	0.446	0.608	0.401	0.598	0.829	0.549	0.971	1.270*	0.669	1.126*	1.490*	0.788	1.302*	1.710*
		Ao (sq. in/	0.146	0.174	0.200	0.175	0.212	0.247	0.204	0.251	0.295	0.265	0.333	0.394	0.297	0.376	0.446	0.329	0.419	0.498
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	0.01" crac	diag. tens	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	0.01" crac	rad. Tens.	ens. & 0.01" c
		D-Load (lb	911.28	1186.2	1411.0	1104.2	1472.5	2083.6	1299.0	2046.5	2883.1	1863.5	3376.4	4362.9	2308.2	3896.6	5044.1	2737.8	4464.4	5687.7
	6	**Ai** (sq. in/	0.300	0.370	0.428	0.350	0.443	0.542	0.399	0.532	0.763	0.500	0.884	1.204*	0.603	1.060	1.424*	0.722	1.236*	1.645*
		Ao (sq. in/	0.145	0.174	0.199	0.174	0.211	0.245	0.203	0.249	0.292	0.262	0.329	0.389	0.293	0.370	0.439	0.324	0.412	0.490
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.	0.01" crac	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens. & 0
		D-Load (lb	908.61	1186.4	1414.0	1107.4	1472.5	1854.4	1300.5	1816.1	2682.5	1693.2	3121.9	4236.3	2086.3	3743.3	4963.0	2531.4	4344.0	5660.74
	7	**Ai** (sq. in/	0.300	0.369	0.426	0.348	0.441	0.517	0.398	0.514	0.702	0.497	0.824	1.143	0.547	1.000	1.363*	0.662	1.176*	1.584*
		Ao (sq. in/	0.145	0.173	0.198	0.173	0.210	0.244	0.202	0.247	0.290	0.260	0.326	0.385	0.290	0.366	0.434	0.32	0.407	0.484
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.
		D-Load (lb	912.36	1188.1	1413.7	1104.5	1472.8	1769.7	1303.2	1758.1	2477.9	1691.9	2933.7	4083.9	1886.0	3575.7	4842.7	2326.5	4199.5	5576.8
	8	**Ai** (sq. in/	0.299	0.368	0.424	0.347	0.439	0.515	0.396	0.512	0.646	0.495	0.767	1.087	0.545	0.943	1.307*	0.605	1.119	1.527*
		Ao (sq. in/	0.144	0.172	0.198	0.172	0.209	0.243	0.201	0.246	0.289	0.258	0.324	0.383	0.288	0.363	0.431	0.318	0.403	0.479
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.	0.01" crac	0.01" crac	rad. Tens.
		D-Load (lb	911.13	1188.4	1411.5	1104.3	1470.9	1770.3	1300.2	1758.5	2278.8	1691.8	2740.3	3923.5	1887.5	3397.7	4706.0	2120.6	4038.8	5463.7

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.80" reinforcing diameter

108" Pipe Diameter

			Fill Height (feet)																	
			5			7.5			10			15			17.5			20		
	fc' (kips)		type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3	type 1	type 2	type 3
10.75" Wall Thickness	4	**Ai** (sq. in/	0.291	0.358	0.413	0.338	0.428	0.579	0.385	0.568	0.933	0.519	0.896*	1.196*	0.675	1.060*	1.402*	0.892	1.224*	1.608*
		Ao (sq. in/	0.137	0.164	0.188	0.163	0.198	0.231	0.190	0.234	0.275	0.246	0.310	0.386	0.275	0.349	0.416	0.305	0.390	0.466
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	diag. tens	0.01" crac	rad. Tens.	rad. Tens.	diag. tens	rad. Tens.	rad. Tens.	diag. tens	rad. Tens. & (	ns. & 0.01'
		D-Load (lb	937.06	1220.9	1450.6	1136.6	1512.7	2125.5	1334.0	2081.6	3474.4	1884.7	3339.1	4398.0	2503.4	3928.7	5075.0	3324.4	4492.4	5711.4
	5	**Ai** (sq. in/	0.290	0.356	0.410	0.336	0.424	0.501	0.382	0.493	0.707	0.476	0.851	1.119*	0.552	0.983*	1.325*	0.663	1.147*	1.531*
		Ao (sq. in/	0.136	0.162	0.186	0.161	0.196	0.229	0.188	0.231	0.272	0.242	0.304	0.361	0.269	0.342	0.407	0.298	0.381	0.454
		Governin	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	flexure	0.01" crac	flexure	diag. tens	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens.	0.01" crac	rad. Tens.	ens. & 0.01" (
		D-Load (lb	940.14	1223.6	1452.8	1138.1	1511.9	1837.9	1334.3	1800.5	2671.2	1729.8	3236.4	4244.6	2044.3	3740.1	4981.3	2495.2	4346.7	5684.9
	6	**Ai** (sq. in/	0.288	0.354	0.408	0.334	0.422	0.493	0.380	0.490	0.636	0.473	0.748	1.048*	0.520	0.912	1.254*	0.592	1.076*	1.460*
		Ao (sq. in/	0.135	0.161	0.185	0.160	0.195	0.227	0.186	0.229	0.270	0.239	0.301	0.357	0.266	0.337	0.402	0.294	0.375	0.447
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	flexure	0.01" crac	rad. Tens.	flexure	0.01" crac	rad. Tens.	0.01" crac	rad. Tens.	rad. Tens. & 0
		D-Load (lb	936.33	1222.4	1454.1	1136.0	1513.9	1814.7	1334.2	1802.1	2410.1	1730.3	2866.5	4047.4	1928.2	3519.6	4823.4	2228.4	4154.5	5571.3
	7	**Ai** (sq. in/	0.288	0.353	0.406	0.333	0.420	0.490	0.378	0.488	0.576	0.470	0.683	0.984	0.517	0.848	1.190*	0.564	1.012	1.396*
		Ao (sq. in/	0.135	0.161	0.185	0.160	0.194	0.226	0.185	0.228	0.268	0.237	0.298	0.354	0.264	0.334	0.398	0.291	0.371	0.442
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	rad. Tens.	flexure	0.01" crac	rad. Tens.
		D-Load (lb	939.78	1223.2	1452.4	1136.3	1512.7	1812.1	1331.6	1803.6	2175.8	1726.9	2622.1	3841.1	1926.8	3297.0	4644.7	2125.3	3951.8	5423.7
	8	**Ai** (sq. in/	0.287	0.352	0.405	0.332	0.419	0.489	0.377	0.486	0.574	0.469	0.623	0.924	0.515	0.787	1.151	0.561	0.952	1.336*
		Ao (sq. in/	0.134	0.160	0.184	0.159	0.193	0.225	0.184	0.227	0.267	0.236	0.296	0.351	0.262	0.332	0.395	0.288	0.368	0.438
		Governin	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	flexure	0.01" crac	0.01" crac	flexure	0.01" crac	diag. tens	flexure	0.01" crac	rad. Tens.
		D-Load (lb	937.97	1222.8	1453.3	1135.4	1513.9	1815.3	1157.3	1802.5	2177.7	1729.5	2384.9	3629.2	1926.6	3068.8	4536.1	2122.6	3742.5	5255.5

