Re-rounding of Deflected Thermoplastic Conduit, Phase 2

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16. Abstract

Re-rounding is a technique for remediating excess deflection in a thermoplastic pipe using a pneumatic device vibrating along the vertical axis and pushing against the inside crown and invert to restore the original pipe shape and redistribute the surrounding backfill. Since the process has not been evaluated on HDPE pipe outside a couple older reports, and the method is routinely used by contractors to remediate deflected thermoplastic pipes, ODOT wanted to evaluate the technology as a lower-cost alternative to removal and reinstallation of deflected pipes. Three 36 in (0.9 m) HDPE pipes were installed in ODOT Structural Backfill Type 1 (Item 304 aggregate), 2 (sand), or 3 (AASHTO #57 aggregate), and two 18 in (0.45 m) pipes were installed in Type 2 and 3 backfill. Pipes were intentionally installed with substantial deflection (10% or more) and then re-rounded by a vendor. The pipe conditions were measured and monitored by collecting profiles, measuring vertical deflections, monitoring soil pressures, soil stiffness, acceleration of soil particles (peak particle velocity), backfill characteristics, and depth of pipe corrugation before and after re-rounding.

Re-rounding successfully reduced vertical deflections in all cases, though not always enough to meet the current serviceability criterion. The pipe in Item 304 backfill were the most resistant to re-rounding, going from -13.91% deflection to -8.62% after three passes with the device. The two pipes in Type 2 backfill (sand) responded better after two passes of the device (-9.89% to -8.57% for the 36 in (0.9 m) pipe and -14.50% to -7.47% for the 18 in (0.45 cm) pipe). Pipes in Type 3 backfill (AASHTO #57 aggregate) were much easier to re-round, taking only one pass of the device to go from -10.18% to -2.52% for the 36 in (0.9 m) pipe and -16.67% to -6.17% for the 18 in (0.45 m) pipe. Pressure data were consistent with redistribution of backfill particles, particularly fines.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(°F-32)/9 or (°F-32)/1.8	Celsius temperature	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2 or psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celsius temperature	1.8°C + 32	Fahrenheit temperature	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2 or psi

* SI is the symbol for the International Symbol of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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1 Project Background

AASHTO LRFD Bridge Construction Specifications, Section 30 on Thermoplastic Culverts indicates that pipes with deflections in excess of 7.5% should be remediated or replaced. This is the basis for the 7.5% deflection limit in the ODOT C&MS Specification 611.13. Under Item 611, the method of remediation is left to the contractor. Replacement is mandated by ODOT if deflection exceeds 12%. Thermoplastic pipes that have experienced deflection in excess of this 7.5% limit, without buckling, cracking, or other structural defects are often remediated using a technique called re-rounding. Re-rounding is performed placing a pneumatic vibratory compactor, such as that shown in Figure 1, inside the pipe which then applies pressure against the pipe wall and vibrates to restore the shape of the conduit and consolidate the backfill. Re-rounding is a technique generally limited to the mid-western US States. The re-rounding process has been allowed by ODOT as an acceptable method of remediating thermoplastic pipes with deflections in excess of 7.5% and requiring remediation in accordance with ODOT C&MS Specification 611. Although the technique has been around since its introduction by Williams Testing in the early 1980s, independent research is needed to ascertain the use and impacts of re-rounding on thermoplastic pipes. The cost of re-rounding also depends on the conduit's diameter and the length of re-rounding required. For example, the cost will be about $5 per foot ($16.40 per m) for a 15 in (380 mm) diameter conduit according to ODOT historical bid data.

The effectiveness of re-rounding may depend on the diameter, shape, corrugation type, and stiffness of the pipe and on the height, type, stiffness, and quality of the backfill. The magnitude of deflection and the elapsed time after installation are also important factors that may affect the success of re-rounding. The maximum deflection that re-rounding can address has not been determined. Another set of unknowns is how re-rounding impacts the mechanical properties of the pipe, backfill, or surrounding embankment. Damage to pipe corrugations and surface depressions in overlying pavement have been reported in some cases. The long-term serviceability of re-rounded pipe installations has not been determined, and there is a concern the original level of deflection could return. Also to be determined are the assumptions, limits, and factors to use in modelling re-rounded pipe and the impacts on strength-limit-state AASHTO LRFD Bridge Design Specifications.

2 Objectives

To answer these questions and address the need for independent research, an investigation was conducted to validate the use of re-rounding thermoplastic pipes as an option for ODOT. This includes determining if and when re-rounding is a viable option for repairing pipe deflection (while giving full consideration to the variables discussed above), and determining the maximum deflection for which the technique can be applied.

The investigation encompasses two phases. In Phase 1, current practices in Ohio and other states were evaluated and relevant parameters determined. Equipment options for re-rounding were also investigated, and a plan was presented for field evaluation of re-rounding techniques. Phase 2, reported here, consisted of execution of the field test plan.

The main objective of the field evaluation is to validate re-rounding as a viable remediation technique for HDPE pipe exceeding maximum allowable deflection and examine the long-term service of re-rounded pipe. The viability was assessed by investigating the reduction in deflection after re-rounding. The effects of installation variables, especially the type of backfill and magnitude of deflection, on the resulting performance of re-rounding was determined by the following measures of success: the reduction in deflection of the pipe, lack of damage to pipe structure or corrugation, lack of pavement damage, and whether these improvements are likely to be long-lasting. In short, is the change in diameter sustainable?

Figure 1. Pipe re-rounding device at pipe entrance [ADS, 2009].

3 Outline of Study

The research team began by conducting a literature search and other investigations as needed to assess the current best practices for re-rounding. The available literature directly related to re-rounding is scant, but there are some related topics, such as the nature of deformations or effect of vibrations on pipes which provided some insights. A survey of state departments of transportation was created and disseminated with the assistance of the ODOT Research Office, and the results are compiled in an appendix and summarized in this report.

The bulk of the research centered on an experimental study involving a series of pipes installed with built-in deflections, which were measured before and after re-rounding. The methods of installation and instrumentation are described. After the first two pipes were studied, a device was created to better ensure a desired level of deflection during installation. The collected data were then analyzed to determine shape profiles and deflections; other parameters measured are discussed as well. There was a limited study at some field sites, described in a brief chapter.

The report ends with a conclusion describing findings and recommendations.

4 Literature Review

4.1 Studies of Re-rounding

Studies of re-rounding in the literature are very limited, with one early report commissioned by a vendor, and a more recent report by a pipe manufacturer. An early report by R. Germann [1982] for Williams Testing evaluated the effect of re-rounding PVC pipe used in sewer lines. PVC pipe with diameters of 8 in (20 cm) and 15 in (38 cm) were each installed in a load cell and an actuator stress of 900 psi (6.2 MPa) was applied, equivalent to a burial depth of 27 ft (8.2 m), making the deflection 10% before re-rounding. The bedding for the pipe consisted of uncompacted bank-run sand and the backfill was uncompacted granular material. The re-rounder was applied through the length of the pipe with the load held constant. After subsequently increasing the load to 1000 psi (6.9 MPa) or 30 ft (9.1 m) depth equivalent, the deflection stayed below 1%. Then at 3000 psi (21 MPa), or 88 ft (27 m) depth equivalent, deflection was under 3%. Similar deflection results after re-rounding were obtained for pipes in bedding consisting of crushed limestone, bank run gravel, or sand.

Compaction measurements after re-rounding were made in the fill 30 in (76 cm) above the pipe centerline and at 12 in (30.5 cm) from the center at the springline. For the 8 in (20 cm) diameter pipe, the density above the crown was measured at 95.46% with 5.6% moisture (optimum was 9%); at the springline the density was 91% at 7.2% moisture; and below the invert the density was 96% at 4.3% moisture. For the 15 in (38 cm) pipe, these values were 91.0% density at 7.2% moisture at the top and 89.8% density at 5.3% moisture at the springline. Thus the author concludes that re-rounding can facilitate installation of PVC pipe by achieving suitable levels of compaction in four different broad classes of soils, including manufactured sand (Class I), clean sand and gravel (Class II), sand with gravel and fines (Class III), and silt and clay (Class IV).

A more recent investigation was conducted by Advanced Drainage Systems, Inc. [ADS, 2009] at two sites with HDPE pipe. The first case was a 60 in (152 cm) diameter pipe in Cleveland under approximately 20 ft (6.1 m) of AASHTO #57 crushed stone backfill, which had been re-rounded ca. 1999. The original re-rounding process increased the minimum vertical diameter from 51 in (130 cm or 15% diameter decrease from the original size) to 55 in (140 cm, or 8.3% diameter decrease). At an inspection in March 2009, the vertical diameter ranged from 55 in (140 cm, 8.3% decrease) to 57 in (145 cm, 5% decrease). The pipe was 'slightly racked", but the deflection did not increase after re-rounding.

The second case studied in the ADS [2009] report was a July 2009 re-rounding demonstration at Williams Testing using their 1980s method. The specimen of 24 in (61 cm) pipe was placed in the load cell and manufactured sand placed as backfill to a height of 3 ft (91 cm) above the crown. Loads were applied of 1200 psi (8.3 MPa), 1800 psi (12.4 MPa), and 700 psi (4.8 MPa). Re-rounding was then performed under a load of 500 psi (3.4 MPa) and the cell loaded to 1100 psi (7.6 MPa) and 1800 psi (12.4 MPa) before applying a load of 1400 psi (9.7 MPa) and performing a second re-rounding procedure at 900 psi (6.2 MPa). The second load in the initial set (1800 psi (12.4 MPa)) led to a 6%-11% deflection that was reduced to 1% or less by the first re-rounding operation. After the additional load stages after re-rounding reached a second application of 1800 psi (12.4 MPa), the deflection in the pipe reached 1.75%-4%, and the second re-rounding operation reduced that to 2% or less. The consolidation from the first 1800 psi (12.4 MPa) load was maintained or increased during the re-rounding procedure, as the deflection under load afterwards was not as large as before. The pipe was removed from the cell after testing and inspected for damage, of which none was observed; highly compacted sand remained in the pipe corrugations.

4.2 Deformation Types

Incorrect backfilling and installation procedures lead to poorly compacted soil which is the major cause of excess deformations in HDPE pipes [Sargand et al., 2016]. This conclusion agrees with the findings of a lab study by Tafreshi and Khalaj [2008] conducted on small diameter HDPE pipes, where uncompacted soil around the pipe led to major damage to the pipe under repeated applied loads.

According to a study by Motahari and Abolmaali [2009], HDPE pipe deformations can be classified into six different shapes as shown in Figure 2: (a) Symmetrical deformation along the horizontal x-axis, (b) Symmetrical deformation along the vertical y-axis, (c) Ovality or racking deformation, (d) Crown flattening, (e) Inverse curvature, (f) Buckling.

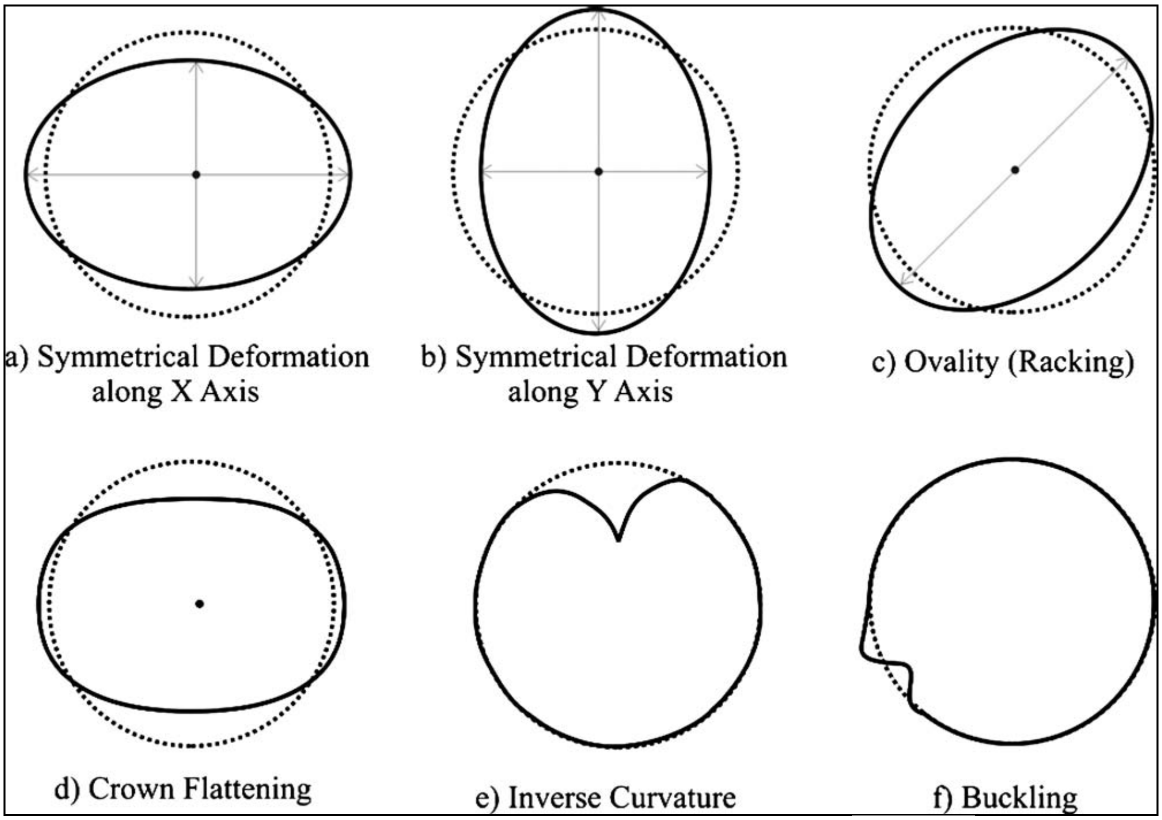

Figure 2. Different types of pipe deformations [Motahari and Abolmaali, 2009].

Motahari and Abolmaali [2009] describe each type of deformation. Symmetrical deformation along the horizontal x-axis occurs when the loads are transferred to the plastic pipe from the soil fill above, causing the pipe to deform and elongate the diameter along the horizontal x-axis. On the other hand, symmetrical deformation along the vertical y-axis occurs when the soil is compacted from the sides, which applies horizontal pressure on the pipe, elongating the diameter along the y-axis. Ovality deformation takes place when the pipe diameter deforms in a diagonal direction, which is also known as racking. Crown flattening deformation depends on the load type and how the backfill soil was compacted; these factors cause the crown of the culvert to flatten and deflect downward. Inverse curvature or "snap through" occurs when the pipe deforms into a reversed shape due to loss of stability, which forces the pipe into tensile strain instead of compressive strain. The last deformation type is called buckling or "out-of-plane deformation" and occurs when the pipe undergoes large circumferential stresses, causing longitudinal and/or radial waves to appear on its surface.

4.3 Pipe Installation Methods and Specifications

The American Association of State Highway Transportation Officials (AASHTO) published a manual of Load Rating Factor Design (LRFD) Specifications [AASHTO, 2017] in two volumes covering bridge design and bridge construction. These volumes govern installation of various types of conduits, including thermoplastic pipe, and define the functions of each of the different embankment areas:

bedding, haunch zone, side-fill, top-fill, and the minimum cover required above the plastic pipe. The LRFD specifications also contain recommended deflection limits for thermoplastic pipes, which trigger a requirement to remediate the damage (e.g. by re-rounding) or replace the pipe. Some suggested solutions to prevent excess deflection during installation are also given.

4.3.1 LRFD Bridge Design Specifications

Section 12 of the AASHTO LRFD Bridge Design Specifications [2017] covers the design of buried structures and tunnel liners. Subsection 12.12 for thermoplastic pipe is a comprehensive design methodology that considers limit states for local buckling, compressive and tensile strain, general buckling, deflection, and handling and installation.

McGrath and Sagan [1999; also Witczak, Mamlouk, Souliman, and Zeiada, 2013] developed the method for assessing local buckling using the effective width concept originally developed for cold-formed steel by Winter [1947]. The method is based on the concept that close to an element support, individual profile elements retain considerable post-buckling capacity. These areas are termed effective areas, and the summation of the element effective areas results in the post-buckling effective area of the profile.

