THE EFFECT OF HIGH DENSITY POLYETHYLENE (HDPE) PIPE PROFILE GEOMETRY ON ITS STRUCTURAL PERFORMANCE

A thesis presented to
the faculty of
the College of Engineering and Technology of Ohio University

In partial fulfillment
of the requirements of the degree
Master of Science

Nadim Ayche
August 2005
This thesis entitled
THE EFFECT OF HIGH DENSITY POLYETHYLENE (HDPE) PIPE PROFILE GEOMETRY ON ITS STRUCTURAL PERFORMANCE

BY
NADIM AYCHE

has been approved for
the Department of Civil Engineering
and the Russ College of Engineering and Technology by

Shad Sargand
Russ Professor of Civil Engineering

Dennis Irwin
Dean, Russ College of Engineering and Technology
AYCHE, NADIM S. M.S. August 2005. Civil Engineering

The Effect of High Density Polyethylene (HDPE) Pipe Profile Geometry on its Structural Performance (121 pp.)

Director of Thesis: Shad Sargand

To investigate the role of profile’s geometry of HDPE pipes on its structural performance, a series of simulations were conducted. These simulations were done using Algor, a finite element analysis software. It was important to find out which profiles are the best among the series, but the study also investigated the role of the cover between corrugations and the role of web of corrugation. Profiles were classified according to the result of maximum principal tension and compression, the positions of these maxima, and the deflection. It has been demonstrated in this study that box-shaped profiles perform better than rounded profiles. The existence of a cover between corrugations has some advantages, but it does not necessary to cause the pipe to perform better; choosing whether or not to have a cover depends on the profile itself. Additionally, curved webs are preferred over straight ones.

Approved:

Shad Sargand

Russ Professor of Civil Engineering
To my mother, Zeinah El-Dabaja, in recognition that, after God, it is only because of her that I got to this stage.
I would like to thank my advisor Dr. Shad Sargand for all that he has done for me so far. I feel a special appreciation for my second family, Saleh, Koste, Mariam and Sarah El-Dabaja for their continuous support throughout the entire time of my studies here. I especially would like to mention Mariam, whom God chose not to be here now and witness this small achievement; hopefully we’ll be together in heaven.

Special thanks are given to Mr. Issam Khoury for his continuous guidance throughout my studies. I also thank Mr. Bashar Tarawna for all his help.

Finally, another special thanks to my sister, Rakaz, for her continuous support throughout all of my life.
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>3</td>
</tr>
<tr>
<td>Dedication</td>
<td>4</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>5</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>6</td>
</tr>
<tr>
<td>List of Tables</td>
<td>9</td>
</tr>
<tr>
<td>List of Figures</td>
<td>11</td>
</tr>
<tr>
<td>Chapter 1. Introduction</td>
<td>16</td>
</tr>
<tr>
<td>1.1 Overview</td>
<td>16</td>
</tr>
<tr>
<td>1.2 Scope of work</td>
<td>17</td>
</tr>
<tr>
<td>1.3 Objectives</td>
<td>18</td>
</tr>
<tr>
<td>1.4 Outline of thesis</td>
<td>18</td>
</tr>
<tr>
<td>Chapter 2. Literature Review</td>
<td>19</td>
</tr>
<tr>
<td>2.1 The influence of profile geometry</td>
<td>19</td>
</tr>
<tr>
<td>2.1.1 Phase I of the study</td>
<td>19</td>
</tr>
<tr>
<td>2.1.2 Phase II of the study</td>
<td>22</td>
</tr>
<tr>
<td>2.2 Parallel plate testing and simulation of corrugated plastic pipes</td>
<td>23</td>
</tr>
<tr>
<td>2.3 Structural performance of buried profile-wall HDPE pipes</td>
<td>24</td>
</tr>
<tr>
<td>2.4 Performance limits of HDPE pipes</td>
<td>25</td>
</tr>
<tr>
<td>2.5 Long-term structural performance of buried pipes</td>
<td>26</td>
</tr>
</tbody>
</table>
Chapter 3. The Profiles of HDPE Pipes.............................................................................28

3.1 Profiles of the ten types without cover ............................................................30
3.2 Profiles of the ten types with cover.................................................................36
3.3 Further study on type 10 and type 20...............................................................42

Chapter 4. The Web of Corrugation And The Cover Between Corrugations............47

4.1 The web of corrugation....................................................................................47
4.2 The cover between corrugations......................................................................53

Chapter 5. Modeling of HDPE Pipes.................................................................................56

5.1 Problem description .........................................................................................56
5.2 Three dimensional modeling of HDPE pipes ..................................................57

Chapter 6. Results and Conclusions...................................................................................64

6.1 The profiles presented in chapter 3..................................................................64
   6.1.1 The ten profiles without cover .........................................................65
   6.1.2 The ten profiles with cover ...............................................................72
6.2 The web of corrugation....................................................................................75
   6.2.1 Without a cover ................................................................................75
   6.2.2 With a cover......................................................................................77
6.3 The cover between corrugations .....................................................................79
6.4 Further study on type 10 and type 20..............................................................81
   6.4.1 Three modifications of type 10.........................................................81
   6.4.2 Three modifications of type 20...........................................................82
6.5 Conclusions.....................................................................................................85
6.6 Recommendations

References

Appendix

A. The maximum principal stresses of the twenty profiles shown in chapter 3

B. The maximum principal stresses of the eight profiles used to study the web of corrugation

C. The maximum principal stresses for the three profiles used to study the cover between corrugations
LIST OF TABLES

Table 3-1 Section properties of the ten profiles without cover.................................35
Table 3-2 Section properties of the ten profiles with cover........................................41
Table 3-3 Section properties of the three modifications of type 10..............................44
Table 3-4 Section properties of the three modifications of type 20 without cover........46
Table 4-1 Section properties of the four profiles without cover..................................52
Table 4-2 Section properties for the four profiles with cover.........................................52
Table 4-3 Section properties for the three profiles used in studying the cover..............55
Table 6-1 Maximum principal stresses for the ten profiles without cover.....................66
Table 6-2 Rank of the ten profiles without cover..........................................................66
Table 6-3 Maximum principal stresses for the ten profiles with cover...........................72
Table 6-4 Rank of the ten profiles with cover...............................................................72
Table 6-5 Rank of the four profiles without cover according to the maximum principal stresses .............................................................................................................................75
Table 6-6 Deflection at the middle of the web at the 0° section.....................................75
Table 6-7 Deflection at the middle of the web at the 90° section....................................76
Table 6-8 Rank of the four profiles with cover according to the maximum principal stresses .............................................................................................................................77
Table 6-9 Deflection at middle of the web at the 0° section.............................................77
Table 6-10 Deflection at middle of the web at the 90° section.........................................77
Table 6-11 Rank of the three profiles according to the maximum principal stresses......79
Table 6-12 Deflection of the middle node in the cover at the 0° section....................80
Table 6-13 Deflection of the middle node in the cover at the 90° section....................80
Table 6-14 Maximum principal stresses for the three modifications of type 10 ..........81
Table 6-15 Maximum principal stresses for the three modifications of type 20 ..........83
LIST OF FIGURES