* Stirrups Required for shear

D-Loads based on Ultimate Flexure

All calculations based on 4" maximum spacing and 0.86" reinforcing diameter

APPENDIX B

36 inch design comparison with direct design and power formula

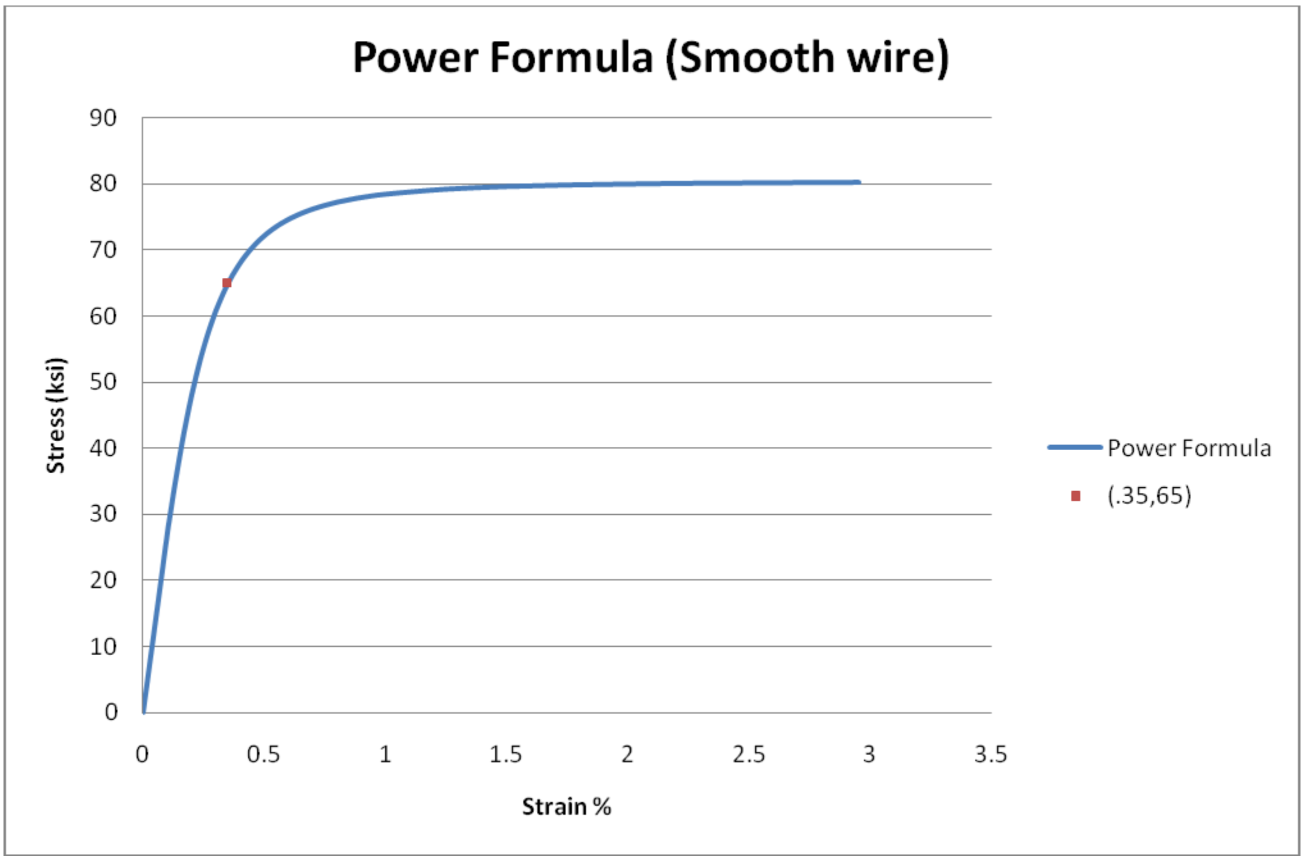
Developed Power Formulas

A power formula was developed for grade 65 smooth wires. This formula passes through the point 65 ksi for yield as specified in ASTM A 82 at 0.0035 strain. The 0.0035 point is specified for high strength wire with 0.005 specified for grade 65 wires. The 0.0035 point better matches the data. The power curve follows the average Es value from the test data, passes through the (0.0035, 65) point and continues following the lower bound curve of the test results. The power formula equation is:

$$f_s = E_s \varepsilon_s \left[Q + \frac{1-Q}{\left[1+((E_s \varepsilon_s / K f_{py})^R\right]^{1/R}} \right] \le f_{pu}$$

The values and constants used in the power formula were determined to be:

fpu	fpy	Q	Es	R	K
80	65	0	28310.54	2.2680	1.23847



Comparison of Pipe Design Methods

Three methods of pipe design were compared for a 33 inch single cage reinforced concrete pipe. The following pipe and installation criteria were used.

- Concrete strength (f'c) 4 ksi
- Steel (fy) 65 ksi
- Concrete weight 150 pcf
- B wall thickness
- Type III installation
- Heger Pressure Distribution
- Soil weight 120 pcf

The three methods compared were the Indirect Design method, the Direct Design method, and the Direct Design method using strain compatibility with the developed power formula. A class three pipe (As= 0.2 in^2) was assumed for the Indirect Design method. Maximum fill heights were compared for each of the three methods for the same area of reinforcement. The results are summarized below.

	Direct Design	Indirect Design	Direct Design with Strain Compatibility
As (in^2)	0.2	0.2	0.2
Max fill height (ft)	10.6	14	15.6