The compressive strain is determined through the summation of the ring compression strain and the compressive component of the flexural strain resulting from pipe deflection. The tensile strain is determined by subtracting the ring compression strain from the tensile component of the flexural strain resulting from flexural pipe deflection. The flexural strain is determined considering 5% vertical deflection which is the limit in the LRFD Bridge Construction Specifications [2017]. The code also places limits of 5% on ring compressive strain and 4.1% on tensile strain. Additionally, the code specifies that the combined (both ring and flexural) compressive strain limit is 50% greater than that for ring compressive strain. The reasoning given is that flexural strain is minimized near the neutral axis of the profile wall and profile elements in this area are unlikely to experience local buckling.

Global wall buckling is controlled by limiting the total wall strain to a value less than that required to initiate global bucking. Global buckling is determined via a simplified version of the continuum buckling equation developed by Moore [1990].

HDPE thermoplastic pipes experience significant circumferential shortening during loading. For this reason, the AASHTO equation for determining total vertical deflection includes an expression for circumferential shortening coupled with Watkins and Spangler's Modified Iowa Equation for predicting the flexural deflection of flexible pipes.

The final design check is an empirically derived parameter to ensure the pipe has sufficient stiffness to resist the forces applied during handling and installation.

4.3.2 LRFD Bridge Construction Specifications

AASHTO also guides the installation of HDPE pipes in Section 30 of AASHTO LRFD Bridge Construction Specifications [2017]. The code provides detailed provisions for trench width; foundation preparation; bedding, backfill, and top fill materials and compaction; and post-construction inspection.

Before describing installation procedures, it is necessary to provide a general overview of AASHTO installation-related nomenclature. There are numerous publications and specifications which detail culvert installation and nomenclature. However, for the sake of consistency, only AASHTO Section 30 will be discussed herein. Reference is made to Figure 3 for the following discussion.

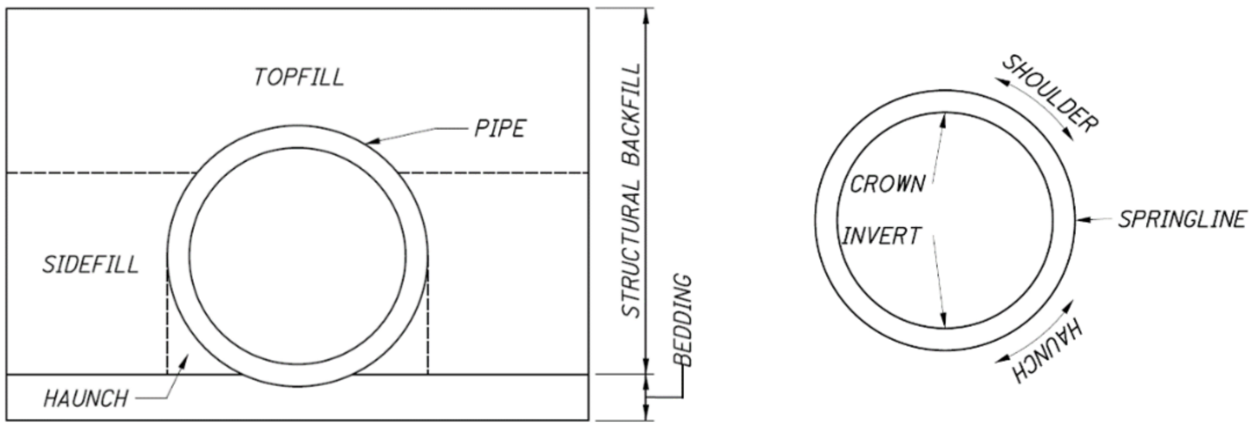

Figure 3. Pipe Installation Nomenclature, adapted from LRFD specifications [AASHTO, 2017].

Installed pipes are typically placed on a prepared bedding which rests on the natural foundation soil. AASHTO LRFD Section 30 allows for the use of the natural foundation as a bedding material if the material meets the bedding material requirements. The bedding thickness should not be less than 6 in (0.15 m) where the foundation consists of rocks and boulders, and not less than 4 in (0.1 m) for soft spots. Non-mandatory language (commentary) recommends the middle one-third of the bedding width be left uncompacted. This allows the pipe to seat itself which precludes invert point loading. The soft middle third also promotes soil arching by allowing the pipe to move downward relative to the surrounding soil.

Above the bedding, compacted material is placed to provide structural support for the pipe. This material is called structural backfill. The structural backfill and the pipe are referred to as the pipe-soil system. The structural backfill consists of three soil zones: the sidefill, topfill, and haunch, shown in Figure 3 above.

The structural backfill between the haunch and the topfill is the sidefill, and it provides resistance to horizontal deformation of the sides of the pipe. The sidefill extends vertically from the top of bedding to the shoulder of the pipe. The topfill is the structural backfill above the sidefill to not more than 6 in (0.15 m) above the top of the pipe. The haunch is the area between the springline of the pipe and the bedding. This area typically requires hand compaction since mechanical compaction equipment cannot fit within this zone.

Section 30 requires the sidefill to be AASHTO A-1 or A-3 soil compacted to 90% of standard Proctor density (SPD), or A-2-4 or A-2-5 soil compacted to 95% of SPD. Bedding compaction requirements are similar. Sidefill must be placed in loose lifts not to exceed 8 in (0.2 m). This ensures uniform soil density and minimizes pipe distortion during installation.

Installations are generally classified as either embankment installations or trench installations, shown in Figure 4. An embankment installation is where the pipe is placed on a prepared bedding above the in-situ ground surface. A trench installation is where the in-situ soil is excavated, and the pipe is placed on the prepared bedding below the in-situ ground surface.

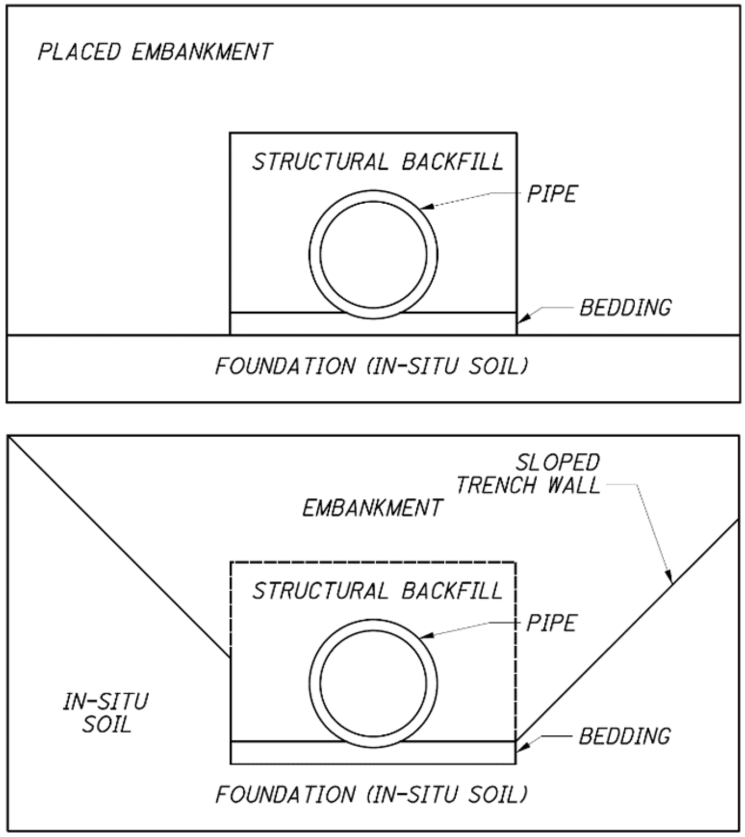

Figure 4. Typical installation types Embankment (above) and Trench (below), adapted from the LRFD Specifications [AASHTO, 2017].

During the post-construction inspection, acceptable vertical deflection is limited to 5%. Deflections greater than 5% but less than 7.5% require evaluation by a Professional Engineer "considering the severity of the deflection, structural integrity, environmental conditions, and the design service life of the pipe." Pipes with deflection above 7.5% require remediation or replacement. While the code permits remediation for locations where deflections could be an issue, the code does not indicate how to remediate any particular defect.

ODOT Construction and Materials Specification (C&MS) 611.13 [ODOT, 2019] also mandates repair or replacement of pipes deflected more than 7.5%; replacement is mandated if deflection exceeds 12%. ODOT Item 611 also requires a minimum 30-day waiting period between the pipe installation and the post-construction performance inspections [Ohio Department of Transportation, 2019]. The literature supports the 30-day waiting period as generally being sufficient time for a pipe installation to stabilize [Cassiday, 1994; Sargand, et al., 2002].

4.4 Vibration Induced Damage

Vibration induced damage primarily affects three types of receivers. Types of damage include annoyance of people, damage to structures, and the interruption of sensitive electronic equipment [Andrews, Buehler, Gill, and Bender, 2013]. Construction damage is important within the context of this research. The vibration produced during re-rounding has the potential to cause structural damage to the conduit or the pavement above the conduit being re-rounded.

The peak particle velocity (PPV) necessary to damage structures has been widely researched. However, most of the research is focused on damage to residential and commercial buildings. The threshold PPV that results in structural damage varies widely depending on the source. Dowding [1996] compiled a table of numerous sources of threshold PPV values necessary to induce structural damage such as cracking of gypsum wallboard or plaster walls, cracking of brick or masonry, and cracking of concrete block. The threshold PPV values vary from 0.8 in/s (20 mm/s) to 12 in/s (300 mm/s).

Table 1. Recommended values for the material damping coefficient α from Caltrans [Andrews, Buehler, Gill, and Bender, 2013].

Investigator	Soil Type	α (ft⁻¹)		α (m⁻¹)	
Forssblad	Silty gravelly sand	0.04		0.13	
Richart	4 in (0.1 m) concrete slab over compacted granular fill	0.006		0.020	
Woods	Silty fine sand	0.079		0.26	
Barkan	Saturated fine grain sand	0.003		0.010	
	Saturated fine grain sand in frozen state	0.018		0.059	
	Saturated sand with laminae of peat and organic silt	0.012		0.039	
	Clayey sand, clay with some sand, and silt above water level	0.012		0.039	
	Marley chalk	0.03		0.10	
	Loess and loessial soil	0.03		0.10	
Dalmatov	Saturated clay with sand and silt	0	0.037	0.00	0.12
	Sand and silt	0.079	0.11	0.26	0.36
Clough and Chameau	Sand fill over bay mud	0.015	0.061	0.05	0.20
	Dune sand	0.076	0.2	0.25	0.66
Peng	Soft Bangkok clay	0.006		0.02	

Note: Dalmatov and Clough and Chameau gave ranges of values.

CalTrans [Andrews, Buehler, Gill, and Bender, 2013] has published threshold values for damage to several structure types based on the source being a transient source or a continuous/frequent intermittent source. These values of PPV are provided in Table 2. AASHTO also has recommended PPV threshold values [1990] which are in relatively close agreement with the Caltrans transient source values.

Damage to asphalt pavements can be assessed considering the endurance limit of the pavement. Fatigue damage consisting of bottom-up fatigue cracking typically does not occur at strain levels below this strain limit [Witczak, Mamlouk, Souliman, and Zeiada, 2013]. The figures and tables in this report present endurance limits that vary anywhere from 1με to approximately 82με. The same report concludes: "HMA exhibits an endurance limit that varies with mixture properties, temperature, and pavement design conditions. There is no single value of the endurance limit for all conditions. The endurance limit varies depending on binder grade, binder content, air voids, temperature, and the rest period between load applications." Tran, et. al. [2016] reported laboratory fatigue endurance limits for typical asphalt pavements in the range of 84με to 151με. Considering the research results presented herein, a fatigue endurance limit for strain in asphalt pavements of 70με is a reasonably conservative value, which has been used for asphalt concrete pavement to withstand bottom-up cracking [Brown and Timm, 2006; Newcomb, 2002; Sargand, Figueroa, and Romanello, 2008; Witczak et al., 2013].

Table 2 Threshold PPV values for vibration damage [Andrews, Buehler, Gill, and Bender, 2013].

	Maximum Peak Particle Velocity (PPV)			
	Transient Sources		Continuous or Frequent Intermittent Sources	
Structure and Condition	(in/s)	(mm/s)	(in/s)	(mm/s)
Extremely fragile historic buildings, ruins, ancient monuments	0.12	3.0	0.08	2.0
Fragile buildings	0.2	5.1	0.1	2.5
Historic and some old buildings	0.5	12.7	0.25	6.4
Older residential structures	0.5	12.7	0.3	7.6
New residential structure	1	25.4	0.5	12.7
Modern industrial/commercial buildings	2	50.8	0.5	12.7

4.5 Consolidation of Granular Soils due to Vibratory Compaction

It is believed that the vibrational energy imparted to the pipe wall and surrounding backfill soil will result in the consolidation of the granular materials typically used as pipe backfill. According to Das [1983], the consolidation of granular soils commonly used as bedding and backfill for an installed thermoplastic pipe can be tested in the laboratory either by the application of repeated vertical stress with minimal vertical acceleration or via the application of repeated vertical accelerations with minimal vertical stress.

The first case, with repeated vertical stresses, was investigated by D'Appolonia [1970]. When controlled vertical stress was applied to dune sand using low accelerations, the ratio of the reduced vertical height of the soil specimen to the initial height of the soil specimen was found to be proportional to the log of the number of load cycles when controlling for the ratio of confining stress to cyclic stress.

The second case, with repeated vertical accelerations, was investigated by D'Appolonia and D'Appolonia [1967] and by Ortigosa and Whitman [1968]. Both teams determined there is very little consolidation of materials at accelerations less than 1g (32.2 ft/s^2 or 9.81 m/s^2).

Höeg [1966] developed a method for determining the response of a linearly elastic hollow cylinder (e.g. a pipe) in a linearly elastic medium. As part of the analytical solution, Höeg introduced the compressibility ratio which is a measure of the relative hoop stiffness of the cylinder and surrounding continuum. The compressibility ratio, C, is defined as:

$$C = \frac{1}{2}\frac{1}{1-\nu}\frac{M}{\frac{E_c}{1-\nu_c^2}}\left(\frac{D}{t}\right)$$

where:

M = one-dimensional soil modulus
ν = one-dimensional Poisson's ratio of the soil
E_c = Young's modulus of the cylinder
ν_c = Poisson's ratio of the cylinder
D = average diameter of the cylinder
t = thickness of the cylinder wall

At that time a novel concept in the installation of reinforced concrete pipe was to surround the pipe in a layer of loose soil. This loose "backpacking" soil would tend to promote positive arching and reduce the load on the installed pipe. Höeg considered this installation technique by modifying the compressibility ratio. He considered the loose soil to be a part of the ring. This increases the effective compressibility ratio.

The re-rounding process presents the interesting possibility of the reversal of Höeg's modified compressibility ratio approach wherein the soil surrounding the ring is stiffened, with a resulting decrease in the effective compressibility ratio.

5 Survey of State DOTs

A survey questionnaire for state department of transportation (DOT) professionals in the area of thermoplastic pipes was drawn up by the research team in consultation with the ODOT subject matter experts. The ODOT research office set up an online form via Formstack and disseminated the link via their contacts across the United States on November 1, 2016. As of the final response on November 15, seventeen responses had been gathered from sixteen states: AL, CA, CT, DE, GA, IL, ME, MI (two responses), MN, MT, NE, ND, TN, UT, VA, WA. The two responses from Michigan were essentially duplicates, so responses were compiled based on sixteen states (N=16). The questions are given in Appendix A. The following summarizes the responses received. A more detailed account is given in Appendix A.

The first question of the survey asked if the state used deflection as a quality control check on thermoplastic pipe installations. Three quarters (75%, 12 states: DE, IL, ME, MI, MN, MT, NE, ND, TN, UT, VA, WA) said that they did, and the rest (AL, CA, CT, GA) said they did not. The maximum deflection criteria given in the responses to Question 5 was 5% deflection for 11 states (69%: DE, GA, IL, ME, MN, NE, UT, WA). DE, GA, and UT further indicated that a 5% deflection triggers an engineer review of the installation, and 7.5% requires removal and replacement, which follows the AASHTO LRFD specifications [2017]. The following criteria were each cited by one state (6.2% of responses): 6% (CT), 7% (MT), and 7.40% (VA). Question 6 asked if pipes failing the criterion must be replaced, and "Yes" was by far the most popular answer, chosen by 12 states (75%, CA ("typically"), CT, DE, GA, IL, ME, MI, MT, ND, TN, UT, VA), with DE, GA, and UT indicating the threshold for removal was 7.5% deflection. MN indicated removal was decided on a case by case basis (Deducting contractor payment was an option), and NE said it was up to engineer discretion.