Figure 2-1 Example of a profile defining the geometry parameters...........................................21
Figure 3-1 HDPE pipe profile type 1..........................................................................................30
Figure 3-2 HDPE pipe profile type 2..........................................................................................30
Figure 3-3 HDPE pipe profile type 3..........................................................................................31
Figure 3-4 HDPE pipe profile type 4..........................................................................................31
Figure 3-5 HDPE pipe profile type 5..........................................................................................32
Figure 3-6 HDPE pipe profile type 6..........................................................................................32
Figure 3-7 HDPE pipe profile type 7..........................................................................................33
Figure 3-8 HDPE pipe profile type 8..........................................................................................33
Figure 3-9 HDPE pipe profile type 9..........................................................................................34
Figure 3-10 HDPE pipe profile type 10......................................................................................34
Figure 3-11 HDPE pipe profile type 11......................................................................................36
Figure 3-12 HDPE pipe profile type 12......................................................................................36
Figure 3-13 HDPE pipe profile type 13......................................................................................37
Figure 3-14 HDPE pipe profile type 14......................................................................................37
Figure 3-15 HDPE pipe profile type 15......................................................................................38
Figure 3-16 HDPE pipe profile type 16......................................................................................38
Figure 3-17 HDPE pipe profile type 17......................................................................................39
Figure 3-18 HDPE pipe profile type 18......................................................................................39
Figure 3-19 HDPE pipe profile type 19......................................................................................40
Figure 3-20 HDPE pipe profile type 20......................................................................................40
Figure 3-21 First modification of type 10 .................................................................43
Figure 3-22 Second modification of type 10 ..............................................................43
Figure 3-23 Third modification of type 10 ...............................................................44
Figure 3-24 First modification of type 20 .................................................................45
Figure 3-25 Second modification of type 20 ..............................................................45
Figure 3-26 Third modification of type 20 ...............................................................46
Figure 4-1 Uncovered profile with a straight web .......................................................48
Figure 4-2 Uncovered profile with web radius equal to 6 in. .......................................48
Figure 4-3 Uncovered profile with web radius equal to 5 in. .......................................49
Figure 4-4 Uncovered profile with web radius equal to 4 in. .......................................49
Figure 4-5 Covered profile with a straight web .........................................................50
Figure 4-6 Covered profile with web radius equal to 6 in. .........................................50
Figure 4-7 Covered profile with web radius equal to 5 in. .........................................51
Figure 4-8 Covered profile with web radius equal to 4 in. .........................................51
Figure 4-9 Profile E: type 1 profile with a straight cover .........................................54
Figure 4-10 Profile F: type 1 profile with upward concaved cover ...............................54
Figure 4-11 Profile G: type 1 profile with downward concaved cover .......................55
Figure 5-1 Geometry of the problem .......................................................................57
Figure 5-2 First part: the rectangle representing the soil ............................................59
Figure 5-3 Second part: 3D model of the solid part ....................................................59
Figure 5-4 Third part: 3D model of the pipe ...............................................................60
Figure 5-5 The result of subtracting the solid part from the soil ..................................61
Figure 5-6 The assembly of all parts..................................................................................61
Figure 5-7 Example of a meshed model ...........................................................................62
Figure 5-8 The constraints and the load applied to a model..............................................63
Figure 6-1 State of stress in an element and Mohr's Circle ...........................................65
Figure 6-2 Maximum principal stresses for type 3 ............................................................68
Figure 6-3 Maximum principal stresses for type 6 ............................................................69
Figure 6-4 The proposed profile for the case without cover............................................70
Figure 6-5 Maximum principal stresses for the proposed profile.....................................71
Figure 6-6 Maximum principal stresses for type 18 ..........................................................74
Figure 6-7 Maximum Principal stresses for the second modification of type 10 ..........82
Figure 6-8 Maximum Principal stresses for the second modification of type 20 ..........84
Figure A-1 Maximum principal stresses for type 1 ..........................................................89
Figure A-2 Maximum principal stresses for type 2 ..........................................................90
Figure A-3 Maximum principal stresses for type 3 ..........................................................91
Figure A-4 Maximum principal stresses for type 4 ..........................................................92
Figure A-5 Maximum principal stresses for type 5 ..........................................................93
Figure A-6 Maximum principal stresses for type 6 ..........................................................94
Figure A-7 Maximum principal stresses for type 7 ..........................................................95
Figure A-8 Maximum principal stresses for type 8 ..........................................................96
Figure A-9 Maximum principal stresses for type 9 ..........................................................97
Figure A-10 Maximum principal stresses for type 10 .....................................................98
Figure A-11 Maximum principal stresses for type 11 .....................................................99
Figure A-12 Maximum principal stresses for type 12 .....................................................100
Figure A-13 Maximum principal stresses for type 13 .....................................................101
Figure A-14 Maximum principal stresses for type 14 .....................................................102
Figure A-15 Maximum principal stresses for type 15 .....................................................103
Figure A-16 Maximum principal stresses for type 16 .....................................................104
Figure A-17 Maximum principal stresses for type 17 .....................................................105
Figure A-18 Maximum principal stresses for type 18 .....................................................106
Figure A-19 Maximum principal stresses for type 19 .....................................................107
Figure A-20 Maximum principal stresses for type 20 .....................................................108

Figure B-1 Maximum principal stresses for the case of straight web without cover ......110
Figure B-2 Maximum principal stresses for the case of web radius equal to 6 in. and
without cover ...................................................................................................................111
Figure B-3 Maximum principal stresses for the case of web radius equal to 5 in. and
without cover ...................................................................................................................112
Figure B-4 Maximum principal stresses for the case of web radius equal to 4 in. and
without cover ...................................................................................................................113
Figure B-5 Maximum principal stresses for the case of straight web with cover............114
Figure B-6 Maximum principal stresses for the case of web radius equal to 6 in. and with
cover.................................................................................................................................115
Figure B-7 Maximum principal stresses for the case of web radius equal to 5 in. and with
cover.................................................................................................................................116
Figure B-8 Maximum principal stresses for the case of web radius equal to 4 in. and with cover

Figure C-1 Maximum principal stresses for the case of straight cover

Figure C-2 Maximum principal stresses for the case of the cover concaved upward

Figure C-3 Maximum principal stresses for the case of the cover concaved downward
1.1 Overview

HDPE pipes are made of polyethylene, a material that gives the pipe a few properties considered as advantages over other pipe materials such as concrete and steel. Due to the use of polyethylene, HDPE pipes are lighter than other pipes; this results in faster and less costly installation. HDPE pipes are very flexible compared to other pipe materials; according to Goddard [1], an HDPE pipe would deflect up to 30% of its original diameter without any imperfection or structural failure. Using HDPE pipes helps significantly in cost savings in manufacturing, installation and maintenance of the pipes. An HDPE pipe has fully restrained joints that make the pipe leak proof. In addition to that, these joints along with the smoothness of the inner surface of HDPE pipes result in a minimal resistance to flow, so the flow remains relatively constant during the lifetime of the pipe.

One of the most important advantages of HDPE pipes over other pipe materials is that HDPE pipes have a high resistance to corrosion and erosion. Due to this advantage and the fact that polyethylene relaxes with time to cause the soil to take its share of the load, the lifetime of HDPE pipes is longer than other pipe materials.

HDPE pipes have a lot of advantages over other pipe materials and these advantages caused it to be widely used in different applications including a buried pipe, which is studied in this thesis.
1.2 Scope of work

HDPE pipes with corrugations have been successfully used as buried pipes. Due to the profile-wall, the pipe would perform better under high earth loads. There are four important parameters for the analysis and design of flexible pipes, the load, the soil stiffness, the pipe stiffness and the profile of the pipe.

This thesis is a study on the geometry of the profile of HDPE pipes; the pipe-soil interaction is not dealt with here. This study is a continuation of a study done by Songwut Hengprathanee [2] in the year 2000 under the title “Evaluation of the Geometry Effect of the Profile of High Density Polyethylene Pipes.” His study was conducted on the first ten profiles shown in Chapter 3, Figure 1 through 10, with the loads represented as concentrated loads on the pipe and only one fourth of the pipe is included in the study.

In this study, half of every pipe was included in the analysis and soil was represented as the real situation as shown in Chapter 5; the load was represented as a distributed load laid over the soil. This study is a parametric study conducted on the geometry of the profile of HDPE pipes. As in every parametric study, all the parameters are fixed except the parameter that is under examination. Finally, it is necessary to mention that this study is a qualitative study and not a quantitative one.
1.3 Objectives

The main objective of this study is to get to the best pipe profile. Furthermore, the effect of adding a cover that would connect the corrugations was highly considered in this study. The curvature of this cover can always play a major role and it needs to be investigated. The curvature of the web of the corrugation has an effect on the pipe’s performance. So, the curvature of the cover and the curvature of the web were studied too.

1.4 Outline of thesis

- Chapter 2 provides a literature review on studies that had been done before related to the topic.
- Chapter 3 details the ten profiles extracted from the type 1 profile, and then details those ten profiles with a cover added between the corrugations.
- Chapter 4 details a study on the corrugation web curvature, and also the curvature of the cover between corrugations in cases where that exists.
- Chapter 5 describes the modeling of HDPE pipes using AutoCAD, Solid Edge and Algor.
- Chapter 6 presents the results and conclusions of the study.
A lot of studies have been conducted on buried pipes over the years. Most of those studies were focusing on the pipe-soil interaction and parameters like the height of soil cover and the pipe diameter. Fewer studies were done on the geometry of the profile of buried flexible pipes; this chapter presents a few of these studies.