The Direct design method gives a lower allowable fill height for the same amount of steel compared to the Indirect Design method. Using strain compatibility, however, produces a fill height greater than the height given by the indirect design method. Further comparison of the Direct Design method and the Direct Design method using strain compatibility is shown below.

	PIPECAR	Strain Compatibility	% Increase
As (in^2)	Mu (ft-kips/ft)	ϕMn (ft-kips/ft)	
0.07	0.87	1.10	26.06
0.08	1.04	1.30	24.79
0.10	1.21	1.60	32.13
0.11	1.38	1.80	30.43
0.13	1.55	2.00	29.10
0.15	1.72	2.30	33.85
0.17	1.89	2.60	37.75
0.19	2.06	2.80	36.14
0.20	2.16	3.00	39.01

Using the Direct Design method with strain compatibility allows for a higher moment capacity than the Direct Design method for equal areas of reinforcement. At 0.2 in^2 of reinforcement, a 39% increase in capacity is shown when strain compatibility is used.

APPENDIX C

Cylinder test results from the experimental installation

Pour Date	Mark Number	Piece Length	Ambient Temp	Concrete Temp	1 Day Avg.	3 Day Avg.	7 Day Avg.	28 Day Avg.
4/27/07	A1	12' 0"	59	66	x	7966	8730	10765
4/27/07	Bell Stub	4' 0"	59	66	x	7966	8730	10765
4/30/07	A2	12' 0"	87	79	5498	x	8570	10238
5/1/07	B1	12' 0"	80	76	4636	x	8204	10520
5/2/07	B2	12' 0"	74	74	4851	x	8856	10556
5/3/07	C2	12' 0"	64	70	5044	x	8513	9966
5/4/07	D1	12' 0"	71	72	x	6821	8008	9954
5/7/07	C1	12' 0"	69	74	4460	x	8581	10660
5/8/07	D2	12' 0"	76	74	4929	x	7589	9302
5/9/07	D3	12' 0"	76	75	5984	x	8484	9839
7/13/07	Spigot Stub	6' 0"	87	87	x	8906	8912	9457
								10184

Design A	
Inner Cage	
Required Steel Area	0.174
Wire Size	7 Gauge (.177)
Wire Spacing	1.6875"
Actual Steel Area	0.175
Outer Cage	
Required Steel Area	0.081
Wire Size	7 Gauge (.177)
Wire Spacing	3.625"
Actual Steel Area	0.081

Design B	
Inner Cage	
Required Steel Area	0.257
Wire Size	2 Gauge (.262)
Wire Spacing	2.5"
Actual Steel Area	0.259
Outer Cage	
Required Steel Area	0.120
Wire Size	7 Gauge (.177)
Wire Spacing	2 .4375"
Actual Steel Area	0.121