Only 1 state (6.2%), AL, said they used re-rounding (Question 4), while many of the others either were interested in adopting the technique ("Yes", 4 states, 25%: DE, GA, ME, UT) or potentially interested ("Maybe", 3 states, 19%: MN, VA, WA). AL was the only state who had any specifications, but those were not supplied (and their answers to various fill-in questions was "123"). Hence, there was no response to the call for documents in Question 5a, no specific re-rounding companies identified in Question 6, and no stories to offer for Question 7 (AL responded "123" to the latter two).

6 Field Study

The Phase 2 work plan included a field study to document and analyze the effects of re-rounding. The field work included determining the site conditions before and after re-rounding, installation of pipes with varying site parameters using ODOT approved materials and installation techniques. The goal was to locate 5 field pipes with excessive vertical deflection. However, during the study, only one site was identified.

The project site is located along Interstate Route 75 in Toledo. The specific section of conduit is a 15 in (0.4 m) conduit identified in the project plans as D-9 to D-10. The location is beyond the pavement limits of the roadway. The pipe location is provided in Figure 5 and the profile view of the conduit is provided in Figure 6. The maximum depth of fill over the conduit is approximately 12 ft (3.7 m). The contractor's installation plan specified either ODOT Structural backfill Type 1 or Type 2, but the research team was not able to obtain more specific information on the backfill.

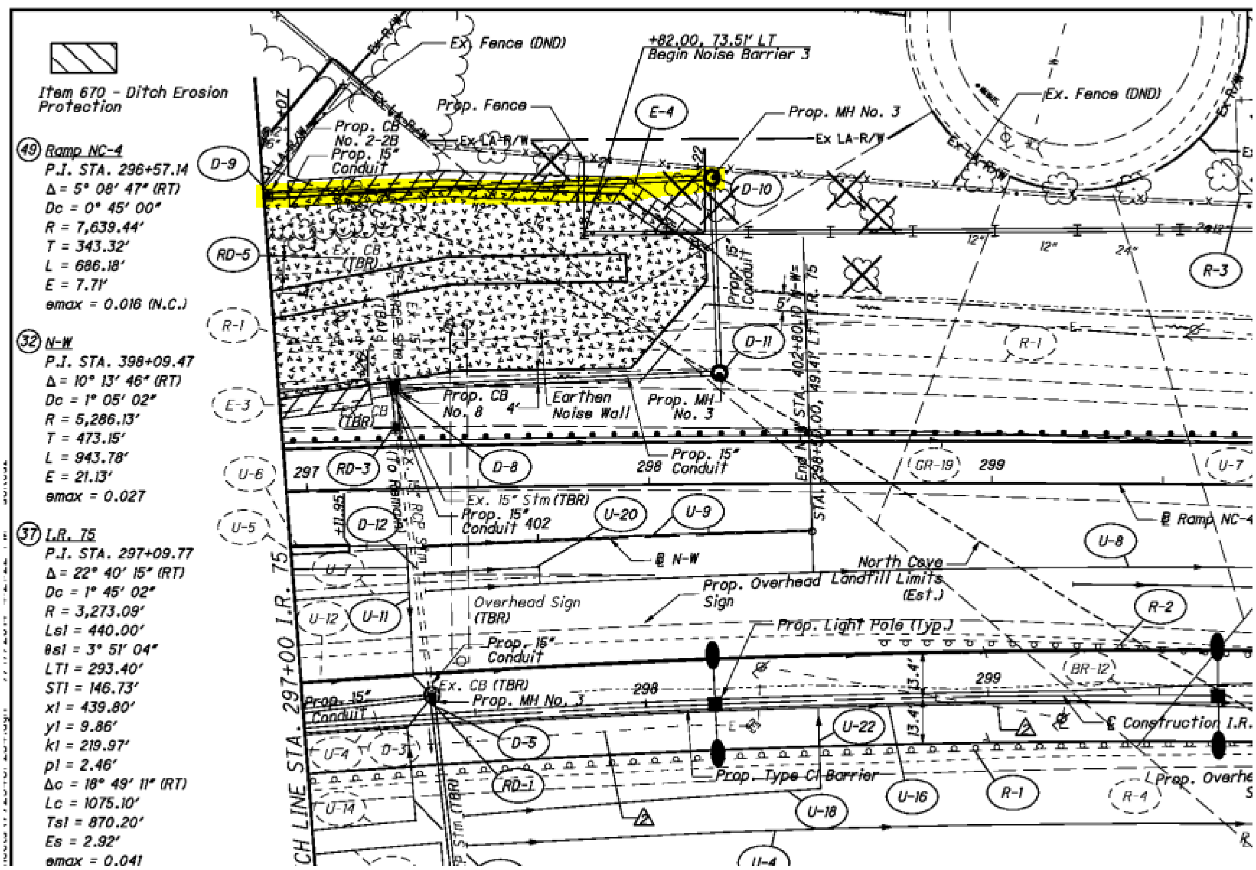

Figure 5. Plan View of Conduit along IR 75 in Toledo. The conduit is highlighted in yellow.

A remote video inspection and laser profile were performed by the contractor on September 28, 2018. The cross-section taken at the location of maximum vertical deflection is shown in Figure 7. The vertical deflection at this location is estimated to be in excess of 15%.

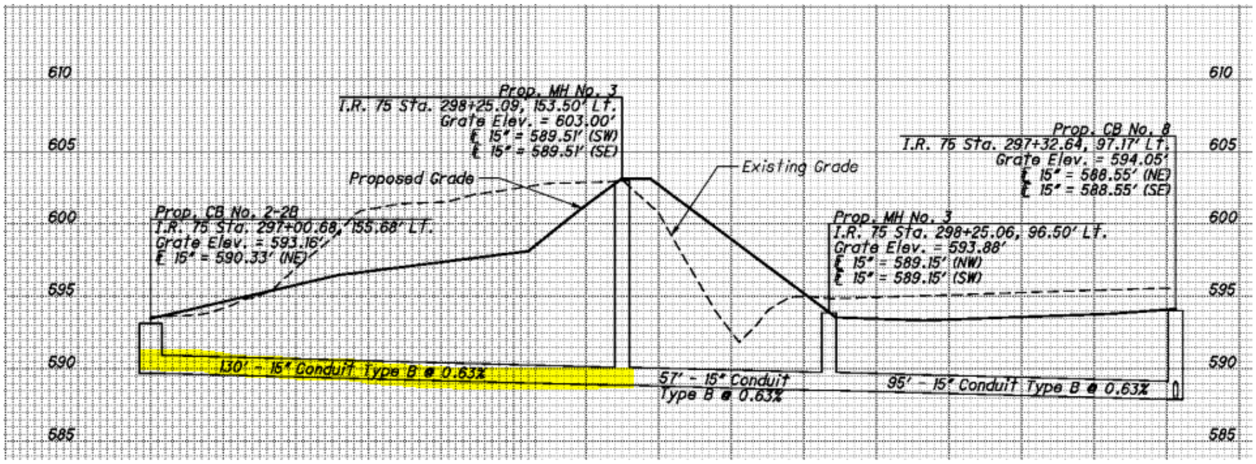

Figure 6. Profile View of Conduit along IR 75 in Toledo. The segment to be re-rounded is highlighted.

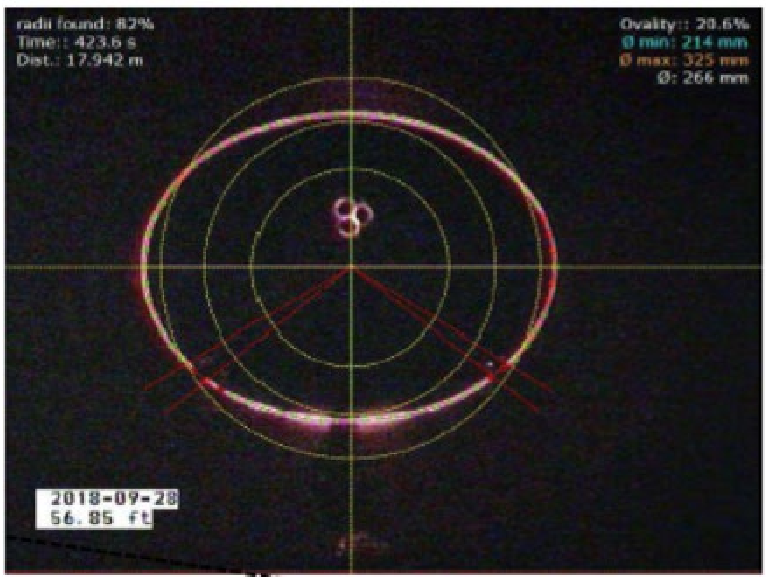

Figure 7. Maximum vertical deflection of conduit along IR 75 in Toledo.

An ORITE team travelled to the project site on December 5 and 6, 2018 to observe the re-rounding process on site. ORITE brought its cone penetrometer truck (CPT) to obtain information regarding the in-situ properties of the backfill material used during installation of the conduit. Unfortunately, the soil above the pipe was too soft to support the truck so CPT measurements could not be collected.

The contractor performed a post-re-rounding laser scan of the conduit on December 6, 2018. The profile plot of the re-rounded conduit is provided in Figure 9. The measurements show a maximum vertical deflection immediately after re-rounding of 7.5%.

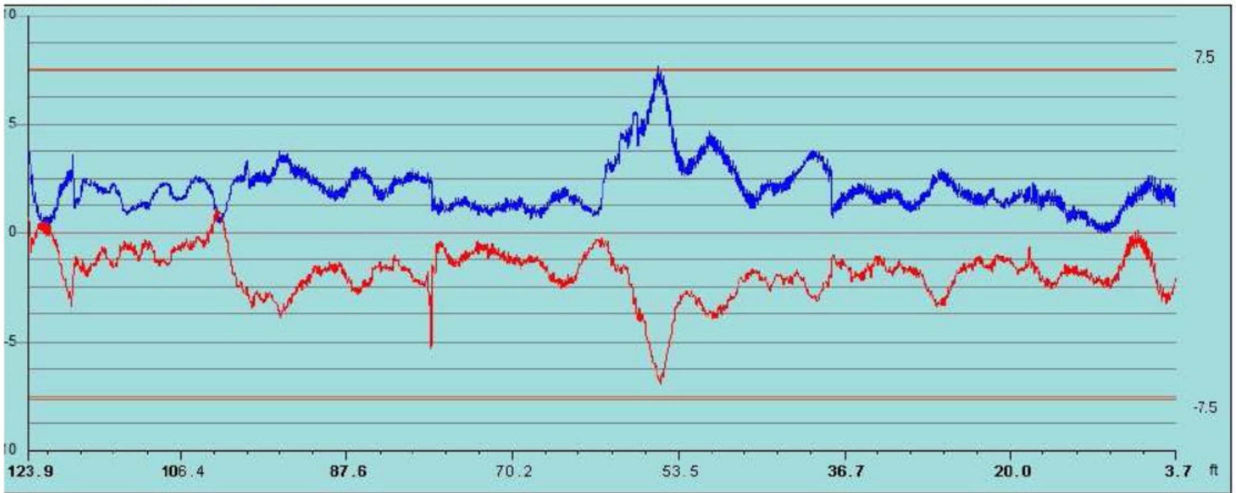

Figure 8. Conduit profile report immediately after re-rounding, showing maximum deflection after re-rounding of 7.5%.

The contractor followed up with another video inspection and laser profile on May 21, 2019, approximately 6 months after the conduit was re-rounded. The results of the profilometer showed a maximum vertical deflection of 7%. The profile report for the conduit is provided in Figure 9.

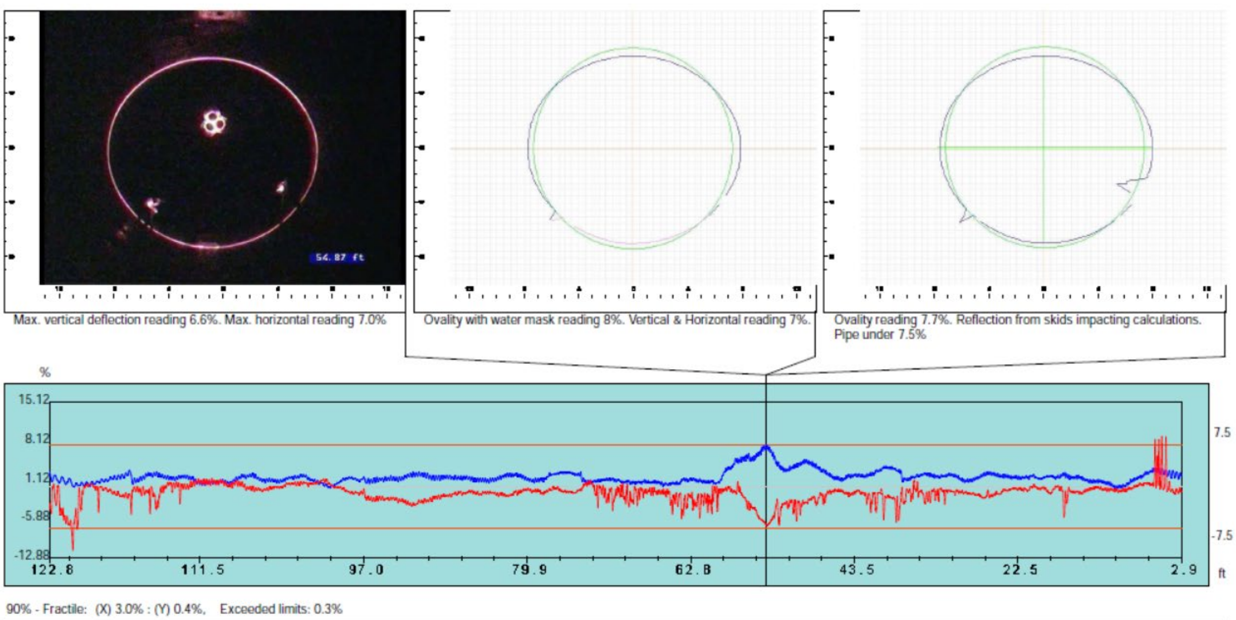

Figure 9. Conduit profile report 6 months after re-rounding. The maximum deflection is 7%, as shown in the profile at top center.

7 Experimental Study Method

7.1 General description of experiment

Phase 2 also included an experimental portion dedicated to understanding the mechanism and impacts of re-rounding on the pipe system and backfill in a controlled and systematic manner. The experiments were conducted at ORITE's load frame facility where pipes can be installed under controlled conditions. The proposed and executed test matrix is given in Table 3, which notes diameter, backfill type, and installed deflection level.

A total of 5 pipes were tested. Pipes consisted of a 20 ft (6.1 m) section with joints at either end connecting to additional lengths of at least 10 ft (3.0 m), all placed in the specified backfill to a depth of twice the diameter and then covered to a depth of 10 ft (3.0 m) with fill dirt, as shown in the schematic diagrams in Figure 10 and Figure 11. All pipes included joints. Three pipes were 36 in (91 cm) diameter double wall. Each was installed according to figure; backfill for the first one was ODOT Item 304 (Type I backfill), the second had sand (Type II backfill), and the third used AASTHO # 57 open-graded aggregate (Type III backfill). The other pipes were 18 in (0.45 m) diameter double wall, with the fourth pipe installed in AASTHO # 57 open-graded aggregate (Type III backfill) and the fifth pipe installed in sand (Type II backfill). A plan to test a sixth pipe in Type I backfill was abandoned after the experiment on Pipe 1 showed pipes in Type I backfill to be very difficult to re-round.