2.1 The influence of profile geometry

A three dimensional finite element studies on the parameters of the profile wall pipe was conducted by Rex P. Burgon, Steven L. Folkman and A.P. Moser [3]. The parameters were under examination included corrugation height, corrugation width, wall thickness, wall angle and profile curvature. Figure 2-1 gives an example of the geometry parameters of a pipe profile. As in any parametric study, only one parameter was varied while all the other parameters remained constant. The strains were considered linear and the material of the pipe was considered elastic.

2.1.1 Phase I of the study

The stiffness of a pipe is approximately calculated by the following equation:

\[ S_c = 6.7 \times \frac{EI}{r^3} \]  \hspace{1cm} (1)

where \( S_c \) is the pipe stiffness, \( E \) is Young’s Modulus, \( I \) is the moment of inertia and \( r \) is the effective radius.
If the height of the section is increased, the moment of inertia of the section will increase, and then the stiffness of the section increases due to that. However, the more the corrugation height is increased the less stable will the section be. The peak stiffness is achieved at a corrugation height close to 3.5 inches. The pipe would be unstable and it could have a premature buckling failure if the corrugation height is above 3.5 inches. On the other side, increasing the arch radius would cause the pipe profile to be more stable but less stiff. Due to the increase in the arch radius, there would be a slight increase in the liner buckling resistance. Rounded profiles in general would provide better resistance to arch buckling, but it decreases the pipe stiffness.

Interestingly enough, decreasing the liner width would increase both the stiffness of the pipe and the arch and liner resistance to buckling. However, it would increase the valley width which might cause a valley buckling due to the soil pressure. Stiffness and buckling are also directly related to the ratio between arch and liner thickness. To reach the maximum stiffness, it is preferable to be closer to the following two ratios: \( \frac{t_{\text{arch}}}{t_{\text{liner}}} = 1.5 \) and \( \frac{t_{\text{arch}}}{D} = 0.005 \), where D is the inner diameter of the pipe.

However, knowing that liner buckling can be controlled directly by controlling liner thickness, and since it is recommended to have the same thickness for all the profile section [4], one may want to approximately equalize the liner and arch buckling loads, which need the ratio between them to be close to the following ratio: \( \frac{t_{\text{arch}}}{t_{\text{liner}}} = 0.9 \).
In general, a rounded pipe profile is better than a box shaped profile. However, the box shaped profile can perform well if the cross-sectional area is increased, which means more material is needed.

Figure 2-1 Example of a profile defining the geometry parameters

Where

H is the corrugation height, $L_{\text{Liner}}$ is the liner width, $W_V$ is the valley width, and $L_P$ is the corrugation width.
2.1.2 Phase II of the study

The theoretical pipe stiffness can be calculated by taking a unit length of a pipe section and treating it as a beam. The equation would be

\[ S_c = 6.7 \frac{EI_c}{r^3} \]  \hspace{1cm} (1)

where \( E \) is the modulus of elasticity of the material of the pipe, \( I_c \) is the moment of inertia of the corrugation cross section per unit length of the pipe, and \( r \) is the effective radius of the pipe measured from the center of the pipe to the centroid of the profile.

This is the most commonly used formula for calculating the pipe stiffness. This equation is based on neglecting the deflections due to thrust stresses, shearing stresses and stability of the pipe, and on assuming that deflections are due to ring-bending stresses only. This assumption is accurate when we are dealing with solid-wall pipe, but when it comes to profile-wall pipe, deflections due to other stresses should be taken into account. A more accurate formula was developed for that purpose. The formula is:

\[ S_{BTS} = \frac{4\pi}{\pi^2 - 8 + \frac{\pi^2}{r^2} \frac{I_c}{A}(k \frac{E}{G} + 1)} \frac{EI_c}{r^3} \]  \hspace{1cm} (2)

where \( A \) is the cross-section area, \( G \) is the shear modulus and \( k \) is a correction factor to account for the assumption that the shearing stress is uniform.

In this study, it has been found that there is a significant change in the deflection due to thrust loads and shearing stresses on a profile-wall pipe. In such a case, it is recommended to use equation (2) instead of equation (1) to calculate the stiffness of the pipe especially when the ratio of the profile height to diameter gets larger.
It should be mentioned that if the thrust and shear stresses are neglected, equation (2) reduces to equation (1), 
\[ S_{BTS} = \frac{4\pi}{\pi^2 - 8} \frac{EI_c}{r^3} \approx 6.721 \frac{EI_c}{r^3} \]

The pipe stiffness calculated using equation (1) would be over predicted, especially with smaller diameter profile pipes that have relatively large profile dimensions. However, it should be noted that equation (2) does not take profile stability and localized profile deflections into account.

2.2 Parallel plate testing and simulation of corrugated plastic pipes

McGrath and Schafer [5] investigated the role of geometry and material on the behavior of corrugated HDPE pipes through a series of finite element simulations and parallel plate tests. The parallel plate tests were conducted on a 60 in. diameter pipe, while the finite element simulations were conducted on 18 in., 30 in., and 60in. diameter pipes.

The behavior of the material in HDPE pipes is known to be non-linear visco elastic-plastic, and this behavior differs in relaxation and creep. However, the ultimate strain capacity and demand in a test like a parallel plate test can be predicted by assuming the material is elastic while doing a finite element simulation, as long as the geometric non-linearity is included.

Due to the out of plate bending stresses and due to the stress redistribution, local strains in the pipe profile can greatly exceed the assumed general strain in the design. It should be noted that hand methods used for the prediction of local buckling are
conservative up to 33% compared to the parallel plate test, knowing that these hand methods ignore the soil support to the pipe.

2.3 Structural performance of buried profile-wall HDPE pipes.

The most important parameters for the analysis and design of flexible pipes are the load, the soil stiffness, the pipe stiffness and the profile design [6]. Deflection of the pipe is a function of the load, soil and pipe stiffness. Deflection is the criterion that usually limits the performance of a flexible pipe, so safety factors are usually based on the deflection and not the load [6]. Structurally, the longer the distance between the material and the neutral axis of the section, the higher the section modulus is, so a bigger height helps in using less material but jeopardizes the safety of the pipe due to the possibility that local buckling would occur. However, adding more material would solve the local buckling problem because wall thickness and area per unit length are very important factors in resisting local buckling. It is recommended to keep the same wall thickness in the whole section profile; this sameness in the thickness includes the liner thickness to avoid any local buckling in the liner due to the ring compression exerted by the soil. However, the area where the liner joins the valley should be thicker. It should be noted that most of the longitudinal stiffness of the pipe is provided by the plastic wall.

Soil plays an important role in the structural performance of flexible pipes. To get to an adequate safety, the surface of the pipe that is in contact with soil should be strong enough to carry shear load. This surface includes the plastic between the inner and outer walls and the plastic between the corrugations, i.e. the plastic in the valley of the pipe.
Since dense soil compresses less than loose soil, flexible pipes would deflect less in dense soil than loose soil. The height of the soil cover has a big effect on the performance of flexible pipes. If this height is high, it is better to use a granular soil that is well compacted. Although the local buckling is mainly due to the ring compression, it is also a function of soil density.

2.4 Performance limits of HDPE pipes

In 2000, Moser [7] investigated the structural performance limits of HDPE pipes through a set of full scale tests at the Utah State University large soil cell. He tried to determine the structural performance limits as a function of cover depth. The pipes were buried and the depth of the soil was represented in the form of the load equivalent to the soil depth. This load is applied by means of 50 hydraulic cylinders.

The soil that has been used in these tests is sitly sand. According to the United Soil Classification System, the soil is classified as SM. It has less quality; this means it presents the worst case. Also, SM soil can be compacted over a wide range of soil densities. It has been found that the pipe deflects more in loose soil than in dense soil because loose soil compresses more. From a structural point of view, if the pipe is under heavy surface loads or is buried under high soil cover, the soil should be granular and carefully compacted.

Dimpling occurs at a depth of cover ranging between 40 feet to 110 feet. Dimpling is a function of the soil density. It should be mentioned that dimpling is not a performance limit, unlike hinging and cracking. The load at which hinging and cracking
start to appear is also a function of the soil density. Compaction plays a major role in the structural performance of HDPE pipes.