Design C	
Inner Cage	
Required Steel Area	0.341
Wire Size	2/0 (.331)
Wire Spacing	3.0"
Actual Steel Area	0.344
Outer Cage	
Required Steel Area	0.161
Wire Size	5 gauge (.207)
Wire Spacing	2.5"
Actual Steel Area	0.161

Design D	
Inner Cage	
Required Steel Area	0.341
Wire Size	2/0 (.331)
Wire Spacing	3.0"
Actual Steel Area	0.344
Outer Cage	
Required Steel Area	0.161
Wire Size	5 gauge (.207)
Wire Spacing	2.5"
Actual Steel Area	0.161

APPENDIX D

Compaction Test Results

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HWS Consulting Group
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Lincoln, NE 68501-0358
402.479.2200 • Fax: 402.479.2276
www.hws.com

February 5, 2008

Mr. Mike Mandery
Lincoln Wastewater System
2400 Theresa Street
Lincoln, Nebraska 68521

REFERENCE: Intermittent Compaction Testing
Soil Compaction Summary Report Number1
Pipe Research Project Number 502460
Bluffs Road Landfill
Lincoln, Nebraska

Dear Mr. Mandery:

From December 6, 2007 through December 10, 2007, City Wastewater System requested that HWS Consulting Group Inc. (HWS) provide intermittent observation and testing services at the referenced site. By HWS' definition, "intermittent observation and testing services" are performed at the request of the Client and/or the Client's representative(s), at a frequency that is less than that which is required to test every lift of fill or backfill. These services consisted of determining the in-place moisture content and dry density of utility backfill.

The backfill material consisted of a Glacial Till sandy clay. The moisture-density relations of a representative sample of the sandy clay was determined in accordance with ASTM D 698-00a, Procedure A, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft^3) (600 kN-m/m^3) in our laboratory. The moisture-density relation curve number 5465 is presented in Figure 1.

In-place moisture content and density determinations were made during placement of the backfill materials with a nuclear moisture-density meter in accordance with ASTM D 3017-96, Standard Test Method for Moisture Content of Soil and Rock in Place by Nuclear Methods (Shallow Depth), and ASTM D 2922-96 Standard Test Method for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth). The test results are shown in the enclosed Soil Compaction Summary Report Number 1, Test Numbers 1 through 14. Each test represents the condition of the backfill at the point tested to the depth shown in Report Number 1. The test results were provided to a City of Lincoln representative as they became available. It should be noted that all of the tests met the specified minimum moisture content and degree of compaction.

These test results may be useful to the Contractor in determining whether the backfill soils are in conformance with the requirements of the Contract Documents and may be used by the Architect-Engineer in conjunction with other available information to determine, on the Owner's behalf, if the backfill is acceptable under the Contract Documents.

This report shall not be reproduced, except in full, without the written approval of HWS Consulting Group Inc.

Please contact HWS if any questions arise concerning this report or if HWS can be of further service.

Sincerely,

HWS CONSULTING GROUP INC.

Raymond Delka Manager
Materials Laboratory

RD/red

Geodata\Project#\PipeReseachProjBackfill_07

Orig. & 1 pc.: City Wastewater System, Mr. Mike Mandery
Enclosures

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FIELD DENSITY TEST - TROXLER NUCLEAR METHOD

ASTM D-2922 D-3017
Test data was obtained and computed using the methods and procedures specified in the latest ASTM method.

Project No.:	52-84-8546.0004	Soil Types:	Glacial Till-Sandy Clay
Client:	City of Lincoln Wastewater	Moisture Spec.:	Grass area workable, and within 10' of manhole Optimum - 3% to +6%
Project Name:	Pipe Research Project at Bluffs Road Landfill	Compaction Specs.:	Grass area 88% and within 10' of manhole 95% of maximum dry density
HWS Project Manager:	Ray Delka		
General Contractor:	Pavers LLC	Description of Work:	Backfill of Utility Trench
Grading Contractor:	Pavers LLC	Test Equipment I.D.:	

Test No.	Date	Location & Description	Layer Thickness Tested (in.)	M/D Curve Number	Moisture (%) Opt.	Moisture (%) Spec.	Moisture (%) Test	Dry Density (pcf) Max.	Dry Density (pcf) Test	Compaction Spec. Min.	Compaction %	Pass/Fail
1	12/6/2007 KRD	Station 0 + 00; 5' Left of Centerline 9' Below Finished Subgrade Elevation	12	5465	20.0	Workable	17.7	102.0	101.3	88+	99.3	Pass
2	12/6/2007 KRD	Station 0 + 40; on Centerline 19' Below Finished Subgrade Elevation	12	5465	20.0	Workable	15.7	102.0	95.2	88+	93.3	Pass
3	12/6/2007 KRD	Station 1 + 00, 4' Left of Centerline 22' Below Finished Subgrade Elevation	12	5465	20.0	Workable	18.7	102.0	101.0	88+	99.0	Pass
4	12/7/2007 NJ	Station 0 + 75; on Centerline 15' Below Finished Subgrade Elevation	12	5465	20.0	Workable	18.9	102.0	99.0	88+	97.1	Pass
5	12/7/2007 NJ	Station 0 + 25; 8.5' Left of Centerline 6' Below Finished Subgrade Elevation	12	5465	20.0	Workable	18.9	102.0	102.6	88+	100.6	Pass
6	12/7/2007 NJ	Station 0 + 26; 15' Right of Centerline 3.5' Below Finished Subgrade Elevation	12	5465	20.0	Workable	18.7	102.0	105.2	88+	103.1	Pass
7	12/7/2007 NJ	Station 0 + 44; on Centerline 8' Below Finished Subgrade Elevation	12	5465	20.0	Workable	18.9	102.0	103.7	88+	101.7	Pass
8	12/8/2007 NJ	Station 0 + 51; 19' Right of Centerline 7' Below Finished Subgrade Elevation	12	5465	20.0	Workable	18.0	102.0	102.9	88+	100.9	Pass
9	12/8/2007 NJ	Station 0 + 72; 22' Right of Centerline 8' Below Finished Subgrade Elevation	12	5465	20.0	Workable	19.0	102.0	104.3	88+	102.3	Pass
10	12/8/2007 NJ	Station 1 + 20; on Centerline 11' Below Finished Subgrade Elevation	12	5465	20.0	Workable	18.5	102.0	96.8	88+	94.9	Pass