Instrumentation included pressure cells, as shown in the schematic diagram in Figure 12, located below the pipe, above the crown, and on both sides at the springline. Parameters monitored in these experiments before, during, and after re-rounding included pipe shape, pipe deflection, soil pressure in backfill, gradation (Item 304 only), backfill stiffness (Pipes 2 and 3), acceleration of backfill/peak particle velocity (Pipes 2-5), and corrugation shape (Pipes 2 and 3), with a few exceptions mentioned in the discussion of the individual experiments. Once those measurements were complete, a forensic study was conducted to determine the movement of material in backfill in response to the vibrations from re-rounding. Table 3 summarizes the instrumentation of the pipes and the dates of installation, re-rounding, and exhumation.

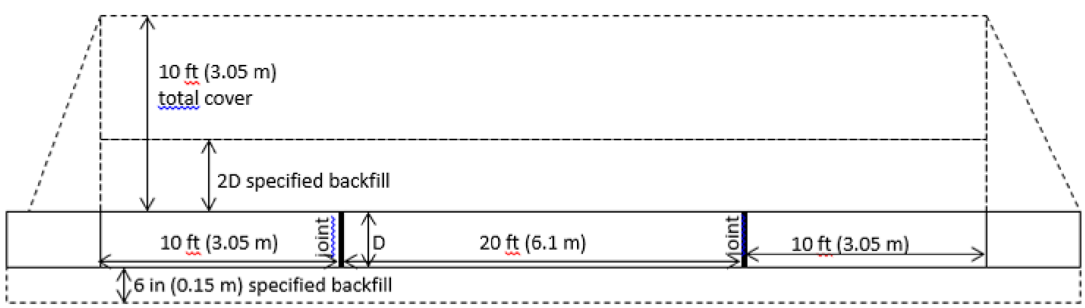

Figure 10. Profile diagram of experimental pipe installation. D is the pipe diameter.

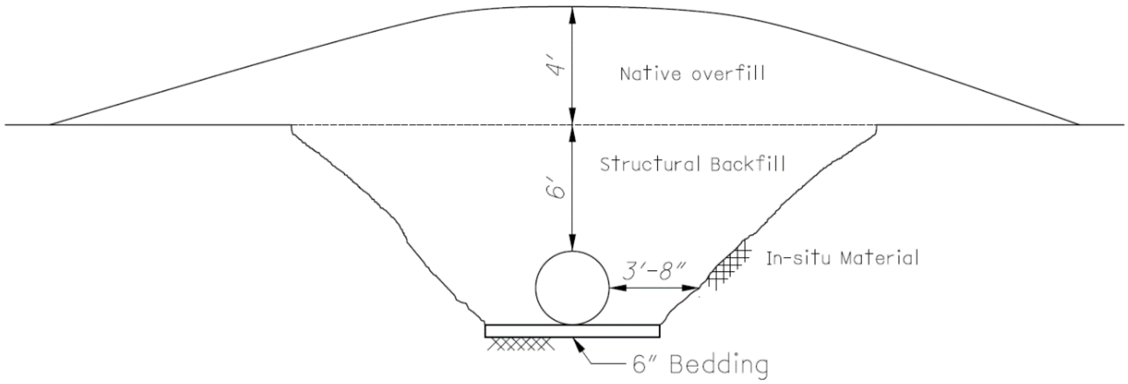

Figure 11. Typical installation cross-section diagram.

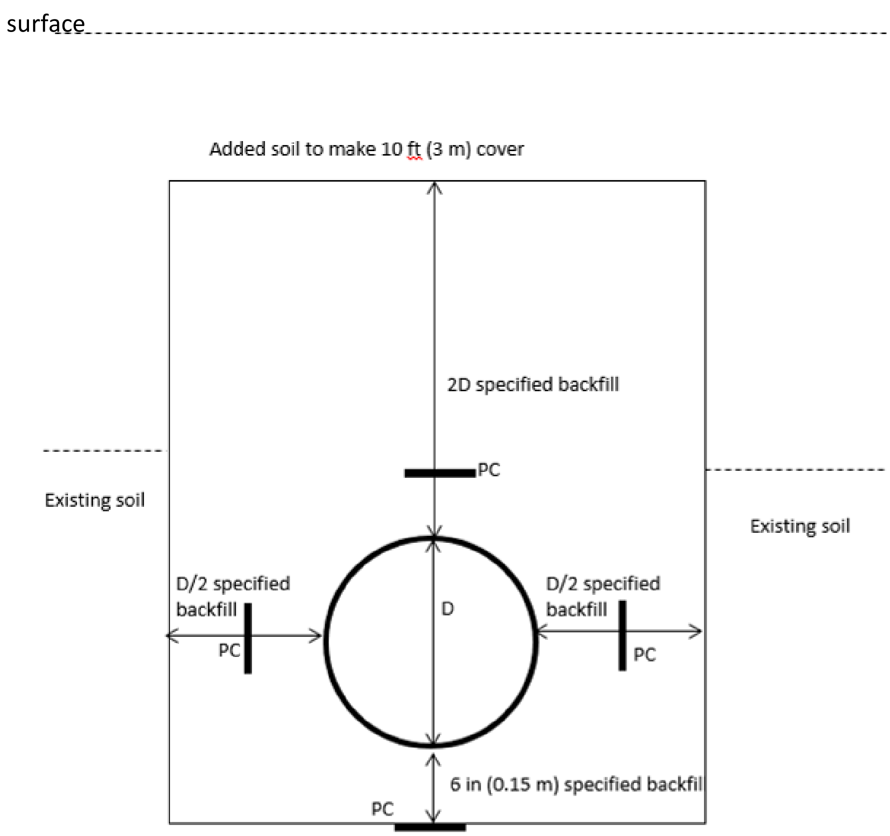

Figure 12. Diagram of experimental pipe installation with pressure cells. D is the pipe diameter.

Table 3. Summary of installation details for Test Pipes 1-5.

Parameter	Pipe 1	Pipe 2	Pipe 3	Pipe 4	Pipe 5
Installation Date	12/07/2017	8/2/2018	12/12/2019	6/24/2020	10/22/2020
Re-Rounding Date	6/14/2018	10/29/2018	1/29/2020	9/10/2020	2/23/2021
Exhumation Date	8/1/2018	5/20/2019	6/23/2020	10/21/2020	3/30/2021
Inner Diameter	36 in (0.9 m)	36 in (0.9 m)	36 in (0.9 m)	18 in (0.45 m)	18 in (0.45 m)
Structural Backfill	Type 1 (304)	Type 2 (sand)	Type 3 (#57)	Type 3 (#57)	Type 2 (sand)
Target Deflection	10%	10%	10%	10%	10%
Pressure cells	Both springlines and crown				
Accelerometers	none	6 in (150 mm) and 18 in (460 mm) above crown			
Soil-stiffness gauge	Shoulder & springline (unsuccessful)	Shoulder & springline	Haunch	none	none
Corrugation depth	yes	yes	yes	no	no
Re-rounding passes	3	2	1	1	2

7.2 Re-rounding vendor selection

There are two companies who perform re-rounding work in Ohio, Drier and Maller, Inc. of Reynoldsburg who employ technology developed by Hurco Technologies of Harrisburg SD, and Williams Testing, Inc., of Harrod OH, who use equipment they developed [Sargand et al., 2017b]. The Williams device is comprised of two semi-circular plates which are pushed against the crown and invert of the pipe while the plates are vibrated via an eccentric vibrator. The Hurco device is a series of increasing diameter mandrels placed along a rod which is pulled through the pipe while vibrating. These devices are depicted in Figure 13.

The original research plan called for using both vendors on various pipes so a comparison could be made. However, after discussions with the local provider of the Hurco procedure, they decided their system would not perform well on HDPE drainage pipes, so they declined to participate further in the study. Thus, all the re-rounding was performed by Williams Testing, Inc. The company website claims re-rounding was invented over 30 years ago by Dick Williams, a sewer contractor, as an improved method to solve flexible pipe deflection problems in sewers up to 60 in (1.5 m) diameter [Williams Testing, 2021]. In the re-rounding process, the device is passed through the pipe, after which a mandrel is used to determine if the re-rounding has been successful or whether another pass is warranted. In these field experiments, the re-rounding success criterion was reducing the pipe deflection to less than 5%, which is the unqualified acceptance level in AASHTO LRFD [2013]. For larger pipes (36 in (0.9 m) nominal diameter) the research team verified deflection levels, while for smaller pipes (18 in (0.45 m) nominal diameter) the deflection was measured via a mandrel.

Figure 13. Re rounding devices: Hurco Re-rounder™ (left, adapted from Hurco brochure [Hurco, 2005]) and Williams re-rounding device in 36 in (0.9 m) diameter pipe (right).

7.3 Experiment 1 Pipe Installation

Three corrugated HDPE pipe sections of diameter 36 in (0.9 m) and length 10 ft (3.0 m), 20 ft (6.1 m), and 10 ft (3.0 m), were combined with standard joints provided by the manufacturer as shown in Figure 10 to make a 40 ft (12.2 m) long conduit and installed on a 6 in (0.15 m) bed of ODOT C&MS Item 304 crushed limestone as shown in Figure 14. The backfill was added, as shown in Figure 15, using the same material to a level 6 ft (1.8 m) above the crown of the pipe, followed with an additional 4 ft (1.2 m) of native clay. A Spectra Physics Laserplane 220, a self-leveling laser level, seen in Figure 16, was used to verify the height of the cover with the aid of a rod, as shown in Figure 17. A space of 3 ft 8 in (1.1 m) on either side of the pipe was cleared for placement of backfill around the pipe. In this controlled experiment, no compaction effort was intentionally applied to the backfill and cover layers as a way of simulating poor installation procedures likely to produce excessive deflection. A backhoe was used to press down on the installation to force the deflection. The final installation is shown in Figure 18.

The laser profiler, shown in Figure 19, was used to record circumferential profiles at 10 positions along the length of the pipe, shown in the diagram in Figure 20. The device rotates a full 360° and records the distance at 119 points (every 3.2°) around the pipe circumference, starting from the zenith. Immediately after backfill was complete, different deflections were observed along the pipe and initial measurements were recorded manually using a tape measure and also with the profiler. Finally, corrugation depth was measured at each of ten points in Figure 20 to investigate changes in the corrugation before and after re-rounding. This was accomplished by drilling a small hole in the smooth interior wall at the crown (all ten locations A through J) and both springlines (locations A through F), then inserting a caliper, shown in Figure 21, until the tip contacted the inside of the outer wall at the peak of a corrugation. Measurements from before and after re-rounding were compared to see if the pipe corrugation had been damaged in the re-rounding process.

Pipe 1 was installed on December 7, 2017, re-rounded 189 days later on June 14, and removed after another 48 days on August 1, 2018. Profiles and other geometric pipe data were collected before and after backfill was placed during installation, before and after each pass of the re-rounder, and immediately before removal.

Figure 14. Corrugated HDPE pipe fabricated from three sections placed on a 6-in (0.15 m) bed of ODOT. C&MS Item 304.

Figure 15. Placing ODOT C&MS Item 304 backfill over HDPE pipe.

Figure 16. Spectra Physics Laserplane 220.

Figure 17. Rod being held during backfill height measurement by laser plane.

Figure 18. Completed installation.

Figure 19. Laser profiler recording a cross-sectional profile.

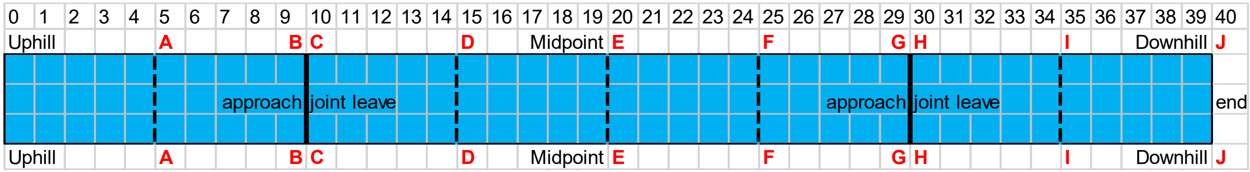

Figure 20. Length profile of pipe showing points A-J where profile data were measured at 5 ft (1.5 m) intervals, with additional profiles collected to include both sides of joints (solid vertical lines). The numbers mark distance in feet from the uphill end (1 ft = 0.30m).

Figure 21. Calipers used to measure corrugation depth. The right end was extended into a hole until it touched the crest of the corrugation.

Three GEOKON pressure cells were around the longitudinal center of the pipe, at distances of 7 in (180 mm) from the outer surface; two at the springline on either side and one above the crown, as shown in Figure 22. The pressure cell over the crown is shown in Figure 23 at time of installation, and Figure 24 shows the pressure cell being installed. Initial pressure cell readings were taken using the GEOKON vibrating wire readout device shown in Figure 25, which read both frequency, which determines soil pressure, and the temperature of the backfill. A device to measure in-situ soil-stiffness was placed at shoulder and springline of Pipe 1, but the device moved and it could not be located after re-rounding to complete the measurements.

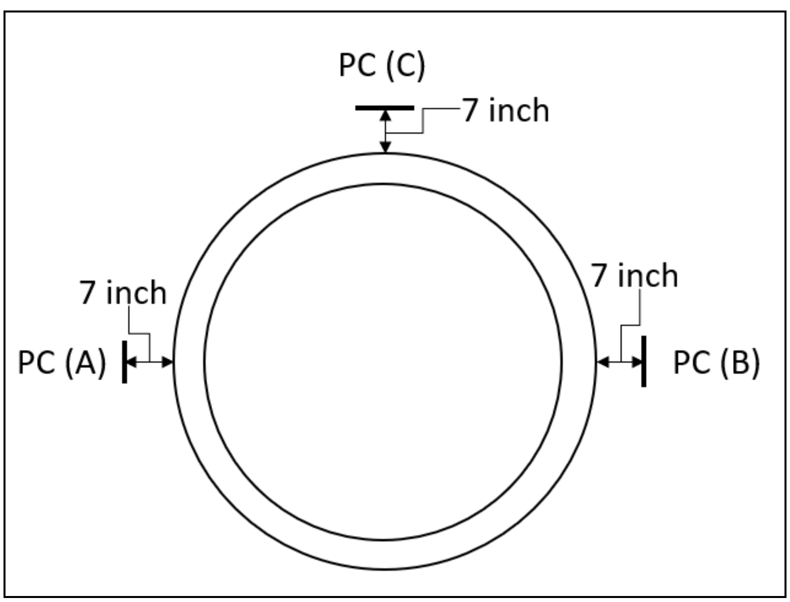

Figure 22. Schematic showing the locations of the pressure cells installed. (7 in = 180 mm)

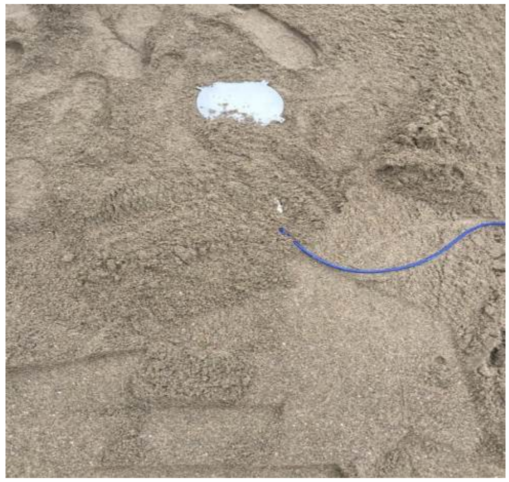

Figure 23. GEOKON pressure cell above crown of the pipe.

Figure 24. Positioning pressure cell above the pipe crown.

Figure 25. Geokon vibrating wire readout device.

A sand cone test, shown in Figure 26, was conducted on two layers of backfill: at the level of the pipe's springline and at the completion of backfilling, in order to determine the dry weight density and degree of compaction in the backfill. After 30 days, the re-rounding was scheduled with Williams Testing, Inc, to occur 189 days after pipe installation. Measurements with the laser profiler were taken at ten locations (designated A-J in Figure 20) along the pipe after completion of cover, again immediately before re-rounding, and after each pass of the re-rounder. The re-rounder was placed at one end of the pipe, as shown in Figure 27 and connected to an air compressor to produce the high-frequency vibrations that reshape the internal surface of the pipe. A cable running through the pipe was connected to the re-rounder at one end and a winch at the other, like that shown in Figure 28. A full pass of the re-rounder through the pipe took 15 to 20 minutes. Three passes of the vibrating re-rounder were performed, and a mandrel run through the pipe to determine if deflection was sufficiently reduced to be successful. During the third pass, the device had become so hot the vendor declared it unsafe for the equipment to be used on another pass. After each pass, the cross-section of each of the ten locations A-J inside the pipe was measured with the laser profiler. Thirty days after re-rounding, the pipe was exhumed and 75 lb (45 kg) of the backfill was collected from around the pipe for a laboratory sieve analysis.