The structural performance limit for poor installation (75 percent Standard Proctor) takes place at 55 feet of soil cover. For good installation (85 percent Standard Proctor) the Structural Performance limit starts to be reached at about 110 feet of soil cover. While for excellent installation (95 percent Standard Proctor) the lowest structural performance limit was at 160 feet of cover.

2.5 Long-Term structural performance of buried pipes

In 1998, Watkins [8] investigated the long-term structural performance of HDPE pipes. It has been found that strength of HDPE pipes regresses over the long-term if subjected to constant high stress. Therefore, when an HDPE pipe is designed under constant stress, the design strength should be equal to the long-term strength.

HDPE pipes relax over time when subjected to constant deformation. Pipe stresses relax over the long-term if the ring deflection is held constant by the soil and the pipe is buried in a good embedment.

The rate of relaxation gets higher with the increase of stress. A good phenomenon can be noticed, strength regression is slower than stress relaxation. Therefore, if fracture does not occur in the initial stage, it will not take place in the long-term.

Due to the non-uniform rates of relaxation across the pipe’s wall, the flexural stresses caused by ring deformation would be redistributed. This redistribution could cause a longitudinal crack to take place on the inside of the pipe after a certain period of
time. It should be mentioned that these cracks take place only after the deformation of a plastic hinge in the rib.

Finally, to prevent the vertical soil strain to be greater than the pipe’s performance limit, it has to be assured that the soil is dense enough, uniformly placed and compacted and of a good quality. It is already known that in the soil-pipe structure interaction, the soil plays the major role.
CHAPTER THREE
THE PROFILES OF HDPE PIPES

In order to model the closest shape to the real HDPE pipe, the pipes’ shapes were scanned as images and then converted into CAD files using software called Algolab. With the use of AutoCAD, the coordinates of the nodes were determined, and then those coordinates were used to create three-dimensional models of the pipes’ profiles using Solid Edge software.

Originally, the ten types of pipes used in this study were derived from type 1, which was determined by sketching a profile of standard corrugated 30-inch diameter HDPE pipe on a graph paper. Basically, the other nine types were built based on the shape of geometry of type 1 in order to search for the most effective profile for HDPE pipes. Type 1 is the original profile that is copied from the cross-section of the standard corrugated 30-inch diameter HDPE pipe specimen. Type 2 was modified by decreasing the liner width at the intersection of the liner and the web. In type 3, the height of the profile was increased by half an inch. Type 4 was modified by increasing the liner width at the intersection of the liner and the web. Type 5 is a combination of type 3 and type 4. Type 6 has the original profile modified by changing the crest of the profile to be flat. The same thing happened in type 7, but this time the crest of the original profile was changed to be more curved. In type 8, the thickness of the liner in the original profile was increased. In type 9, the thickness of the web in the original profile was increased. Finally, type 10 is a new profile that is designed based on a semi-circular shape for the
purpose of study only. The profiles of the mentioned ten shapes are shown in figures 3-1 through 3-10.

The same ten types were tested with additional cover added to every one of them that would connect the crests of corrugations. The profiles of the ten shapes with covers are shown in figure 3-11 through 3-20. The dimensions of all figures are in inches.
3.1 Profiles of the ten types without cover

Figure 3-1 HDPE pipe profile type 1

Figure 3-2 HDPE pipe profile type 2
Figure 3-3 HDPE pipe profile type 3

Figure 3-4 HDPE pipe profile type 4
Figure 3-5 HDPE pipe profile type 5

Figure 3-6 HDPE pipe profile type 6
Figure 3-7 HDPE pipe profile type 7

Figure 3-8 HDPE pipe profile type 8
Figure 3-9 HDPE pipe profile type 9

Figure 3-10 HDPE pipe profile type 10
Table 3-1 shows the section properties of every profile. The table includes the area and the moment of inertia about X-axis ($I_x$) and Y-axis ($I_y$).

![Table 3-1 Section properties of the ten profiles without cover](image-url)
3.2 Profiles of the ten types with cover

Figure 3-11 HDPE pipe profile type 11

Figure 3-12 HDPE pipe profile type 12
Figure 3-13 HDPE pipe profile type 13

Figure 3-14 HDPE pipe profile type 14
Figure 3-15 HDPE pipe profile type 15

Figure 3-16 HDPE pipe profile type 16
Figure 3-17 HDPE pipe profile type 17

Figure 3-18 HDPE pipe profile type 18
Figure 3-19 HDPE pipe profile type 19

Figure 3-20 HDPE pipe profile type 20
Table 3-2 shows the section properties of every profile. The table includes the area and the moment of inertia about X-axis (Iₘ) and Y-axis (Iₙ).

<table>
<thead>
<tr>
<th>Type</th>
<th>Area (in²)</th>
<th>Iₘ (in⁴)</th>
<th>Iₙ (in⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.8074</td>
<td>3.3437</td>
<td>20.7683</td>
</tr>
<tr>
<td>2</td>
<td>4.1086</td>
<td>3.6041</td>
<td>22.1344</td>
</tr>
<tr>
<td>3</td>
<td>4.2281</td>
<td>5.2199</td>
<td>22.7640</td>
</tr>
<tr>
<td>4</td>
<td>3.7036</td>
<td>3.3363</td>
<td>20.3350</td>
</tr>
<tr>
<td>5</td>
<td>4.1229</td>
<td>5.0409</td>
<td>22.6470</td>
</tr>
<tr>
<td>6</td>
<td>3.8760</td>
<td>3.4075</td>
<td>21.0679</td>
</tr>
<tr>
<td>7</td>
<td>3.8872</td>
<td>3.3943</td>
<td>20.8750</td>
</tr>
<tr>
<td>8</td>
<td>4.1514</td>
<td>3.7202</td>
<td>22.0149</td>
</tr>
<tr>
<td>9</td>
<td>4.3137</td>
<td>3.5720</td>
<td>23.6058</td>
</tr>
<tr>
<td>10</td>
<td>3.3769</td>
<td>3.0426</td>
<td>16.9669</td>
</tr>
</tbody>
</table>

Table 3-2 Section properties of the ten profiles with cover
3.3 Further Study on type 10 and type 20

As it can be seen from table 3-1 and table 3-2, the values of the area and inertia of type 10 and type 20 are less than the values for the other types, which means that the stiffness of type 10 and type 20 is much less than the stiffness of the other types. On the other hand, type 10 and type 20 have a better resistance to buckling, so they are expected to perform better or the same when their inertia is improved to be compatible with the box shaped profiles.

To study that, three modifications were made to type 10. In the first modification, the thickness of the profile was increased as shown in figure 3-21. In the second modification, the inner width of corrugation was made wider as shown in figure 3-22. In the third modification, the sides of the corrugations were made steeper than the original profile in type 10, to do so; the width of corrugation had to be increased as shown in figure 3-23.
Figure 3-21 First modification of type 10

Figure 3-22 Second modification of type 10
The same three modifications were run with a cover added between the corrugations for the purpose of comparing with type 20. These three modifications are shown in figures 3-24, 3-25, and 3-26.
Figure 3-24 First modification of type 20

Figure 3-25 Second modification of type 20
Figure 3-26 Third modification of type 20

<table>
<thead>
<tr>
<th>Modification Number</th>
<th>Area (in²)</th>
<th>( I_x (\text{in}^4) )</th>
<th>( I_y (\text{in}^4) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.5078</td>
<td>3.8410</td>
<td>22.2386</td>
</tr>
<tr>
<td>2</td>
<td>4.5383</td>
<td>3.8871</td>
<td>22.8294</td>
</tr>
<tr>
<td>3</td>
<td>5.3752</td>
<td>4.7054</td>
<td>40.2100</td>
</tr>
</tbody>
</table>

Table 3-4 Section properties of the three modifications of type 20 without cover
CHAPTER FOUR

THE WEB OF CORRUGATION AND THE COVER BETWEEN CORRUGATIONS

After studying the ten profiles shown in chapter 3 with and without a corrugation cover, a local study was conducted on the web of corrugation in both cases, with cover and without cover. Another study was conducted on the cover between corrugations and how much its curvature affected the performance of the pipe. Type 1 and type 11 were used in the Phase I, and type 11 was used in the Phase II. The decimal numbers in the dimensions of the profiles were not used since there was not a need for them in this case.