*AASHTO DESIGNATION:
*ASTM DESIGNATION: D-698; Procedure "A"

Tests Performed By: K.Delka & N. Jones
Test Data Reviewed By: R. Delka

Report Number: 1
Sheet: 3 of 5

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FIELD DENSITY TEST - TROXLER NUCLEAR METHOD

ASTM D-2922 D-3017

Test data was obtained and computed using the methods and procedures specified in the latest ASTM method.

Project No.:	52-84-8546.0004	Soil Types:	Glacial Till-Sandy Clay
Client:	City of Lincoln Wastewater	Moisture Spec.:	Grass area workable, and within 10' of manhole Optimum - 3% to +6%
Project Name:	Pipe Research Project at Bluffs Road Landfill	Compaction Specs.:	Grass area 88% and within 10' of manhole 95% of maximum dry density
HWS Project Manager:	Ray Delka		
General Contractor:	Pavers LLC	Description of Work:	Backfill of Utility Trench
Grading Contractor:	Pavers LLC	Test Equipment I.D.:	

Test No.	Date	Location & Description	Layer Thickness Tested (in.)	M/D Curve Number	Moisture (%) Opt.	Moisture (%) Spec.	Moisture (%) Test	Dry Density (pcf) Max.	Dry Density (pcf) Test	Compaction Spec. Min.	Compaction %	Pass/Fail
11	12/10/2007 NJ	Station 0 + 61; 5' Left of Centerline At Finished Subgrade Elevation	12	5465	20.0	Workable	18.1	102.0	98.5	88+	96.6	Pass
12	12/10/2007 NJ	Station 0 + 94, 1' Left of Centerline At Finished Subgrade Elevation	12	5465	20.0	Workable	18.7	102.0	96.0	88+	94.1	Pass
13	12/10/2007 NJ	Station 0 + 80, 3' Right of Centerline At Finished Subgrade Elevation	12	5465	20.0	Workable	20.5	102.0	97.1	88+	95.2	Pass
14	12/10/2007 NJ	Station 1 + 20; on Centerline 1' Below Finished Subgrade Elevation	12	5465	20.0	Workable	18.6	102.0	107.6	88+	105.5	Pass

*AASHTO DESIGNATION:
*ASTM DESIGNATION: D-698; Procedure "A"

Tests Performed By: N. Jones
Test Data Reviewed By: R. Delka

Report Number: 1
Sheet: 4 of 5

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Soil Compaction Curve
STANDARD COMPACTIVE EFFORT
ASTM Designation: D 698 - 91

Job No.: 52-84-8546 Lab No. 23357 Curve No. 5465 Date 8-Oct-07

Project: City of Lincoln- Waste Water Pipe Research Project

Location: Hwy 77 and Bluff Road

Material: Glacial Till Sandy Clay

Classification	
Liquid Limit	
Plastic Limit	
Plasticity Index	
Specific Gravity	Assumed 2.70

Total Percent Retained On:

No. 4 Sieve	
3/8-in. Sieve	
3/4-in. Sieve	
Oversize Fraction	%

Standard Maximum Dry Unit Weight	102.0 lb/ft^3
Standard Optimum Water Content	20.0 %
As Received Water Content	%
Preparation Method:	Dry
Procedure Used: Mechanical Rammer	A