Figure 26. Sand cone test.

Figure 27. Re-rounder positioned at entrance to the pipe at start of re-rounding.

Figure 28. Winch placed at exit of the pipe to pull the re-rounder through.

7.4 Experiment 2 Pipe Installation

The second pipe was installed on August 2, 2018, following the same method as for Pipe 1, except the bedding and backfill were ODOT Type 2 backfill (sand). Pipe 2 itself was identical to Pipe 1, consisting of three sections of 36 in (0.9 m) diameter thermoplastic pipe with total length 40 ft (12 m) and two joints. Two passes of the re-rounder were made 88 days later on October 29, 2018, and the pipe was removed on May 20, 2019, 209 days after re-rounding. Figure 29 shows the bedding layer being compacted before placement of Pipe 2.

Six inches (0.15 m) of compacted ODOT Type 2 sand was prepared as a bedding (see Figure 17) for the installation of Pipe 2. The full conduit was buried in a structural backfill of the same material used for bedding, as shown in Figure 18. The same procedures for pressure cell placement, markings inside the pipe, and laser profile-meter readings after the pipe's burial for initial readings were all repeated for this second experiment.

Figure 29. Compacting the 6-in (150 mm) bedding layer of ODOT Type 2 backfill sand before placing Pipe 2.

Figure 30. Placing ODOT Type 2 backfill sand around Pipe 2.

The instrumentation on Pipe 2 was the same as that previously described for Pipe 1, with the addition of four accelerometers and a soil stiffness measurement device. The corrugation depth was measured at the crown and right springline at locations D and E only. A cubical unit containing a pair of perpendicular (x-y) accelerometers was placed 7 in (180 mm) above the crown of the pipe and 15 ft (4.6 m) from the uphill side (i.e., at the location of the first profile measurement, Point A), as shown in Figure 31. A second pair of accelerometers was placed 18 in (460 mm) above the crown of the pipe and directly above the first pair of accelerometers, surrounded by a layer of red-dyed sand to trace movement after re-rounding, as shown in Figure 32. The main function of the accelerometers installed is to collect data when the vibrator starts hitting the inner surface of the pipe and then use the data to perform a Fourier Transform to find the frequency domain that the soil experienced while re-rounding. Figure 33 is a diagram showing the placement of the accelerometers. Figure 34 shows the locations of the three pressure cells installed surrounding the pipe at the springline and the crown at the longitudinal midpoint.

Finally, the apparatus shown in Figure 35 was installed on the right shoulder of the pipe (between the crown and springline) to measure the soil stiffness before and after re-rounding. Figure 36 shows a schematic of the apparatus installed between the pipe corrugations. Figure 37 shows a hydraulic jack connected to the apparatus mentioned to read the soil resistance data.

Figure 31. Positioning accelerometers above crown of Pipe 2.

Figure 32. Upper accelerometer 18 in (460 mm) above pipe crown with red sand surrounding.

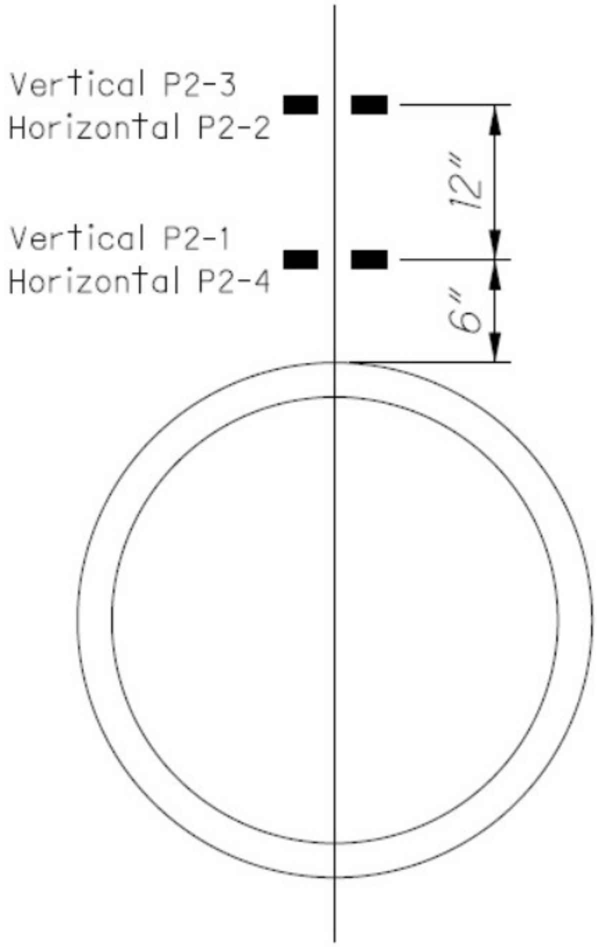

Figure 33. Accelerometer orientation and location for Test Pipe 2. (6 in = 150 mm, 12 in = 305 mm)

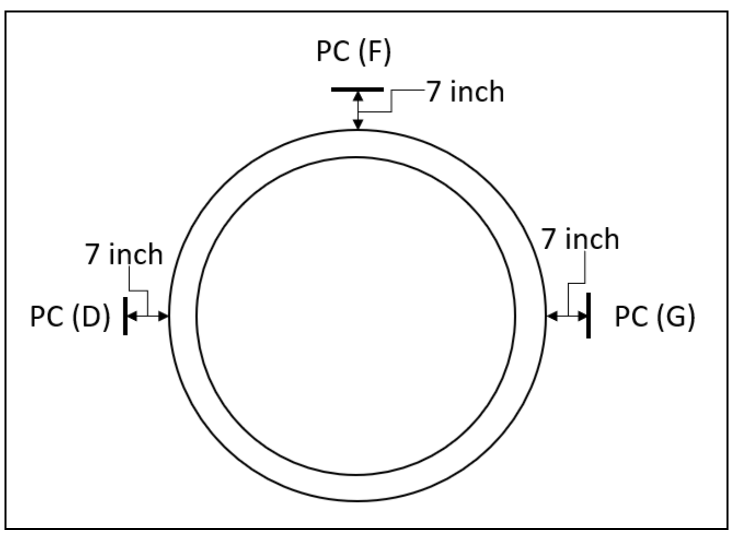

Figure 34. Drawing showing locations of pressure cells around pipe cross-section (7 in = 180 mm).

Figure 35. Left: The circled apparatus was installed at the shoulder of the pipe to measure soil resistance before and after re-rounding; Right: A closer view of the device.

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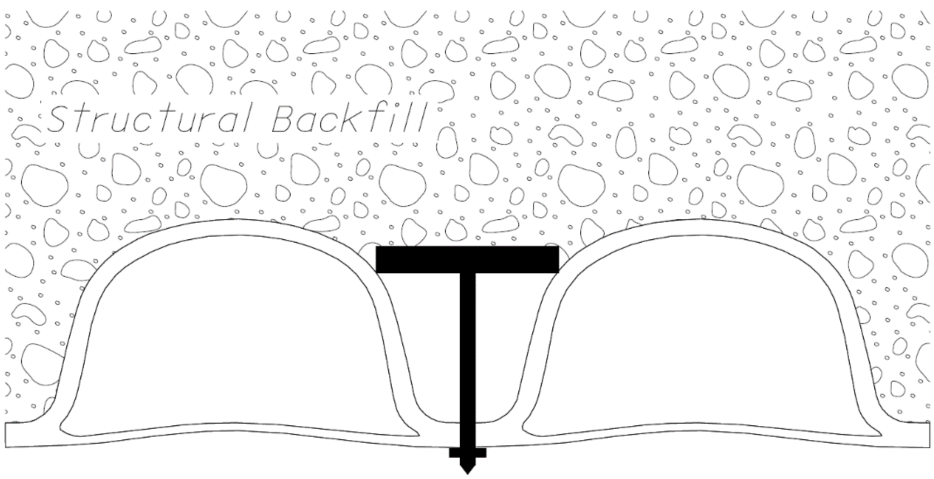

Figure 36. Drawing showing detail of the soil resistance measuring device installed on the shoulder of Pipe 2.


Figure 37. A hydraulic jack was used to measure soil resistance before and after re-rounding.

7.5 Pipe Experiment 3

7.5.1 May 21, 2019 Installation

The pipe, identically configured to Test Pipes 1 and 2, was placed on a 6 in (150 mm) bed of Structural Backfill Type 3, specifically AASHTO #57 crushed stone aggregate. The pipe was then backfilled with the same material to approximately crown height. Figure 38 shows the placement of the structural backfill. To simulate the poor construction procedures believed to produce excessive vertical deflection, compactive effort was not applied to the Structural Backfill material until the material was above the crown of the pipe. Once the aggregate level reached the crown of the pipe, a hydraulic plate compactor was used to compact the structural backfill (see Figure 39). Despite the application of significant compaction energy, the deflection in the pipe was minimal. When the pipe was damaged by the backhoe in the attempt to create sufficient deflection, this experiment was aborted so a replacement pipe could be installed.

Figure 38. Placement of Structural Backfill Type 3 on Test Pipe 3.

Figure 39. Compaction of the Structural Backfill Type 3 over Test Pipe 3 using a hydraulic plate compactor.

7.5.2 Development of a deflection apparatus

Personal experience and anecdotal evidence provided by ODOT personnel indicate that excessive deflection in thermoplastic pipe installed using Structural Backfill Type 3 is more likely than with the other backfill types [Hans Gucker, personal communication with K.E. White, July 2019]. Additionally, the research plan for the project included investigating the impact of re-rounding on a deflected thermoplastic pipe for all ODOT structural backfill materials, so it was necessary to repeat the installation.

Since the problem with the installation method was insufficient deflection of the pipe, the Ohio University team developed a device capable of deflecting pipe from the inside prior to placement of the structural backfill. Once the backfill is placed, the mechanism is removed from the pipe.

The device is comprised of two 8 ft (2.4 m) long steel plates curved to match the inner curvature of the pipe with two hydraulic actuators positioned in between, and the entire apparatus placed on a cart designed to position the curved plates to contact the pipe along the horizontal diameter. The actuators then expand outward to create a horizontal displacement in the pipe. Figure 40 shows the device in the laboratory and Figure 41 shows a schematic representation of the device. Figure 42 shows the deflection device and delivery system in place within a segment of Test Pipe 3. Two of these devices were built and used to deflect a total length of 16 ft (4.9 m) of pipe.

Figure 40. Pipe deflector assembled at ORITE laboratory.

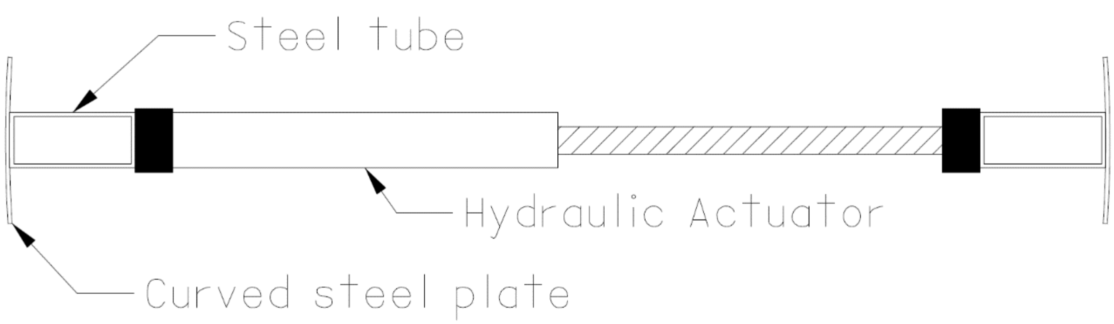

Figure 41. Schematic of the deflection device.

Figure 42. Actuated deflection device and delivery system deforming Pipe 3.

7.5.3 December 12, 2019 Installation and re-rounding of replacement Test Pipe 3

A new Test Pipe 3, configured identically to those in the preceding experiments, was installed on a 6 in (150 mm) bedding of Structural Backfill Type 3. The specific material type utilized was a crushed AASHTO #57 aggregate. Two of the deflection devices were positioned inside the pipe at the approximate mid-point along the length of the pipe. The hydraulic actuators applied a horizontal force to the inside wall of the pipe until a target deflection of 10% was reached. The deformed pipe with the deflection apparatus inside is shown in Figure 43.

Figure 43. Actuated deflection device and delivery system showing the deformed pipe section.

The pre-deflected pipe was then backfilled with the same AASHTO #57 aggregate approximately to the crown. To further simulate the poor construction procedures believed to produce excessive vertical deflection, compactive effort was not applied to the structural backfill material until the material was above the crown, at which time a hydraulic plate compactor was used to compact the placed structural backfill until a final height of 10 ft (3 m) above the crown of the pipe was established.

Instrumentation was installed for Test Pipe 3 included three pressure cells following the approach used on the first two test pipes. Figure 44 shows the pressure cell orientation, location, and naming convention relative to the pipe cross-section. Accelerometers were installed in a like manner as Test Pipe 2; Figure 45 shows a schematic layout of the accelerometers. The in-situ soil stiffness mechanism was installed at the haunch of the pipe, similar to Test Pipe 2. A layer of the AASHTO #57 aggregate was painted red to identify the location of the accelerometers. Similar to Test Pipe 2, the painted material was used to trace migration of the backfill material. Immediately after backfilling, the initial shape of the pipe was measured using a tape measure and pressure cell readings were obtained. The corrugation depth was measured at the crown and right springline at locations D and E only, as was the case for Pipe 2.