4.1 The web of corrugation

The curvature of the web of corrugation is potentially a significant factor that needs to be studied. The focus was mainly on the concavity of the web, so four different curvatures were studied by using arcs with different radii, 4 in., 5 in., 6 in., and the last one was a straight line. Figures 4-1 through 4-4 show the web radius of the profiles that are without cover. Figures 4-5 through 4-8 show the web radius of the profiles that are with cover.
Figure 4-1 Uncovered profile with a straight web

Figure 4-2 Uncovered profile with web radius equal to 6 in.
Figure 4-3 Uncovered profile with web radius equal to 5 in.

Figure 4-4 Uncovered profile with web radius equal to 4 in.
Figure 4-5 Covered profile with a straight web

Figure 4-6 Covered profile with web radius equal to 6 in.
Figure 4-7 Covered profile with web radius equal to 5 in.

Figure 4-8 Covered profile with web radius equal to 4 in.
Tables 4-1 and 4-2 show the section properties of the eight profiles. The tables include the area and the moment of inertia about X-axis ($I_x$) and Y-axis ($I_y$).

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Web Radius (in)</th>
<th>Area (in$^2$)</th>
<th>$I_x$ (in$^4$)</th>
<th>$I_y$ (in$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Straight Web</td>
<td>3.3287</td>
<td>2.5754</td>
<td>20.4806</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>3.3307</td>
<td>2.5955</td>
<td>20.6079</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>3.3326</td>
<td>2.6006</td>
<td>20.6442</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>3.3359</td>
<td>2.6085</td>
<td>20.7029</td>
</tr>
</tbody>
</table>

Table 4-1 Section properties of the four profiles without cover

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Web Radius (in)</th>
<th>Area (in$^2$)</th>
<th>$I_x$ (in$^4$)</th>
<th>$I_y$ (in$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Straight Web</td>
<td>3.7606</td>
<td>3.3391</td>
<td>20.7120</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>3.7672</td>
<td>3.3525</td>
<td>20.8759</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>3.7695</td>
<td>3.3557</td>
<td>20.9149</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>3.7733</td>
<td>3.3606</td>
<td>20.9777</td>
</tr>
</tbody>
</table>

Table 4-2 Section properties for the four profiles with cover
4.2 The cover between corrugations

The cover between corrugations is an important factor that would increase the stiffness of the pipe significantly. Connecting the corrugations is also supposed to make them act together instead of acting individually. Three cases were studies. In the first one, the cover between the corrugations was straight; in the second one, the cover between the corrugations was concaved upward with a maximum value at the center equal to 0.25 in.; in the third one, the cover between the corrugations was concaved downward with a maximum value at the center equal to 0.25 in. The three profiles were derived from type 11 shown in chapter 3. Figures 4-9, 4-10 and 4-11 show the geometry of the three profiles.
Figure 4-9 Profile E: type 1 profile with a straight cover

Figure 4-10 Profile F: type 1 profile with upward concaved cover
Figure 4-11 Profile G: type 1 profile with downward concaved cover

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Cover Concavity</th>
<th>Area (in²)</th>
<th>$I_x$ (in⁴)</th>
<th>$I_y$ (in⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Straight</td>
<td>3.8172</td>
<td>3.3862</td>
<td>20.7652</td>
</tr>
<tr>
<td>F</td>
<td>Upward</td>
<td>3.8277</td>
<td>3.6471</td>
<td>20.2275</td>
</tr>
<tr>
<td>G</td>
<td>Downward</td>
<td>3.7605</td>
<td>3.1665</td>
<td>20.1039</td>
</tr>
</tbody>
</table>

Table 4-3 Section properties for the three profiles used in studying the cover
CHAPTER FIVE
MODELING OF HDPE PIPES

Since the analysis of HDPE pipes was done using Algor, a professional finite element analysis software, the modeling of the pipes had to be done using Solid Edge, a 3D modeling software. At the beginning, the profiles were drawn using AutoCAD as shown in chapters 3 and 4, and then the coordinates of the points along the curvature of each profile were determined to be entered into Solid Edge, and revolved into a 3D model of an HDPE pipe.

5.1 Problem description

This study is conducted only on the profiles of HDPE pipes, so all the variations were applied to the parameters of a profile, while other parameters such as the height of the soil cover, the diameter of the pipe and the soil type, were fixed throughout the study. A description of the problem is shown in figure 5-1. The diameter of the pipe is equal to 30 in., the height of the soil cover is equal to 45 in., and all the dimensions in the figure are in inches. Since the analysis is linear elastic, the parameters needed to determine the material properties of the soil and the plastic pipe are the Young’s modulus, Poisson’s ratio, and density. For the HDPE pipes, the value of Young’s modulus used in this study is equal to 126,000 psi, the Poisson’s ratio is equal to 0.45 and the density of HDPE pipes used is equal to 0.035 lb/in$^3$. For the soil, the value of Young’s modulus used is equal to
10,000 psi, the Poisson’s ratio is equal to 0.25 and the density of the soil used is equal to 0.075 lb/in$^3$.

5.2 Three dimensional modeling of HDPE pipes

*Solid Edge* is a software that allows assembling different parts together. Using this advantage, each pipe that was modeled was constructed as an assembly of three parts. The first part is the rectangle shown in figure 5-2; the dimensions of this part are 81x60x8.5 inches, where the 8.5 represents the thickness of the box which is equal to the width of the portion of the pipe that is under study. This part is used to represent the soil later on. The second part is the solid shown in figure 5-3. It is a part that has been used to subtract the space in the soil that the pipe would occupy. So the solid is created by revolving the outer curvature of the pipe profile only so the pipe would fit in that place.
after the pipe and the soil were joined together in one assembly. The third part is the pipe itself. The profile of the pipe was created using AutoCAD, and then the coordinates of those points were entered into Solid Edge and revolved to create the pipe as it is shown in figure 5-4.
Figure 5-2 First part: the rectangle representing the soil

Figure 5-3 Second part: 3D model of the solid part
To model the pipe and the soil, the second part is subtracted from the first part as shown in figure 5-5, and then the pipe is attached to the resulting part to form the whole assembly shown in figure 5-6. After doing all this, the model was then sent to Algor to be analyzed. In Algor, the model was meshed, constraints were applied in a way that would represent the behavior of the soil and the pipe, and a load of 100 psi was applied as a surcharge. From here, the model would be analyzed. Figure 5-7 shows the meshing of the pipe and the soil, and figure 5-8 shows the application of the constraints and the load on the pipe and the soil.
Figure 5-5 The result of subtracting the solid part from the soil

Figure 5-6 The assembly of all parts
Figure 5-7 Example of a meshed model
Figure 5-8 The constraints and the load applied to a model
CHAPTER SIX
RESULTS AND CONCLUSIONS

After performing all the finite element analyses, the results were collected for studying and comparing. The results were divided into four categories; the first category is for the ten profiles without cover shown in chapter 3, the second category is for the ten profiles with cover also shown in chapter 3, the third category is for the eight profiles used to study the behavior of the web of the pipe, and the last category is for the three profiles used to study the behavior of the cover between corrugations.

6.1 The profiles presented in chapter 3

As it is mentioned in chapter 3, the ten profiles of HDPE pipes were analyzed without a cover connecting the corrugations, and then the same profiles were analyzed with a cover added to them. Since this study is a qualitative study and not a quantitative one, a ranking of the profiles according to the maximum principal stresses was established. The maximum principal stresses are the tension and compression values when the value of the shear equals zero as shown in figure 6-1.
6.1.1 The ten profiles without cover

A grading was done separately for the maximum principal tension and maximum principal compression; these values are shown in table 6-1. A grade from +1 to +10 was given to each profile of the ten profiles based on its maximum stress value classified from the worst to the best in order. The grades for maximum principal tension and maximum principal compression were summed for each pipe. Based on the summation values, every profile was given a rank from 1 to 10, with 1 being the best profile and 10 being the worst. Table 6-2 shows the ranking of the profiles.
### Maximum Principal Stresses (psi)