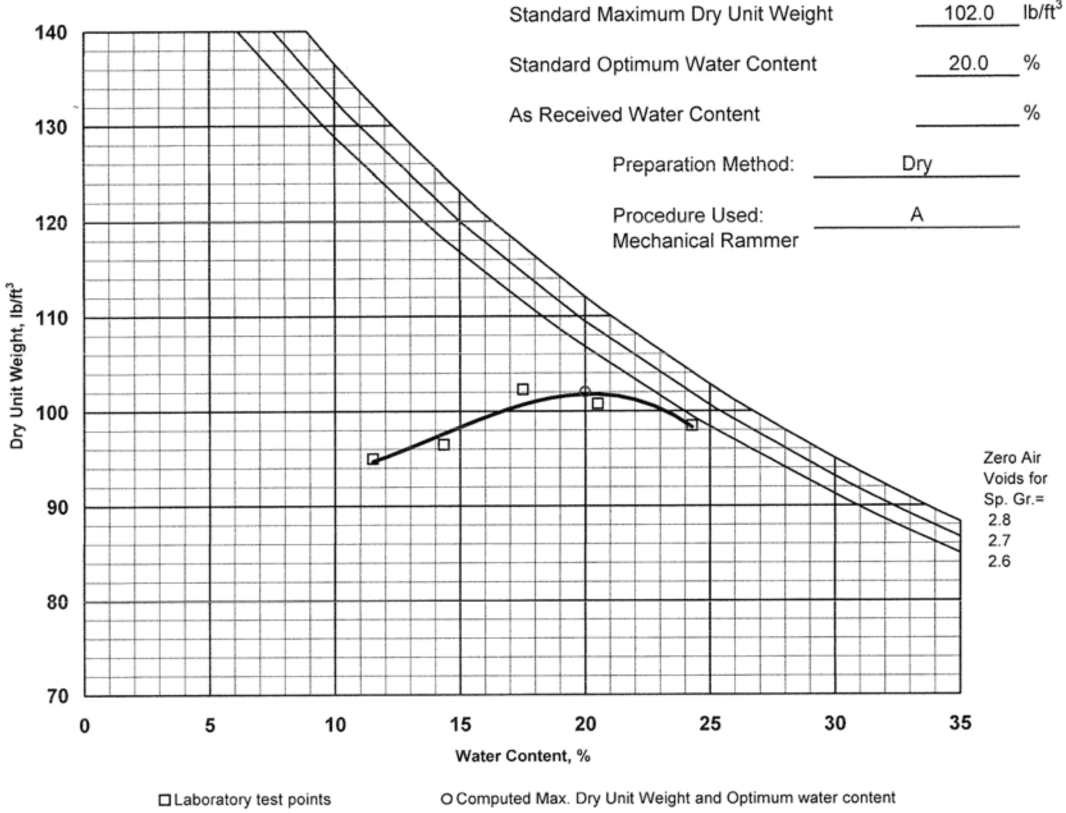


Figure 1

APPENDIX E

Responses to NDOR TAC comments

First of all, we would like to thank NDOR TAC for their thorough review of the draft report and their organized and valuable comments and helpful corrections. This document provides responses to each of the items listed below, with references to changes made in the new version of the final report.

-Drs. Erdogmus & Tadros

1. (Executive Summary) Perhaps more discussion is necessary regarding the TEB test. NDOR uses this test for quality control purposes, and is not needed by our Direct Design approach.

This comment of NDOR is justified, so a clarification is added to the executive summary

May we also suggest making this point really clear in the NDOR specs with a statement similar to:

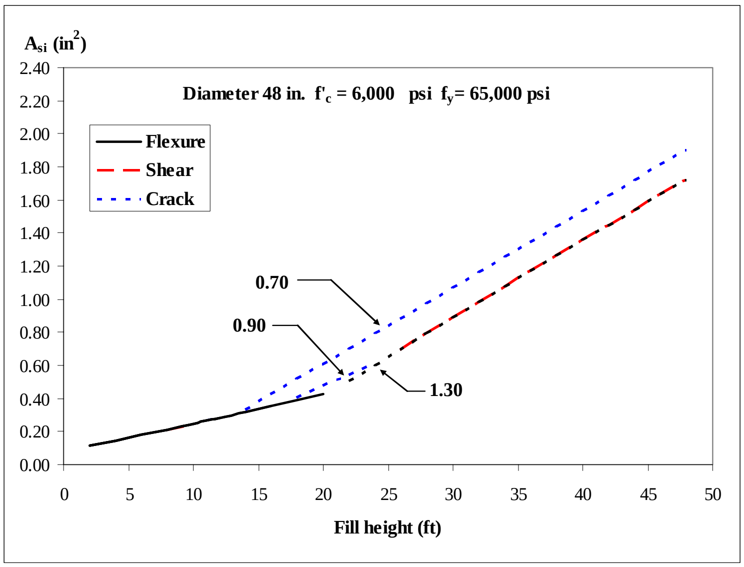
"PIPE designed according to the NDOR specs do NOT need to be subjected to TEB testing. Quality control checks according to ASTM C1417 are required instead."

2. (Page 2) Elimination of crack control (as recommended by the author) from DD (or ID design) needs more attention, especially since for over 75 years it has been an industry standard, and employed as a service load design criterion. Even though Professor Schlick (of Iowa State University) originally developed the 0.01" crack width as a way of establishing comparative strength of RCP in TEB tests, the empirical tests and observations were related to in situ conditions. It came to be used as a physical indicator of transitional load stress transfer within the cracked RCP wall section at points of high moment and shear forces. It should be noted that RCP is designed with 1 inch of concrete cover over the reinforcing steel, however, ASTM C 76 (AASHTO M170) specifications allow a manufacturing tolerance cover limit as low as ½ inch over the reinforcing steel. It could be argued that this would make the 0.01" service load crack criteria even more significant as the concrete cover is reduced by 50% in actual service conditions (indicating a need for a less than 0.01" criteria). By contrast, perhaps a larger (than 0.01") crack criteria would be appropriate if the actual cover is in excess of 1 inch.