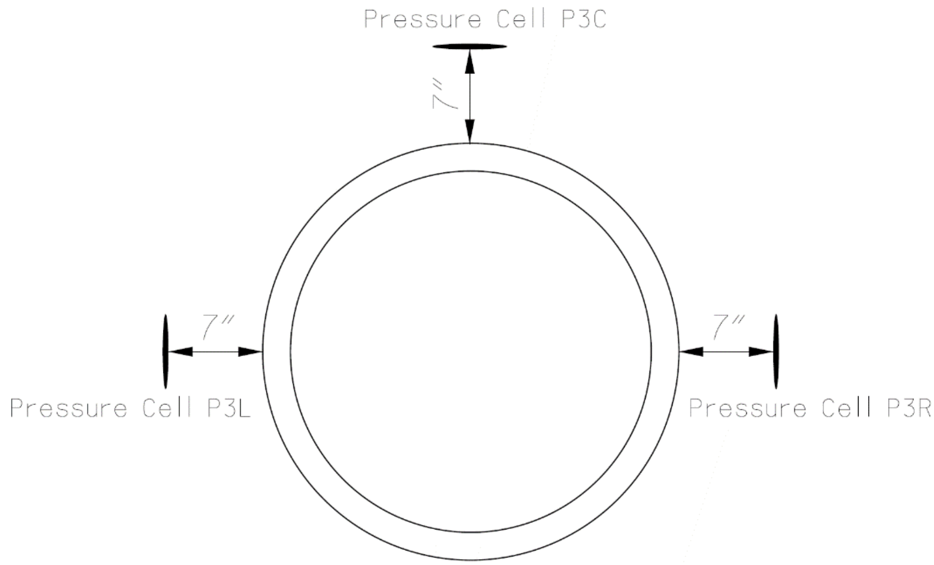

Figure 44 Pressure cell orientation, location and naming convention for Test Pipe 3. (7 in =180 mm)

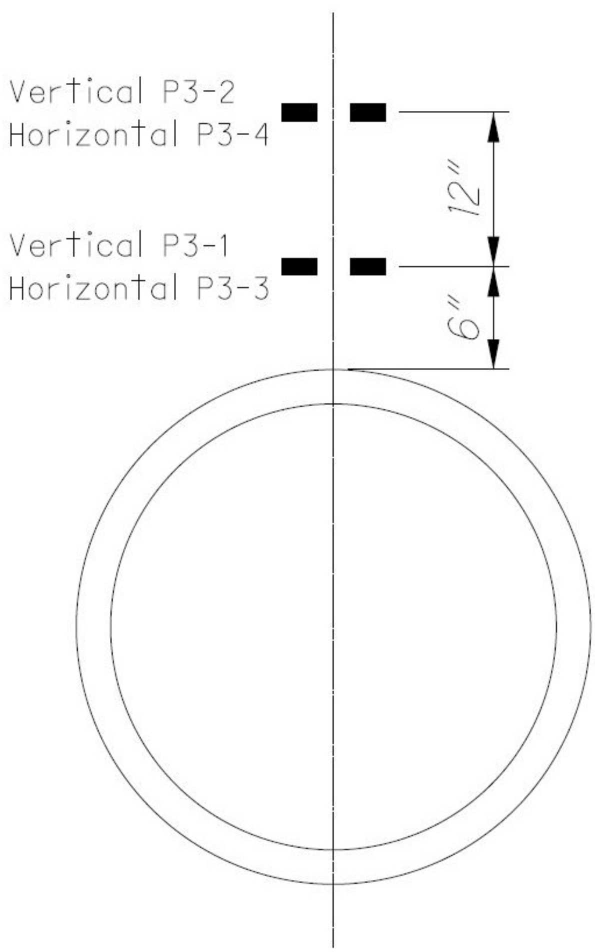

Figure 45. Accelerometer orientation and location for Test Pipe 3. (6 in = 150 mm, 12 in = 305 mm)

Pipe re-rounding occurred on January 29, 2020, after a waiting period of 48 days, exceeding the 30-day waiting period required by ODOT Item 611. Before starting the re-rounding process, the laser profilometer recorded the shape of the pipe and pressure cell readings were obtained. The re-rounding procedure followed that used on the first two test pipes except the device was only pulled through the pipe once. Before re-rounding, pressure cell readings were obtained, corrugation depth was measured at the crown and springline at distances of 16 ft (4.9 m) and 21 ft (6.4 m) from the inlet of the pipe, and the in-situ soil stiffness was measured at the haunch of the pipe. Accelerometer data were obtained during the re-rounding. After re-rounding, pressure cell readings, soil stiffness, and corrugation depth measurements were obtained. The following day, January 30, 2020, the laser profilometer recorded the pipe shape was obtained at each of the 10 pipe cross-section locations A-H identified in Figure 20. Additionally, readings were obtained from each pressure cell and the corrugation depth was measured at the two test locations. Final readings and profiles were collected and the pipe exhumed on June 23, 2020.

7.6 LiDAR profiler

A new profiler was developed by ORITE to measure pipe profiles. It is based on Light Detection And Ranging (LiDAR) (also called Laser Imaging, Detection, And Ranging) principles and uses an updated laser system centered between two plastic spacer disks. The device is shown in Figure 46. The LiDAR unit recorded between 305 and 352 radius readings at intervals of 1.02° to 1.18°; most runs collected at least 342 readings (1.05° intervals).

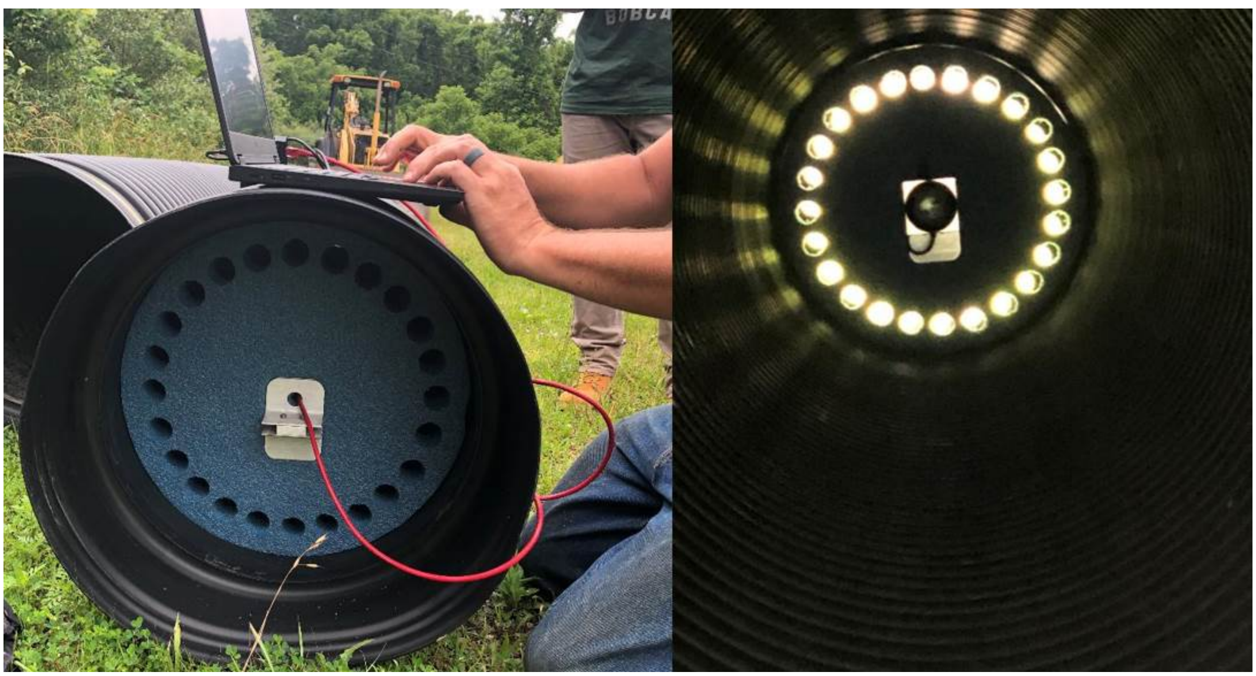

Figure 46. LiDAR pipe profiler in use. Left: Profiler placed in pipe and connected to controller laptop. Right: View of profiler from inside pipe.

7.7 Pipe Experiment 4

Test Pipe 4 was configured like the preceding pipes, except it had an inner diameter of 18 in (0.45 m). It was installed on June 24, 2020 in Structural Backfill Type 3 (AASHTO #57 aggregate) similarly to Test Pipe 3. The pipe deflector device discussed in 7.5.2 was used to create a >10% deflection while the backfill was placed around the pipe, as shown in Figure 47; two deflector units were applied in the pipe at the two joints at 10 ft (3 m) from either end. Instrumentation was the same as for Test Pipe 3, except there was no soil-stiffness gauge installed. The installation of a pressure sensor and accelerometer are shown in Figure 48.

Test Pipe 4 was re-rounded on September 10, 2020, 78 days after installation. Figure 49 shows views of the re-rounding operation. Only one pass of the re-rounder was required to adequately restore the pipe profile. Figure 50 shows the LiDAR profiler being used on the pipe. The final profile was collected 41 days after re-rounding, on October 21, 2020, followed by exhumation of the pipe.

Figure 47. The pipe deflector was used to deform Test Pipe 4 during installation. Left: Deflector being inserted into pipe. Right: Deflector in operation.

Figure 48. Installation of sensors around Test Pipe 4. Left: Pressure cell placed over crown. Right: Accelerometers and colored aggregate.

Figure 49. Views of re-rounding of Test Pipe 4: a) Re-rounder and operator at inlet of pipe; b) Reels with pneumatic and electrical cables connected to re-rounder; c) Winch at outlet to pull re-rounder through pipe; d) and e) Close-up views of re-rounder inside pipe.

Figure 50. LiDAR profiler being used on Test Pipe 4. Top: Profiler being prepared by graduate student for insertion; Bottom: Profiler inside pipe.

7.8 Pipe Experiment 5

Test Pipe 5 was installed on October 22, 2020. The pipe is identical to Test Pipe 4 and placed in ODOT Structural Backfill Type 2 (sand), comparable to Test Pipe 2. Instrumentation was the same as for Test Pipe 4. Figure 51 shows some views of the installation of Test Pipe 5.

Test Pipe 5 was re-rounded on February 23, 2021, 4 months after installation, and excavated on March 30, 2021, 35 days after re-rounding. During the first pass, the re-rounder and mandrel could not be passed through the entire length of the pipe, so the re-rounder and mandrel were also brought in through the other direction. On the second pass, the device successfully traversed the entire pipe and the mandrel indicated a satisfactory result to the vendor.

Figure 51. Views of installation of Test Pipe 5 on October 22, 2020: a) Testing accelerometer; b) Levelling backfill above crown in preparation for placing accelerometer; c) Placement of second (higher) accelerometer; e) Checking pressure cell readout; f) view inside pipe.

8 Results and Analysis of Pipe Experiments

8.1 Introduction

The test pipes were subjected to poor installation methods to induce excessive vertical deflection. The pipes were then re-rounded using the vibratory re-rounding device described in the previous chapter. Profile, soil pressure, and other data were collected at the time of installation; immediately before, during, and immediately after the re-rounding process; and immediately before the pipe was removed from the test site. The data were analyzed to determine the vertical and horizontal deflections, soil pressures, corrugation height, *in-situ* soil stiffness, and soil accelerations caused by the re-rounding process. Soil properties were also collected for a limited subset of pipes. This chapter presents the collected data as well as an analysis of the data for each of the test pipes.

8.2 Test Pipe Shape Analysis

Figure 20 on page 21 shows the location of the various cross-section locations (A-A through J-J) along the length of the installed pipe. The convention for measuring pipe deflection is that a negative value represents a decrease in the diameter and a positive value represents an increase in diameter. The following sub-sections present shape data for each test pipe at the three central cross-sections, D-D, E-E, and F-F. The remaining shape plots are provided in Appendix B.

8.2.1 Test Pipe 1 Shape Data

Test Pipe 1 was a 36 in (0.9 m) nominal diameter HDPE pipe. The initial vertical and horizontal inside diameters were measured at 35.95 in (0.9131 m) and 36.15 in (0.9182 m), respectively before installation. The pipe was backfilled using a well-graded material meeting the requirements of ODOT Structural Backfill Type 1. Additional information on the backfill material utilized can be found in Section 8.4. Fill material was placed to a height of 10 ft (3 m) above the crown of the pipe. A plot of the longitudinal profile of the test pipe is provided in Figure 52.

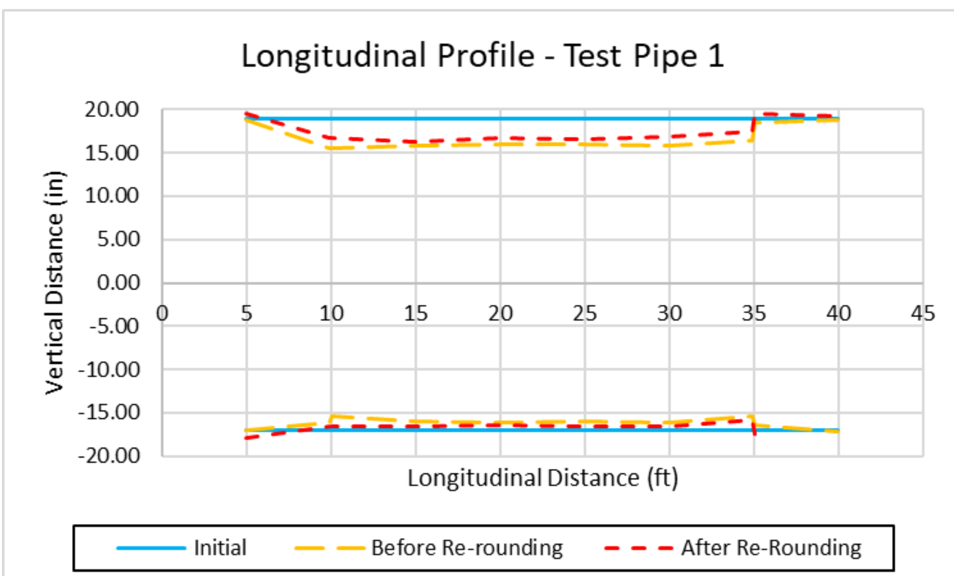

Figure 52. Longitudinal profile of Test Pipe 1 (1 in = 25.4 mm).

Figure 53 shows the shape of the test pipe at cross-section D-D. This cross-section is located approximately 15 ft (4.6 m) from the inlet of the pipe or 5 ft (1.5 m) from the inlet end of the second pipe section. For this cross-section, several data points obtained immediately before re-rounding were obvious erroneous data points most likely caused by moisture on the pipe surface which refracted the laser signal resulting in the erroneous readings. These points were not considered when determining the deflected pipe dimensions.

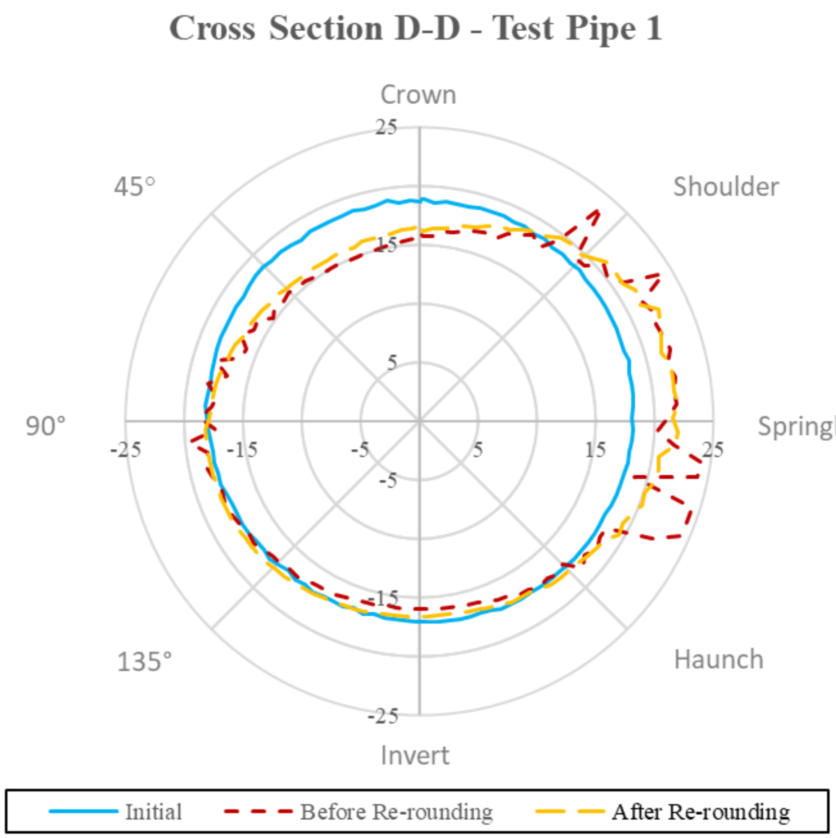

Figure 53. Deflected cross-section D-D of Test Pipe 1 (1 in = 25.4 mm).

Figure 54 shows the shape of the test pipe at cross-section E-E. This cross-section is located approximately 20 ft (6.1 m) from the inlet of the pipe which is the mid-point of the second pipe section. For this cross-section, several data points obtained immediately before re-rounding were obviously erroneous and most likely caused by moisture on the pipe surface refracting the laser light. These points impact the horizontal dimensions. Only vertical diameter data are presented for cross-section E-E.

The vertical diameter immediately before re-rounding was 32.08 in (0.8148 m), indicating a vertical deflection immediately before re-rounding of -10.76%. After three passes of the re-rounder the vertical dimension was 33.22 in (0.8438 m), an increase of 1.14 in (29.0 mm). The vertical deflection after re-rounding was -7.61%, a net change in vertical deflection of +3.15%.