<table>
<thead>
<tr>
<th>Profile Number</th>
<th>Tension</th>
<th>Compression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>603.331</td>
<td>675.054</td>
</tr>
<tr>
<td>Type 2</td>
<td>611.705</td>
<td>608.380</td>
</tr>
<tr>
<td>Type 3</td>
<td>596.274</td>
<td>535.932</td>
</tr>
<tr>
<td>Type 4</td>
<td>701.338</td>
<td>484.959</td>
</tr>
<tr>
<td>Type 5</td>
<td>571.463</td>
<td>965.440</td>
</tr>
<tr>
<td>Type 6</td>
<td>513.429</td>
<td>671.242</td>
</tr>
<tr>
<td>Type 7</td>
<td>844.190</td>
<td>839.660</td>
</tr>
<tr>
<td>Type 8</td>
<td>532.999</td>
<td>706.440</td>
</tr>
<tr>
<td>Type 9</td>
<td>843.333</td>
<td>620.131</td>
</tr>
<tr>
<td>Type 10</td>
<td>986.366</td>
<td>1231.845</td>
</tr>
</tbody>
</table>

Table 6-1 Maximum principal stresses for the ten profiles without cover

### Rank of the ten profiles without cover

<table>
<thead>
<tr>
<th>Profile Number</th>
<th>Grade for Tension</th>
<th>Grade for Compression</th>
<th>Total Profile Grade</th>
<th>Profile Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>+6</td>
<td>+5</td>
<td>+11</td>
<td>6</td>
</tr>
<tr>
<td>Type 2</td>
<td>+5</td>
<td>+8</td>
<td>+13</td>
<td>4</td>
</tr>
<tr>
<td>Type 3</td>
<td>+7</td>
<td>+9</td>
<td>+16</td>
<td>1</td>
</tr>
<tr>
<td>Type 4</td>
<td>+4</td>
<td>+10</td>
<td>+14</td>
<td>3</td>
</tr>
<tr>
<td>Type 5</td>
<td>+8</td>
<td>+2</td>
<td>+10</td>
<td>7</td>
</tr>
<tr>
<td>Type 6</td>
<td>+10</td>
<td>+6</td>
<td>+16</td>
<td>1</td>
</tr>
<tr>
<td>Type 7</td>
<td>+2</td>
<td>+3</td>
<td>+5</td>
<td>9</td>
</tr>
<tr>
<td>Type 8</td>
<td>+9</td>
<td>+4</td>
<td>+13</td>
<td>4</td>
</tr>
<tr>
<td>Type 9</td>
<td>+3</td>
<td>+7</td>
<td>+10</td>
<td>7</td>
</tr>
<tr>
<td>Type 10</td>
<td>+1</td>
<td>+1</td>
<td>+2</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 6-2 Rank of the ten profiles without cover
Type 10 is the weakest among the profiles. This is due to the fact that rounded profiles would increase the resistance to arch and liner buckling, but it would decrease the stiffness of the pipe significantly. As it is shown in table 3-1, the moment of inertia of type 10 is the weakest among all the types.

Type 3 and type 6 have the highest and same grade equal to +16. Type 3 has the highest stiffness due to the fact that it has the biggest height and the smallest liner width. This made it stiffer than type 5, although it has the same height equal to 3.007 inches. However, comparing the maximum stresses of type 3 and type 6, we find that the maximum principal compression value in type 6 is very high compared to type 3. This acts as another advantage for type 3 over type 6, especially in that the height of the section in type 3 is still almost half an inch away from the critical corrugation height. Also the positions of the maximum stress points are in the web and in the valley of type 3, while they are in the web and in the region connecting the valley and the liner in type 6. Equal credit is given to both of them based on the second criterion. However, due to the first criterion, type 3 is preferred over type 6.

Other observations also have to be mentioned. Type 5 has the same height as type 3 but with wider liner width, which weakens the liner and makes the profile more vulnerable. Due to the very narrow liner in type 2, the valley was more vulnerable than other parts of the profile. Unlike in type 5, the liner in type 4 is strong even though the liner width is the same. This is due to the height of corrugation in type 4, which gives more stability to the liner and to the whole profile. Type 7 had the same problem in stiffness as type 10 because of its rounded profile, but the problem is less in type 7
because it is not a fully rounded profile. Increasing the thickness of the liner in type 8, along with having a reasonable liner width solved the problem of the liner. Although type 2 and type 8 have the same grade equal to +13, the positions of maximum principal stresses in type 2 are in the valley, which is more critical than their positions in type 8 that are mainly in the web. This difference gives an advantage for type 8 over type 2. Increasing the web thickness in type 9 did not contribute much to the performance of the pipe even though it increased the stiffness a little bit. The sequence of the ten types from the best to the worst is 3, 6, 4, 8, 2, 1, 5, 9, 7, and 10.

Figure 6-2 Maximum principal stresses for type 3
Figure 6-3 Maximum principal stresses for type 6

Load Case: 1 of 1

Maximum Value: 513.429 lb/in^2
Minimum Value: -671.241 lb/in^2
Based on the previous analysis, a new profile is proposed based on type 3 and type 8. This profile is the same as the profile in type 3, except that the liner thickness is increased to 0.15 inch, which is equal to the liner thickness in type 8. Figure 6-4 shows the profile of the new proposed pipe section. As it can be seen in figure 6-5, the maximum principal tension of the proposed profile is 417.621 lb/in$^2$, which is much less than the lowest value of the maximum principal tension among the ten profiles which is equal to 513.429 lb/in$^2$. The maximum principal compression in the proposed profile is almost equal to that of the profile in type 3 that is ranked as number 1. It should be noted that in the proposed section the positions of maximum principal tension and compression had moved to the web rather than being in the valley as in type 3, which would make it less critical.

![Figure 6-4 The proposed profile for the case without cover](image)
Figure 6-5 Maximum principal stresses for the proposed profile

Load Case: 1 of 1

Maximum Value: 417.621 lb/(in²)

Minimum Value: -537.911 lb/(in²)
### 6.1.2 The ten profiles with cover

<table>
<thead>
<tr>
<th>Profile Number</th>
<th>Maximum Principal Stresses (psi)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tension</td>
<td>Compression</td>
</tr>
<tr>
<td>Type 11</td>
<td>581.753</td>
<td>556.840</td>
</tr>
<tr>
<td>Type 12</td>
<td>667.153</td>
<td>535.658</td>
</tr>
<tr>
<td>Type 13</td>
<td>682.248</td>
<td>503.863</td>
</tr>
<tr>
<td>Type 14</td>
<td>727.098</td>
<td>607.595</td>
</tr>
<tr>
<td>Type 15</td>
<td>703.301</td>
<td>869.999</td>
</tr>
<tr>
<td>Type 16</td>
<td>857.518</td>
<td>863.801</td>
</tr>
<tr>
<td>Type 17</td>
<td>467.537</td>
<td>608.315</td>
</tr>
<tr>
<td>Type 18</td>
<td>509.466</td>
<td>576.584</td>
</tr>
<tr>
<td>Type 19</td>
<td>640.986</td>
<td>977.082</td>
</tr>
<tr>
<td>Type 20</td>
<td>840.246</td>
<td>1524.740</td>
</tr>
</tbody>
</table>

Table 6-3 Maximum principal stresses for the ten profiles with cover

<table>
<thead>
<tr>
<th>Profile Number</th>
<th>Grade for Tension</th>
<th>Grade for Compression</th>
<th>Total Profile Grade</th>
<th>Profile Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 11</td>
<td>+8</td>
<td>+8</td>
<td>+16</td>
<td>1</td>
</tr>
<tr>
<td>Type 12</td>
<td>+6</td>
<td>+9</td>
<td>+15</td>
<td>3</td>
</tr>
<tr>
<td>Type 13</td>
<td>+5</td>
<td>+10</td>
<td>+15</td>
<td>3</td>
</tr>
<tr>
<td>Type 14</td>
<td>+3</td>
<td>+6</td>
<td>+9</td>
<td>6</td>
</tr>
<tr>
<td>Type 15</td>
<td>+4</td>
<td>+3</td>
<td>+7</td>
<td>8</td>
</tr>
<tr>
<td>Type 16</td>
<td>+1</td>
<td>+4</td>
<td>+5</td>
<td>9</td>
</tr>
<tr>
<td>Type 17</td>
<td>+10</td>
<td>+5</td>
<td>+15</td>
<td>3</td>
</tr>
<tr>
<td>Type 18</td>
<td>+9</td>
<td>+7</td>
<td>+16</td>
<td>1</td>
</tr>
<tr>
<td>Type 19</td>
<td>+7</td>
<td>+2</td>
<td>+9</td>
<td>6</td>
</tr>
<tr>
<td>Type 20</td>
<td>+2</td>
<td>+1</td>
<td>+3</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 6-4 Rank of the ten profiles with cover
Adding a cover to the ten profiles increased the stiffness of the pipes significantly as it is shown in tables 3-1 and 3-2. At the same time, the existence of the cover had decreased the contact area between the pipe and the soil. This area is a major contributor in carrying the shear exerted on the pipe. It should be noted that the stiffness of the pipe is not the only factor that affects the pipe’s performance. Although adding the stiffness would increase the pipe’s strength, other factors might decrease the strength of the pipe more than the amount the stiffness would increase it. It should be mentioned also that adding the cover to the profile and thus increasing the stiffness of the pipe would not prevent the local concentration of stresses that could occur in the liner, valley or any critical region in the profile. So adding a cover would not necessarily decrease the maximum internal stresses in the pipe.