We believe that NDOR TAC may have misunderstood *the extent*, *the context, and the rationale* of our recommendation regarding crack control. While it is the authors' opinion that this limit state can be ignored, especially if the pipe is lined, and it is "experimented with" in the installation design. However, it is not used for the NDOR tables or the suggested procedures.

Rationale behind the recommendation regarding the elimination of crack control:

1) Based on collective expertise on strength design of concrete structures, 0.01inch crack width is not enough to cause structural failure. Most of the time, such a crack shows that the reinforcement will be engaged, as it is expected for any reinforced concrete element. Other concrete elements, such as bridge girders, are not subjected to such a strict criterion. 2) We do understand that pipe is subject to different scenarios than structural elements in bridges or buildings: exposed to earth, at times carrying hazardous fluids, etc… For this reason, however, most pipe is lined. If pipe is lined, there is no chance for water penetration through the wall and cause corrosion. Thus, if pipe is lined; the stringent 0.01in crack control criterion *can* be eliminated, *if* the owners *wish* to do so, in order to make the pipe design *more economical*. 3) Crack control only controls in a very small window of fill heights (see graph in ASCE 15-98, page 24, Figure C-1). According our dimensioned re-creation of a similar graph (see below), this window corresponds to relatively deeper fill heights (20-25 ft), which –we were told- is not usually necessary for NDOR designs –yet are more commonly used by CoL sanitary sewer pipe, which are always required to be lined.



3. (page 4 Introduction) The author states that "the DD method do not have any accompanying quality control test or ASTM Standard". Suggestion, see ASTM C 1417 and applicable sections of ASTM C 76 as well.

-DONE> This omission was caught and corrected before the presentation at NDOR on August 25, 2009. The report is revised accordingly as well.

4. (Page 4) Author states that DD has not been fully studied for smaller pipe (under 36"). Suggestion, see University of Massachusetts study funded by NSF, FHWA, and eleven other contributing states. Also, studies conducted in conjunction with the Canadian Research Council, as well as research conducted at Ohio University to name a few.

Pipe smaller than 36 inch diameter is single cage and thus behaves differently than the double-cage larger pipe. We carried out literature review and also held meetings with the technical experts at the ACPA, who are also current with technical publications relating to the concrete pipe research. The problem we are referring to is that the difference in answers (allowed fill heights for the same reinforcement area, for example) between indirect design and direct design is larger for smaller diameter pipe. Please see the appendix, where a comparison is made for a 33 inch single cage reinforced concrete pipe. DD can approach or exceed the capacity suggested by ID, which was proven by experimental results, but only if necessary adjustments are made, recognizing the actual behavior of the materials, such as the power formula suggested in the attached document.

5. (Bottom p. 6) Typo error? Should read "not relevant to DD method"?

-DONE> Yes, this was a typo and is now corrected. Thanks.

6. (P 14) An excellent report by Erdogmus is cited, however the conclusions of that report highly favors the DD approach, while the current research under review takes conflicting steps backward trying to validate the ID Design (which has proven inadequacies with regard to limit state design components such as excessive wall compression failure, radial and diagonal tension (which are not even addressed in the ID method). Further, the subjectively developed (and perhaps overstated) bedding factors in the ID approach results in inherent reduction in safety factors, especially when using the ID Design method with the incorporation of the SIDD Direct Designed installation conditions, (which were more specifically developed for use with DD).

-The reviewers may have misunderstood our position in this respect. We still favor the DD approach, and recommend it for all designs, EXCEPT small diameter pipe <u>at the current state</u> of DD theory (as discussed in item 4 above). The only other related comment we make is that, if the hired consultants or other designers insist on using ID related phenomena such as bedding factors, class types, TEB testing, ASTM C76; it may be a better, cleaner, more appropriate design, if ID is used all the way through. Otherwise, DD is the rational method to use.

7. (p. 16 Summary) Author states that the 0.01" crack criteria is perhaps inappropriate for ID design as well as DD, however, while the ID design is recommended by the author (for 36" and smaller diameters), it should be noted that even the most recent documents for ID methodology still employ applied factors of safety using the long accepted 0.01" crack load from the TEB test. This crack criteria is included in current AASHTO as well as ACPA design publications, which include modifications to incorporate the "borrowed" SIDD standard installations. As a result of completely dropping the 0.01" crack criteria, modifications to the standards would be necessary, including proper application of safety factors, appropriately addressed in subsequent standards of practice.

-Please refer to crack control discussion above in item 2.
Also, it should be noted that the statement on page 16 is not a design suggestion; it is a an opinion based on engineering assessments. It is true that, if TEB with 0.01in crack control is eliminated, the ID needs to be adjusted to accommodate this. However, we do not encourage or suggest this. Because we DO promote DD design to be improved, and ID to be eventually fully abandoned. Ideally: ID would be fully abandoned. DD would be used by everyone, after it is improved with further work in a national study prompted by ASTM, ASCE, and/or FHWA, such that the true behavior and true strengths of the materials are taken into account, appropriate ASTM standards (as user friendly as ASTM C76) are developed, and either new testing method is developed, or ASTM C1417 is more vigorously promoted.