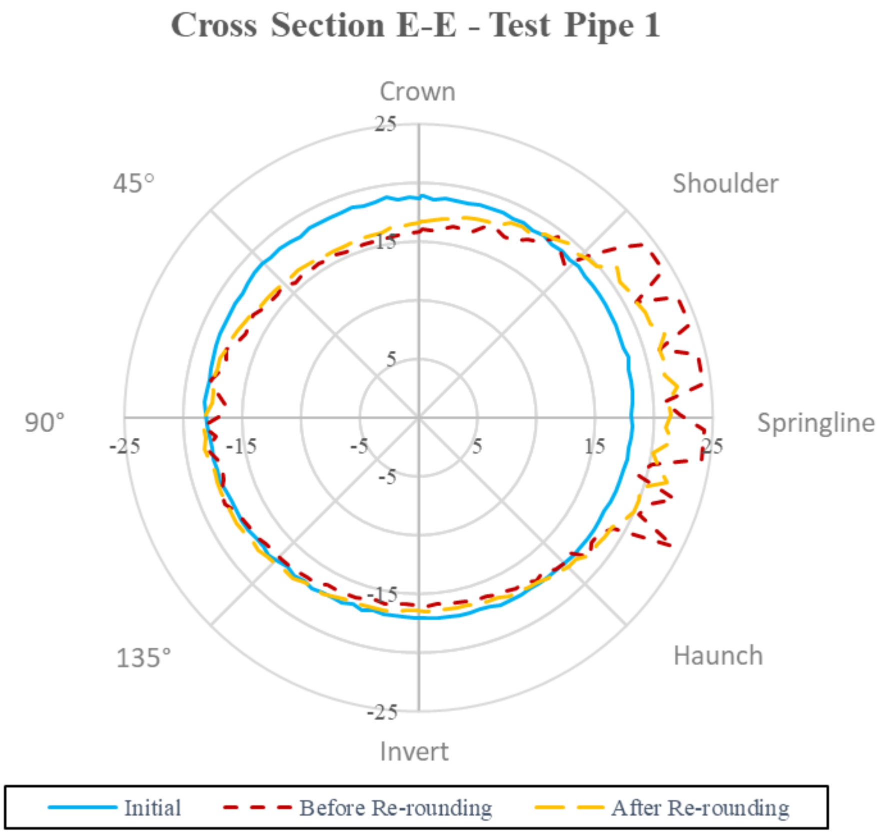

Figure 54. Deflected cross-section E-E of Test Pipe 1 (1 in = 25.4 mm).

Figure 55 shows the shape of the test pipe at cross-section F-F. This cross-section is located approximately 25 ft (7.6 m) from the inlet of the pipe or 5 ft (1.5 m) from the outlet end of the second pipe section. For this cross-section, several data points obtained immediately before re-rounding were obviously erroneous and most likely caused by moisture on the pipe surface which refracting the laser light. These points impact the horizontal dimensions, so only the vertical diameter data are presented for cross-section F-F.

The vertical diameter immediately before re-rounding was 31.85 in (0.8090 m), a vertical deflection of -10.40%. After three passes of the re-rounder, the vertical diameter was 33.12 in (0.8412 m). The vertical deflection after re-rounding was -7.88%, a net change of +3.52%. After the third pass, the re-rounder stopped the procedure due to the unit becoming extremely hot.

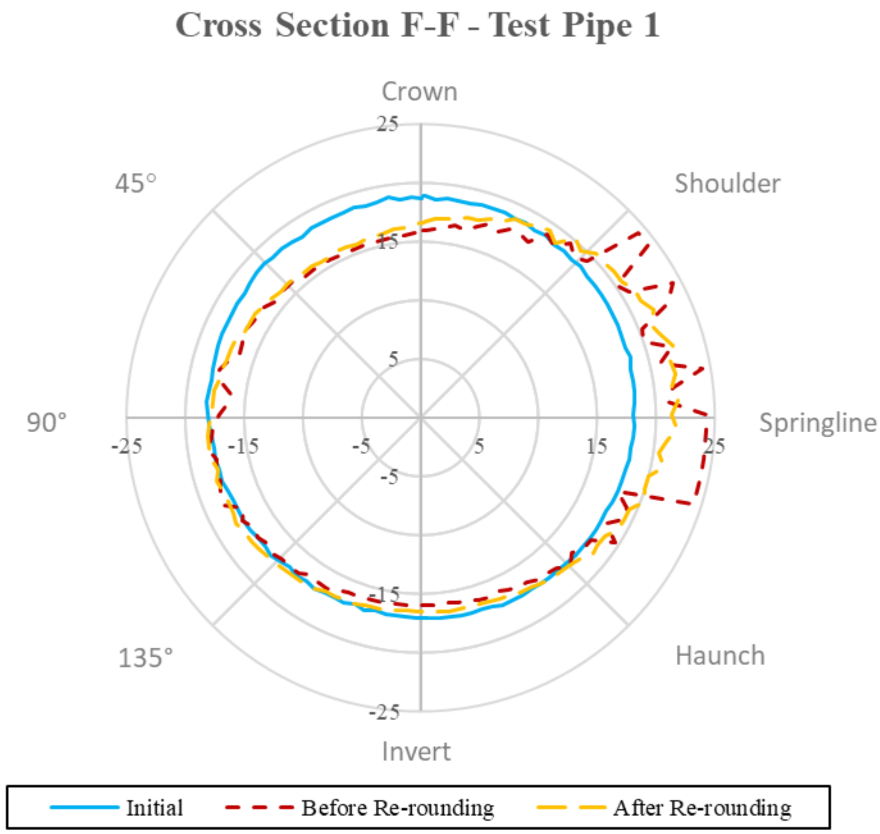

Figure 55. Deflected cross-section F-F of Test Pipe 1 (1 in = 25.4 mm).

The diameter measurements at each cross-section before and after re-rounding for Test Pipe 1 are provided in Table 4 and the deflection percentages are provided in Table 5.

Table 4. Summary of diameter measurements for Test Pipe 1.

Cross-Section	Initial Diameter				Diameter Before Re-rounding				Diameter After Re-rounding			
	Vertical		Horizontal		Vertical		Horizontal		Vertical		Horizontal	
	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)
A-A	35.95	0.9131	36.15	0.9182	35.87	0.9111	36.02	0.9149	37.41	0.9502	35.61	0.9045
B-B	*	*	*	*	31.53	0.8009	39.25	0.9970	33.33	0.8466	39.66	1.0074
C-C	*	*	*	*	30.95	0.7861	39.35	0.9995	33.36	0.8473	39.55	1.0046
D-D	*	*	*	*	31.77	0.8070	39.79	1.0107	32.85	0.8344	39.52	1.0038
E-E	*	*	*	*	32.08	0.8148	**	**	33.22	0.8438	39.59	1.0056
F-F	*	*	*	*	31.85	0.8090	**	**	33.12	0.8412	39.10	0.9931
G-G	*	*	*	*	31.96	0.8118	38.59	0.9802	33.32	0.8463	39.22	0.9962
H-H	*	*	*	*	31.72	0.8057	39.47	1.0025	33.25	0.8446	38.84	0.9865
I-I	*	*	*	*	34.92	0.8870	35.33	0.8974	36.89	0.9370	35.38	0.8987
J-J	*	*	*	*	35.89	0.9116	35.66	0.9058	**	**	36.60	0.9296

* Initial measurement made at cross-section A-A and assumed the same for all locations

** Data unreliable due to measurement noise

Table 5 shows the vertical deflection of Test Pipe 1 before and after re-rounding at each of the named cross-sections. Cross-sections A-A, I-I, and J-J are excluded from further consideration since these cross-sections were under very minimal soil cover and thus experienced very little vertical deformation during installation. The vertical deflection along the length of the pipe varied from -10.76% at E-E to -13.92% at C-C.

After three passes of the re-rounder, the pipe deflections varied from -7.21% at C-C to -8.64% at cross-section D-D. Re-rounding was most effective at cross-section C-C with a reduction in vertical deflection of 6.72%. Re-rounding was least effective at cross-section D-D with a reduction in vertical deflection of 2.98%. Before re-rounding, each of the seven named cross-sections were deflected greater than the AASHTO 7.5% remediation/replacement limit, which is also used as ODOT's criterion. After re-rounding, cross-sections B-B, C-C, and G-G were below the 7.5% threshold, but the remaining four cross-sections remained above the 7.5% threshold. Because each pass of the re-rounder resulted in a decrease in the vertical deflection, it is likely that further reduction could have occurred with additional passes of the re-rounder.

Table 5. Summary of deflection percentages for Test Pipe 1.

Cross-Section	Before Re-rounding		After Re-rounding		Recovered Deflection	
	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)
A-A	-0.22%	-0.36%	4.06%	-1.49%	4.28%	-1.13%
B-B	-12.29%	8.58%	-7.29%	9.71%	5.01%	1.13%
C-C	-13.91%	8.85%	-7.20%	9.41%	6.70%	0.55%
D-D	-11.63%	10.07%	-8.62%	9.32%	3.00%	-0.75%
E-E	-10.76%	*	-7.59%	9.52%	3.17%	*
F-F	-11.40%	*	-7.87%	8.16%	3.53%	*
G-G	-11.10%	6.75%	-7.32%	8.49%	3.78%	1.74%
H-H	-11.77%	9.18%	-7.51%	7.44%	4.26%	-1.74%
I-I	-2.87%	-2.27%	2.61%	-2.13%	5.48%	0.14%
J-J	-0.17%	-1.36%	*	1.24%	*	2.60%

* Data unreliable due to measurement noise

Test Pipe 1 was exhumed 48 days after re-rounding, after recording final measurements using the laser profilometer. Figure 56 shows the shape of the pipe immediately after re-rounding and just before removal. The shape of the pipe is essentially unchanged between re-rounding and removal.

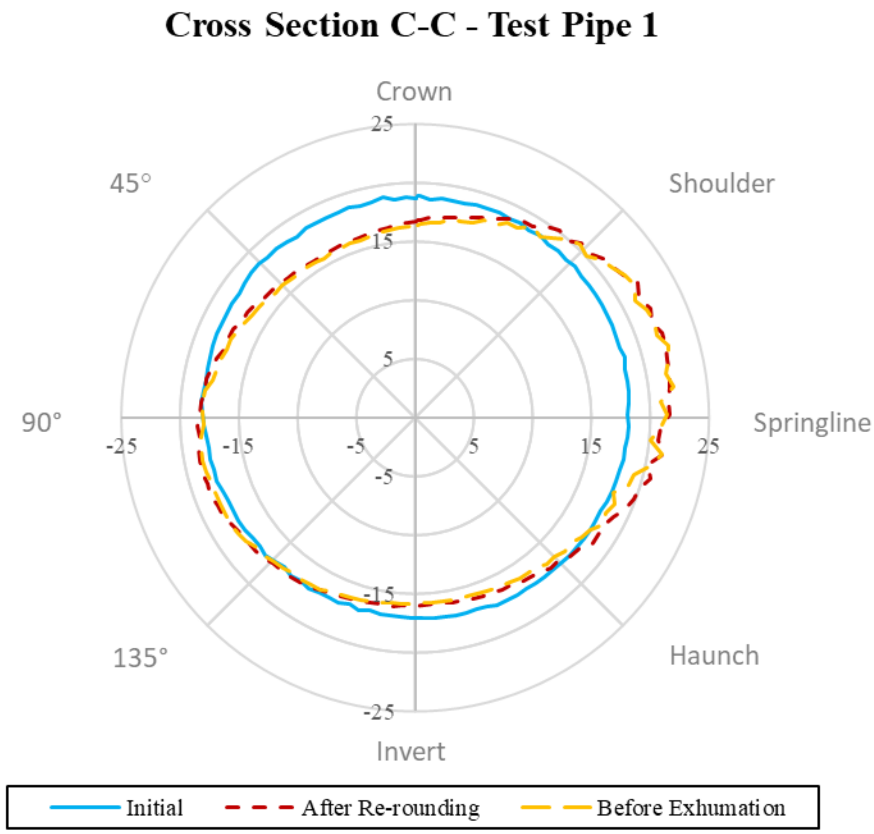

Figure 56. Long-term cross-section C-C of Test Pipe 1 (1 in = 25.4 mm).

8.2.2 Test Pipe 2 Shape Data

Test Pipe 2 was a 36 in (0.9 m) nominal diameter HDPE pipe. The initial vertical and horizontal inside diameters were measured at each of the cross-sections A-A through J-J. The results are provided in Table 6. The pipe was backfilled using a sand meeting the requirements of ODOT Structural Backfill Type 2. The fill material was placed to a height of 10 ft (3 m) above the crown of the pipe. A plot of the longitudinal profile of Test Pipe 2 is provided in Figure 57.

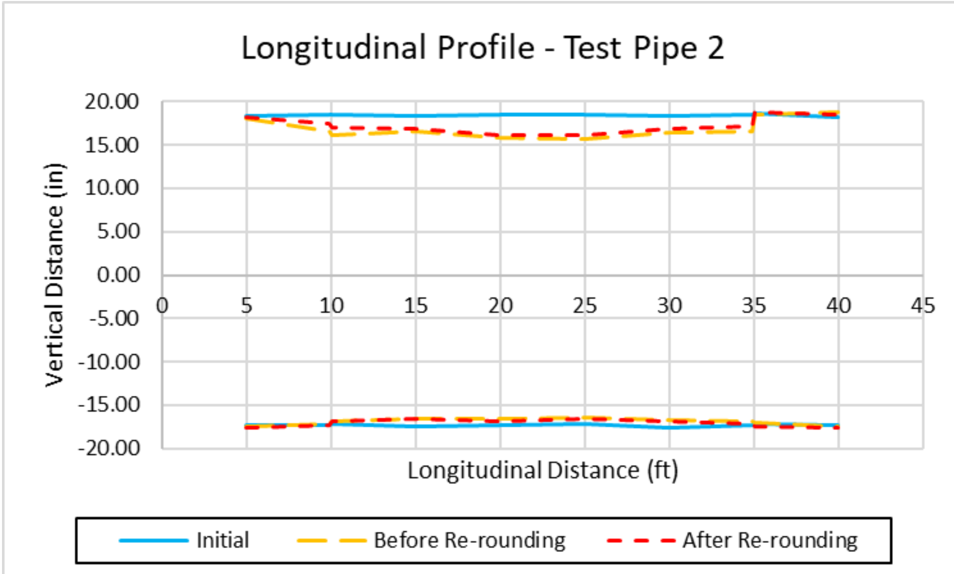

Figure 57. Longitudinal profile of Test Pipe 2 (1 in = 25.4 mm).

Figure 58 shows the shape of the test pipe at cross-section D-D. This cross-section is located approximately 15 ft (4.6 m) from the inlet of the pipe or 5 ft (1.5 m) from the inlet end of the second pipe section. The vertical and horizontal diameters immediately before re-rounding were 33.09 in (0.8405 m) and 37.94 in (0.9637 m), respectively giving a vertical deflection of –7.33% and a horizontal deflection of +6.83%. After two passes of the re-rounder the vertical and horizontal diameters were 33.54 in (0.8519 m) and 37.12 in (0.9243 m), respectively, giving a vertical deflection measured after re-rounding of -6.06% and a horizontal deflection of +4.52%. The re-rounding process resulted in a net change of +1.27% in vertical deflection and -2.31% in horizontal deflection.

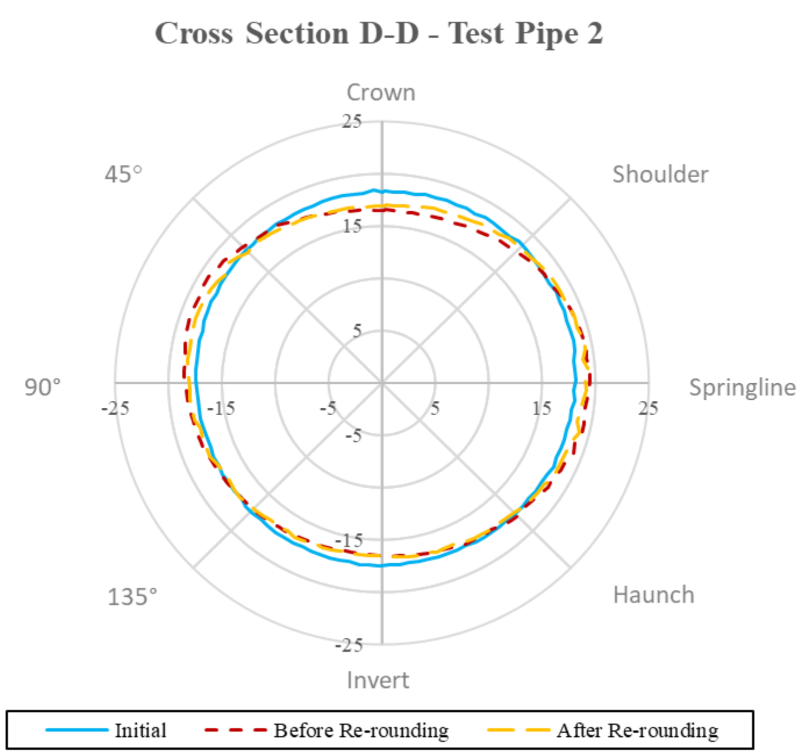

Figure 58. Deflected cross-section D-D of Test Pipe 2 (1 in = 25.4 mm).