Type 20 was the worst among all the ten types. Again, this is a result of its low stiffness due to its fully circular profile. Type 11 and type 18 have the highest and same grading equal to +16. Type 18 had some advantages over type 11. Due to the increase in the liner thickness, the critical points moved from the liner in type 11 to the web in type 18. The positions of maximum principal stresses are in the web of type 18 and in the liner of type 11. Also, the values of the maximum principal tension and compression of the two types give another push towards preferring type 18.

Among type 12, type 13 and type 17 that have the same grade equal to +15, type 17 is the most critical because the maximum principal tension is in the region connecting the liner and the valley, and the maximum principal compression is in the liner. Between type 14 and type 19, type 19 is more critical because both the maximum principal tension
and compression are in the valley, while in type 14 they are located in the web and the cover. The sequence of the ten types from the best to the worst is 18, 11, 13, 12, 17, 14, 19, 15, 16, and 20. If a new profile would be proposed, it should be a combination of type 18 and type 11. This means that the proposed profile would be the same as the profile of type 18.

Figure 6-6 Maximum principal stresses for type 18
6.2 The web of corrugation

As it is shown in chapter 4, the four profiles used to study the effect of the curvature of the web are analyzed twice, once without a cover and once with a cover.

6.2.1 Without a cover

The same grading system of section 6.1 is used in sections 6.2.1 and 6.2.2. The new scale is from +1 to +4 as it is shown in table 6-5.

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Web Radius (in.)</th>
<th>Maximum Principal Tension</th>
<th>Grade</th>
<th>Maximum Principal Compression</th>
<th>Grade</th>
<th>Grades Sum</th>
<th>Profile Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Straight Web</td>
<td>558.984</td>
<td>+4</td>
<td>776.460</td>
<td>+1</td>
<td>+5</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>579.790</td>
<td>+3</td>
<td>614.208</td>
<td>+4</td>
<td>+7</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>582.873</td>
<td>+2</td>
<td>614.504</td>
<td>+3</td>
<td>+5</td>
<td>2</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>591.755</td>
<td>+1</td>
<td>702.982</td>
<td>+2</td>
<td>+3</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 6-5 Rank of the four profiles without cover according to the maximum principal stresses

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Web Radius (in.)</th>
<th>Deflection Magnitude</th>
<th>Deflection Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Straight Web</td>
<td>0.216105</td>
<td>Inward</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>0.228151</td>
<td>Inward</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>0.228392</td>
<td>Inward</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>0.227940</td>
<td>Outward</td>
</tr>
</tbody>
</table>

Table 6-6 Deflection at the middle of the web at the 0° section
Table 6-7 Deflection at the middle of the web at the 90° section

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Web Radius (in.)</th>
<th>Deflection Magnitude</th>
<th>Deflection Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Straight Web</td>
<td>0.545367</td>
<td>Outward</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>0.547938</td>
<td>Outward</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>0.548849</td>
<td>Outward</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>0.547702</td>
<td>Outward</td>
</tr>
</tbody>
</table>

The sequence of the profiles according to the deflection values from the least to
the most is the same for both sections as it can be seen from table 6-6 and table 6-7. The
sequence of the profiles is: A, D, B, and C. However, the direction of deflection is
preferred to be in the inward direction (i.e. deflecting to the direction of the pipe) in the
cases where the web is curved. This would cause the web to deflect toward becoming
straight. So if the direction of deflection is inward, it will give an advantage for a curved
web over a straight one. And it causes the value of the deflection at a curved web to be
relative, while, in the case of a straight web, the deflection value would be an absolute
value. Since the values of deflection are very close, a lot more weight should be given to
the deflection direction. This will give an advantage to profile B and profile C over the
other two profiles. Combining this conclusion with the rank in table 6-5, the best profile
would be profile B. Thus, it is preferred to have a curved web but with a big radius.
6.2.2 With a cover

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Web Radius (in.)</th>
<th>Maximum Principal Tension</th>
<th>Grade</th>
<th>Maximum Principal Compression</th>
<th>Grade</th>
<th>Grades Sum</th>
<th>Profile Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Straight Web</td>
<td>531.574</td>
<td>+4</td>
<td>844.038</td>
<td>+1</td>
<td>+5</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>565.045</td>
<td>+2</td>
<td>560.869</td>
<td>+2</td>
<td>+4</td>
<td>4</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>562.799</td>
<td>+3</td>
<td>560.424</td>
<td>+3</td>
<td>+6</td>
<td>1</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>616.601</td>
<td>+1</td>
<td>558.867</td>
<td>+4</td>
<td>+5</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6-8 Rank of the four profiles with cover according to the maximum principal stresses

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Web Radius (in.)</th>
<th>Deflection Magnitude</th>
<th>Deflection Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Straight Web</td>
<td>0.228356</td>
<td>Inward</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>0.227131</td>
<td>Inward</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>0.227365</td>
<td>Inward</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>0.227504</td>
<td>Inward</td>
</tr>
</tbody>
</table>

Table 6-9 Deflection at the middle of the web at the 0° section

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Web Radius (in.)</th>
<th>Deflection Magnitude</th>
<th>Deflection Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Straight Web</td>
<td>0.549141</td>
<td>Inward</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>0.545216</td>
<td>Inward</td>
</tr>
<tr>
<td>C</td>
<td>5</td>
<td>0.544962</td>
<td>Inward</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>0.545791</td>
<td>Inward</td>
</tr>
</tbody>
</table>

Table 6-10 Deflection at the middle of the web at the 90° section

It is noticed from the values in tables 6-9 and 6-10 that, with the existence of a cover, the value of the deflection in profile A is higher than in the other three profiles. Also, the direction of the deflection is inward in all the profiles at both sections, which
leaves profile A behind profiles B, C and D. Profile B has the least deflection value at the
0° section, while profile C has the least deflection value at the 90° section. Combining
this with the ranking in table 6-8, profile C is preferred in the case of using a cover
between corrugations.
6.3 The cover between corrugations

<table>
<thead>
<tr>
<th>Profile Name</th>
<th>Cover Concavity</th>
<th>Maximum Principal Tension</th>
<th>Grade</th>
<th>Maximum Principal Compression</th>
<th>Grade</th>
<th>Grades Sum</th>
<th>Profile Rank</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Straight</td>
<td>636.850</td>
<td>+2</td>
<td>513.285</td>
<td>+3</td>
<td>+5</td>
<td>1</td>
</tr>
<tr>
<td>F</td>
<td>Upward</td>
<td>692.988</td>
<td>+1</td>
<td>860.684</td>
<td>+1</td>
<td>+2</td>
<td>3</td>
</tr>
<tr>
<td>G</td>
<td>Downward</td>
<td>598.683</td>
<td>+3</td>
<td>545.163</td>
<td>+2</td>
<td>+5</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6-11 Rank of the three profiles according to the maximum principal stresses

The same grading system that is used in section 6.1 is also used in this section. The grades in this section are from +1 to +3. These grades are shown in table 6-11. The performances of profile E and profile G are much better than the performance of profile F in terms of the maximum principal tension and compression. The deflection of the cover itself is an important criterion to determine which curvature is preferable to be used. The deflection is measured at the middle node of the cover in two sections; one is at the 0° and the other is at the 90°. At the 0° section, the deflection measured is in the y-direction, while, at the 90° section, the deflection measured is in the z-direction.
At the 0° section, the direction of the deflection of the middle node is outward (i.e. the cover deflects toward the soil). In this case, profile G has less deflection than the other two profiles, as shown in table 6-12, while profile F has the highest deflection. This is due to the fact that it is concaved in the opposite direction of deflection. At the 90° section, the situation is exactly the opposite. The direction of the deflection at the middle node is inward. In this case, profile F has less deflection value than the other two profiles, as it is shown in table 6-13, while profile G has the highest deflection.