In short, we are aware that the related parties are not ready for the elimination of either TEB or 0.01in crack control, thus we did not suggest the former, or utilize the latter in our final tables.

8. (Bot. p. 16) Implications are that while NDOR uses DD, "additional limitations" in the pipe design are imposed by adherence to ASTM C 76 quality control standards. NDOR does not agree, nor apply limitations to our pipe designs by employing the TEB test. As a matter of fact, for over 40 years, the TEB test (especially for pipe larger than 36" diameter) is not even conducted or required unless the test is requested by the manufacturer.

>We agree and understand that NDOR's additional limitations come from adherence to ASTM C76. It is NOT from utilizing TEB testing. A further clarification is added to the report.

9. (Bot. p. 18, #2) The Standard Installation referred to requires a minimum, not "maximum" compaction of 95% as indicated.

> DONE. Typo corrected. Thank you.

10. (Middle p. 22) Designers do not "ignore outer steel reinforcement; it is one of the input variables in the SIDD program computations.

>> This is true. However, when ASTM C76 is consulted AFTER the use of DD for design, the outer reinforcement design defaults back to 60% of inner cage reinforcement.

11. (Top of p. 23) The statement about concrete strength implies that the "standard mix" for all RCP manufacturers is an 8000 psi mix, which is not accurate. Also, the statement in the same paragraph with regard to removing the 0.01" crack control, does not cause flexure to govern all designs in general (perhaps only specific ones in this study, is the implication).

>Please note that both of these statements are under the section titled “Experimental Full Scale RCP installation. Thus the discussion is for the specific case of the installation pipe:
-The manufacturer’s mixture (and was their standard mixture) was 8000psi in this case for all segments
- and for all segments where crack control limit state was ignored, flexure governed.

These neither are general statements for how all pipe design should be nor are recommendations utilized in NDOR tables (i.e. multiple concrete strength is allowed for the suggested tables, and crack control is obeyed).

12. (Tables 12 & 13, pp. 25-26) Percentage differences between methods shown in these tables are of questionable import, especially since really only two methods are under consideration, ID and DD. Disregarding crack control may lead to overstated conclusions, especially when comparing “special designs” with industry standards installed using questionable installation assumptions.

> Our design in the experimental design is daring, and it is testing a set of hypotheses: Can we use DD without crack control limit AND for higher fill loads than they are designed for and still have satisfactory results? And the answer seems to yield that, yes, there is more reserve capacity that can be used, and DD can be further improved if more studies are undertaken in the future.

>The issue of “questionable installation assumptions” is addressed below in Item 13. But it should be noted that the comparison tables mentioned compare all methods with the same installation assumption. Numbers in this table, therefore, are not affected by the actual compaction of the final product.

13. (Bot. P. 33) Author states that pressure cells were used to confirm the bedding type assumed (Type 3 Installation, Table 9, p23), however, goes on to qualify the pressure cell readings as only “estimates”. Argument is presented for a Type 3 Design Installation solely based upon the questionable pressure cell readings. We assert that the most compelling evidence for the design assumption would involve examination of the compaction and soil stiffness data which are not included anywhere in this study. Even when forced to use the admittedly variable pressure “estimates” provided; in our opinion, there is a better overall correlation between the actual vs. theoretical pressure readings favoring the Type 1 Installation, not the Type 3 Installation as assumed in this study.

>DONE. The numbers were double were checked and corrected before the August 25 meeting. As we also presented during that meeting, NDOR TAC is correct in that the actual installation is somewhere between Type 1 and 2, and not Type 3. This actually is a good case, where “more support” is gathered then was asked from the contractors. The contractors, unfortunately, probably aspired to do a good job for “the research

installation” and over-compacted the soil. The only negative outcome of this situation is that our pipe did not experience as high stresses as we hoped. This is reflected in the revised conclusions for the experimental installation.

The compaction data is amended to the final report and correct tables as shown at the August 25 meeting are used in the revised report.

Final Observations and Comments:

1. Specific data was not presented with regard to the soil testing; including supporting soil stiffness, or compaction results, before, during or after installation.

>Reports attached to the final report.

2. Actual material test results for the installed pipes, including results from cylinder tests, core tests, and steel tests (including final product wire placement) were not included in the report for review.

> Reports attached to the final report.

3. Computations or discussion was absent regarding the effect of load transfer between adjacent pipe sections joined using the R4 joints. Sections are not unique unto themselves, and therefore, in variable loading conditions, assumptions and conclusions drawn require further explanation and documentation.

> This was out of the scope of the project. By the CoL we were asked this question: Is regular R4 joint satisfactory or the additional reinforcement (as they require) necessary. We utilized regular R4 joints, so that if they were cracked, crushed, displaced, dislocated, etc… we would conclude that modifications would be needed to the joint. Since we did not observe such failure, we concluded that regular R4 joints perform satisfactorily.

4. Factors of safety can be greatly overstated if initial assumptions (especially with regard to Installation Type) are assumed and not conclusively proven. It is NDOR’s opinion (based upon information presented and practical experience) that the installed pipes in this study are Installation Type 1, not Installation Type 3 as presented.

>Correct. See Item 13 above.