Profile E stands as a compromise between the two other profiles F and G when it comes to deflection. Also, profiles E and G have an advantage over profile F when it comes to the maximum principal stresses. Based on that, using a straight cover is preferred over using a curved one.
6.4 Further study on type 10 and type 20

6.4.1 Three modifications of type 10

All three modifications have shown improvement in the performance of type 10. Although the improvement in the maximum principal tension is not significant in the first modification, it is very significant in the maximum principal stresses in the second and third modification.

<table>
<thead>
<tr>
<th>Modification Number</th>
<th>Maximum Principal Stresses (psi)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tension</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>969.377</td>
<td>823.621</td>
</tr>
<tr>
<td>2</td>
<td>682.999</td>
<td>576.041</td>
</tr>
<tr>
<td>3</td>
<td>742.020</td>
<td>658.263</td>
</tr>
</tbody>
</table>

Table 6-14 Maximum principal stresses for the three modifications of type 10

To compare the three modifications, the second one was performing much better than the other two modifications as shown in table 6-14. This shows the importance of widening the inner width of corrugation. At the same time, these modifications did not result in making type 10 perform better than the other nine types shown in table 6-1, however, type 10 had make a huge jump in the ranking of the ten types to be ranked as number 4 instead of being number 10.
6.4.2 Three modifications of type 20

As shown in table 6-15, the second modification of type 20 had performed much better than the other two. As matter of fact, the other two modifications performed better than type 20 in compression, but not in tension. Again, this shows the importance of widening the inner width of corrugation.
Table 6-15 Maximum principal stresses for the three modifications of type 20

The second modification of type 20 has also performed better than the other nine types shown in table 6-3. Widening the inner width of corrugation made type 20 to be ranked as number 1 instead of being number 10. This modification of type 20 has also performed better than all the profiles tested in this thesis whether with or without a cover.

It can be noticed that the second modification had improved type 10 a lot but not as much as it did to type 20. This tells us again that using or not using a cover depends on the profile itself. It is not always true that using a cover will improve the performance.
Figure 6-8 Maximum Principal stresses for the second modification of type 20
6.5 Conclusions

Based on the previous sections in this chapter, several conclusions can be made. Looking at the whole profile, box-shaped profiles perform much better than circular profiles because box-shaped profiles have a higher stiffness than circular profiles.

Using a cover between the corrugations is not necessarily to improve the performance of the pipe; choosing between using a cover and not using a cover depends on the profile itself. However, it should be noted that using a cover will improve the performance of the web of corrugation. Also, since in the case of cover the web is not in contact with the soil, it would eliminate the direct pressure exerted on the web from the soil. The cover also increases the stiffness of the pipe significantly. However, increasing the stiffness can also be achieved by increasing the height of corrugation. In other words, increasing the pipe stiffness is not an enough reason to use a cover.

In the case a cover is used, it is recommended to use a straight cover. It is also recommended to use a curved profile for the web of corrugation instead of using a straight web. A curved web would give more stability to the profile. Finally, the width of corrugation should be divided in a balanced way between the liner of corrugation and the valley between corrugations. Unbalanced division of the corrugation width between the liner and the valley would result in a weak liner or valley.
6.6 Recommendations

It is important for future research to conduct experimental tests and determine the limits of some profile parameters such as corrugation width, corrugation height, the liner width and the valley width.

It is highly recommended to perform the same simulations that are done in this study using a visco-elastic material model instead of the linearly elastic material used in this thesis.
REFERENCES


   


11. ALGOR FEMPRO Version 15.0.
APPENDIX A

THE MAXIMUM PRINCIPAL STRESSES OF THE TWENTY PROFILES
SHOWN IN CHAPTER THREE
Figure A-1 Maximum principal stresses for type 1

Load Case: 1 of 1
Maximum Value: 603.331 lbf/in²
Minimum Value: -675.054 lbf/in²
Figure A-2 Maximum principal stresses for type 2
Load Case: 1 of 1
Maximum Value: 596.274 lb/in²
Minimum Value: -559.932 lb/in²

Figure A-3 Maximum principal stresses for type 3
Load Case: 1 of 1
Maximum Value: 701.333 lbf/\text{in}^2
Minimum Value: -464.959 lbf/\text{in}^2

Figure A-4 Maximum principal stresses for type 4
Figure A-5 Maximum principal stresses for type 5

Load Case: 1 of 1

Maximum Value: 571.463 lb/in^2

Minimum Value: -965.441 lb/in^2
Figure A-6 Maximum principal stresses for type 6
Figure A-7 Maximum principal stresses for type 7

Load Case: 1 of 1

Maximum Value: 840.632 lbf/in²

Minimum Value: -984.525 lbf/in²
Load Case: 1 of 1

Maximum Value: 728,378 lbf/in²

Minimum Value: -689,366 lbf/in²

Figure A-8 Maximum principal stresses for type 8
Load Case: 1 of 1
Maximum Value: 043.333 lbf/in
Minimum Value: -529.131 lbf/in

Figure A-9 Maximum principal stresses for type 9
Figure A-10 Maximum principal stresses for type 10
Figure A-11 Maximum principal stresses for type 11
Figure A-12 Maximum principal stresses for type 12
Figure A-13 Maximum principal stresses for type 13

Load Case: 1 of 1
Maximum Value: 682.248 lbf/in²
Minimum Value: -503.863 lbf/in²
Figure A-14 Maximum principal stresses for type 14

Load Case: 1 of 1

Maximum Value: 727.088 lbf/in²
Minimum Value: -607.555 lbf/in²
Load Case: 1 of 1
Maximum Value: 703,301 lbf/\text{in}^2
Minimum Value: -969,959 lbf/\text{in}^2

Figure A-15 Maximum principal stresses for type 15
Figure A-16 Maximum principal stresses for type 16

Load Case: 1 of 1

Maximum Value: 557.516 lbf/in²

Minimum Value: -963.301 lbf/in²
Figure A-17 Maximum principal stresses for type 17
Figure A-18 Maximum principal stresses for type 18

Load Case: 1 of 1

Maximum Value: 509.466 lbf/in²

Minimum Value: -575.554 lbf/in²
Load Case: 1 of 1
Maximum Value: 640.966 lbf/in²
Minimum Value: -977.362 lbf/in²

Figure A-19 Maximum principal stresses for type 19
Load Case: 1 of 1

Maximum Value: 340.246 lbf/in²

Minimum Value: -1524.737 lbf/in²

Figure A-20 Maximum principal stresses for type 20
APPENDIX B

THE MAXIMUM PRINCIPAL STRESSES OF THE EIGHT PROFILES USED TO STUDY THE WEB OF CORRUGATIONS
Figure B-1 Maximum principal stresses for the case of straight web without cover

Load Case: 1 of 1
Maximum Value: 556.964 lb/lin²
Minimum Value: -776.421 lb/lin²
Figure B-2 Maximum principal stresses for the case of web radius equal to 6 in. and without cover
Figure B-3 Maximum principal stresses for the case of web radius equal to 5 in. and without cover
Figure B-4 Maximum principal stresses for the case of web radius equal to 4 in. and without cover
Figure B-5 Maximum principal stresses for the case of straight web with cover

Load Case: 1 of 1

Maximum Value: 531.574 lb/ln²

Minimum Value: -944.038 lb/ln²
Figure B-6 Maximum principal stresses for the case of web radius equal to 6 in. and with cover
Figure B-7 Maximum principal stresses for the case of web radius equal to 5 in. and with cover
Figure B-8 Maximum principal stresses for the case of web radius equal to 4 in. and with cover
APPENDIX C

THE MAXIMUM PRINCIPAL STRESSES OF THE THREE PROFILES USED TO STUDY THE COVER BETWEEN CORRUGATIONS
Figure C-1 Maximum principal stresses for the case of straight cover

Load Case: 1 of 1
Maximum Value: 636.85 lbf/in^2
Minimum Value: -513.25 lbf/in^2
Figure C-2 Maximum principal stresses for the case of the cover concaved upward
Figure C-3 Maximum principal stresses for the case of the cover concaved downward