Figure 59 shows the profile of test pipe at cross-section E-E. This cross-section is located approximately 20 ft (6.1 m) from the inlet of the pipe which is the mid-point of the second pipe section. The vertical and horizontal dimensions immediately before re-rounding were measured as 32.47 in (0.8247 m) and 38.09 in (0.9675 m), respectively, making the vertical deflection immediately before re-rounding -9.38%% and the horizontal deflection of +6.68%. After two passes of the re-rounder the vertical and horizontal diameters were 32.94 in (0.8367 m) and 37.65 in (0.9563 m), respectively, making the vertical deflection after re-rounding -8.04% and the horizontal deflection +5.45%. The net change was +1.34% in vertical deflection and -1.23% in horizontal deflection.

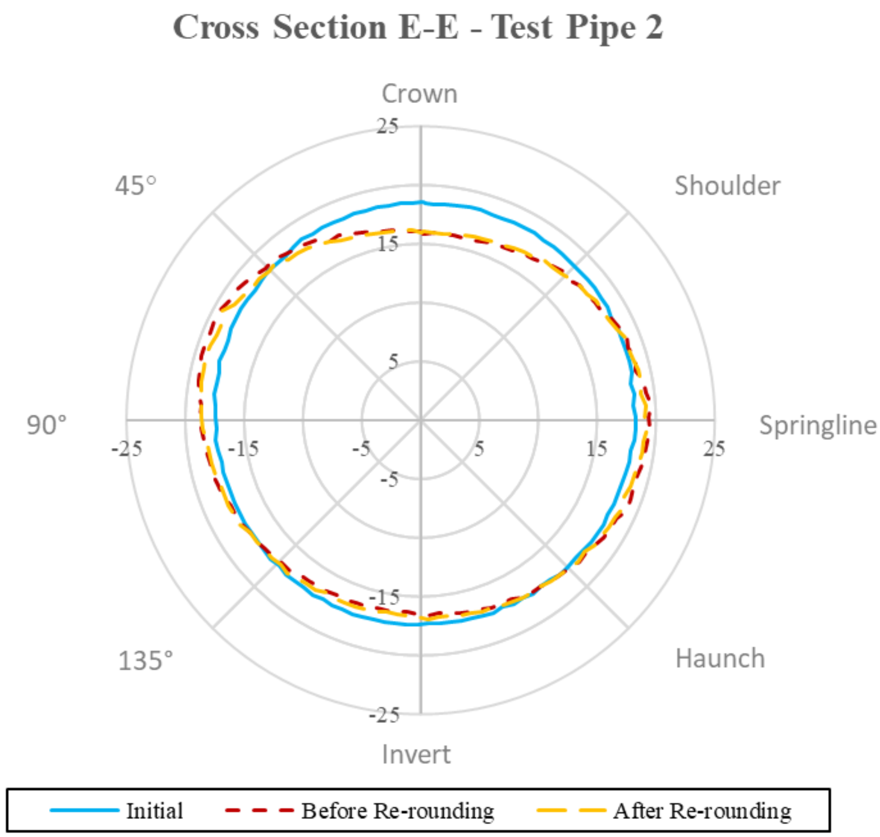

Figure 59. Deflected cross-section E-E of Test Pipe 2 (1 in = 25.4 mm).

Figure 60 shows the shape of the test pipe at cross-section F-F. This cross-section is located approximately 25 ft (7.6 m) from the inlet of the pipe or 5 ft (1.5 m) from the outlet end of the second pipe section. The vertical and horizontal diameters immediately before re-rounding were measured as 32.16 in (816.9 mm) and 37.85 in (961.4 mm), respectively, making a vertical deflection of -9.89% and a horizontal deflection of +7.32%. After two passes of the re-rounder the vertical and horizontal diameters were 32.63 in (828.8 mm) and 37.94 in (963.7 mm), respectively, making a vertical deflection of -8.56% and a horizontal deflection of +7.56% after re-rounding. The re-rounding process resulted in a net change in vertical deflection of +1.33% and +0.25% in the horizontal direction.

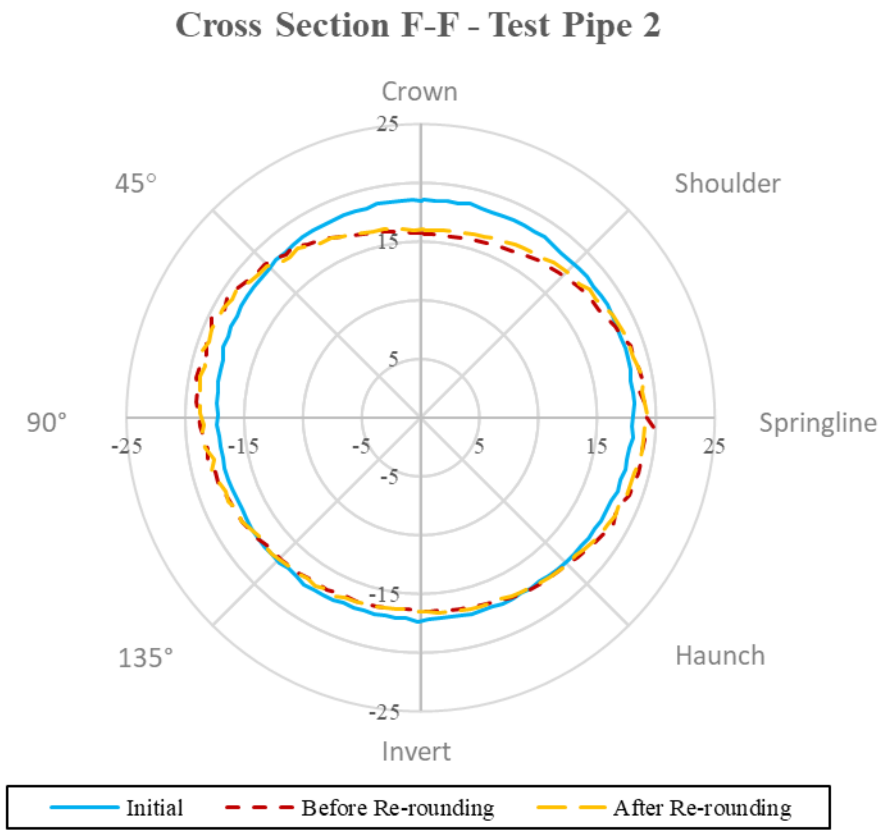

Figure 60. Deflected cross-section F-F of Test Pipe 2 (1 in = 25.4 mm).

A summary of the results of deflection measurements for Test Pipe 2 is provided in Table 6 and a summary of deflections percentages is provided in Table 7.

Table 6. Summary of deflections for Test Pipe 2.

Cross-Section	Initial Diameter				Diameter Before Re-rounding				Diameter After Re-rounding			
	Vertical		Horizontal		Vertical		Horizontal		Vertical		Horizontal	
	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)
A-A	35.71	0.9070	35.32	0.8971	35.49	0.9014	35.64	0.9053	35.86	0.9108	34.60	0.8788
B-B	35.80	0.9093	35.25	0.8954	33.64	0.8545	37.19	0.9446	34.75	0.8827	35.93	0.9126
C-C	35.77	0.9086	35.53	0.9025	32.95	0.8369	37.43	0.9507	33.86	0.8600	36.46	0.9261
D-D	35.70	0.9068	35.52	0.9022	33.09	0.8405	37.94	0.9637	33.54	0.8519	37.12	0.9428
E-E	35.83	0.9101	35.71	0.9070	32.47	0.8247	38.09	0.9675	32.94	0.8367	37.65	0.9563
F-F	35.69	0.9065	35.27	0.8959	32.16	0.8169	37.85	0.9614	32.63	0.8288	37.94	0.9637
G-G	35.97	0.9136	35.11	0.8918	33.08	0.8402	37.07	0.9416	33.71	0.8562	36.82	0.9352
H-H	35.84	0.9103	35.37	0.8984	33.44	0.8494	37.15	0.9436	34.26	0.8702	36.52	0.9276
I-I	35.89	0.9116	35.81	0.9096	35.50	0.9017	35.75	0.9081	36.14	0.9180	35.03	0.8898
J-J	35.49	0.9014	35.74	0.9078	36.17	0.9187	35.30	0.8966	36.12	0.9174	34.57	0.8781

Table 7. Summary of deflection percentages for Test Pipe 2.

Cross-Section	Before Re-rounding		After Re-rounding		Recovered Deflection	
	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)
A-A	-0.62%	0.91%	0.42%	-2.04%	1.04%	-2.94%
B-B	-6.03%	5.50%	-2.93%	1.93%	3.10%	-3.57%
C-C	-7.88%	5.35%	-5.34%	2.62%	2.54%	-2.73%
D-D	-7.31%	6.81%	-6.05%	4.50%	1.26%	-2.31%
E-E	-9.38%	6.66%	-8.07%	5.43%	1.31%	-1.23%
F-F	-9.89%	7.31%	-8.57%	7.57%	1.32%	0.26%
G-G	-8.03%	5.58%	-6.28%	4.87%	1.75%	-0.71%
H-H	-6.70%	5.03%	-4.41%	3.25%	2.29%	-1.78%
I-I	-1.09%	-0.17%	0.70%	-2.18%	1.78%	-2.01%
J-J	1.92%	-1.23%	1.78%	-3.27%	-0.14%	-2.04%

* Data unreliable due to measurement noise

Table 7 shows the vertical deflection of Test Pipe 2 before and after re-rounding at each of the named cross-sections. Cross-sections A-A, I-I, and J-J are excluded from consideration since these cross-sections were under very minimal soil cover and thus experienced very little vertical deformation. Otherwise, the vertical deflection along the length of the pipe varied from -6.03% at B-B to -9.89% at E-E.

After two passes of the re-rounder, the vertical pipe deflections varied from -4.41% at H-H to -8.56% at cross-section F-F. Re-rounding was most effective at cross-section B-B with a reduction in vertical deflection of 3.10%. Re-rounding was least effective at cross-section D-D with a reduction in vertical deflection of 1.27%. Before re-rounding four cross-sections (C-C, E-E, F-F, G-G) were deflected greater than the AASHTO 7.5% remediation/replacement limit. After re-rounding, only cross-sections E-E and F-F remained above the 7.5% threshold. All remaining cross-sections were below 7.5%. Additional passes of the re-rounder might result in an additional reduction in the vertical deflection. However, the re-rounder decided to end the re-rounding effort due to concerns about overheating and damaging the device.

Test Pipe 2 was exhumed 209 days after re-rounding. The shape of the pipe was recorded using the laser profilometer. Figure 61 shows the shape of the pipe immediately after re-rounding and just before removal. The shape of the pipe is essentially unchanged since re-rounding.

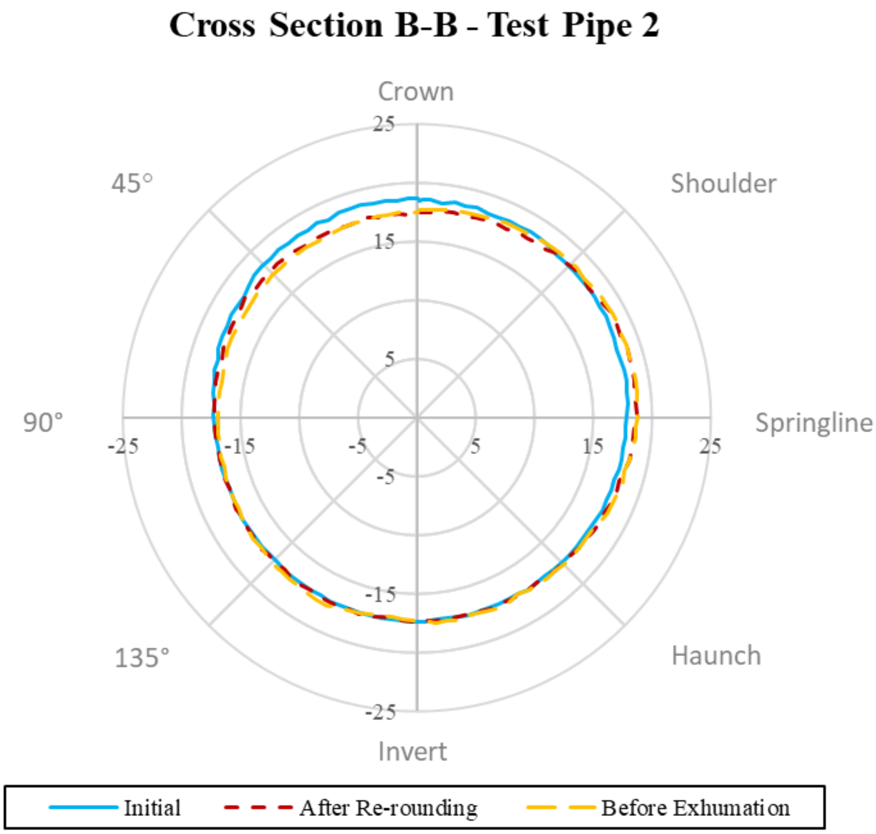

Figure 61. Long-term cross-section B-B of Test Pipe 2 (1 in = 25.4 mm).

8.2.3 Test Pipe 3 Shape Data

Test pipe 3 was a 36 in (0.9 m) nominal diameter HDPE pipe. The initial vertical and horizontal inside diameters were measured at 35.65 in (905.5 mm) and 34.89 in (886.2 mm), respectively. The pipe was backfilled using an open-graded aggregate meeting the requirements of ODOT Structural Backfill Type 3 which is equivalent to an AASHTO #57. Fill material was placed to a height of 10 ft (3 m) above the crown of the pipe. A plot of the longitudinal profile of the test pipe is provided in Figure 62.

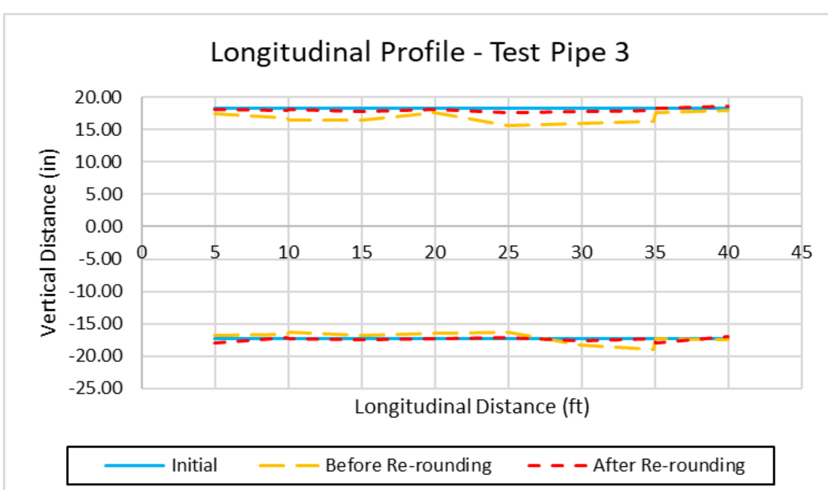

Figure 62. Longitudinal profile of Test Pipe 3 (1 in = 25.4 mm).

Figure 63 shows the shape of the test pipe at cross-section D-D. This cross-section is located approximately 15 ft (4.6 m) from the inlet of the pipe or 5 ft (1.5 m) from the inlet end of the second pipe section. The vertical and horizontal diameters immediately before re-rounding were 33.28 in (845.3 mm) and 37.58 in (954.5 mm), respectively, making the pre-re-rounding vertical deflection -6.67% and horizontal deflection +7.69%. After a single pass of the re-rounder the vertical and horizontal diameters were 35.17 in (893.3 mm) and 35.75 in (908.0 mm), respectively, yielding post-re-rounding vertical deflection of -1.36% and horizontal deflection of +2.45%. The net change in vertical deflection was +5.31% and -5.25% in the horizontal direction.

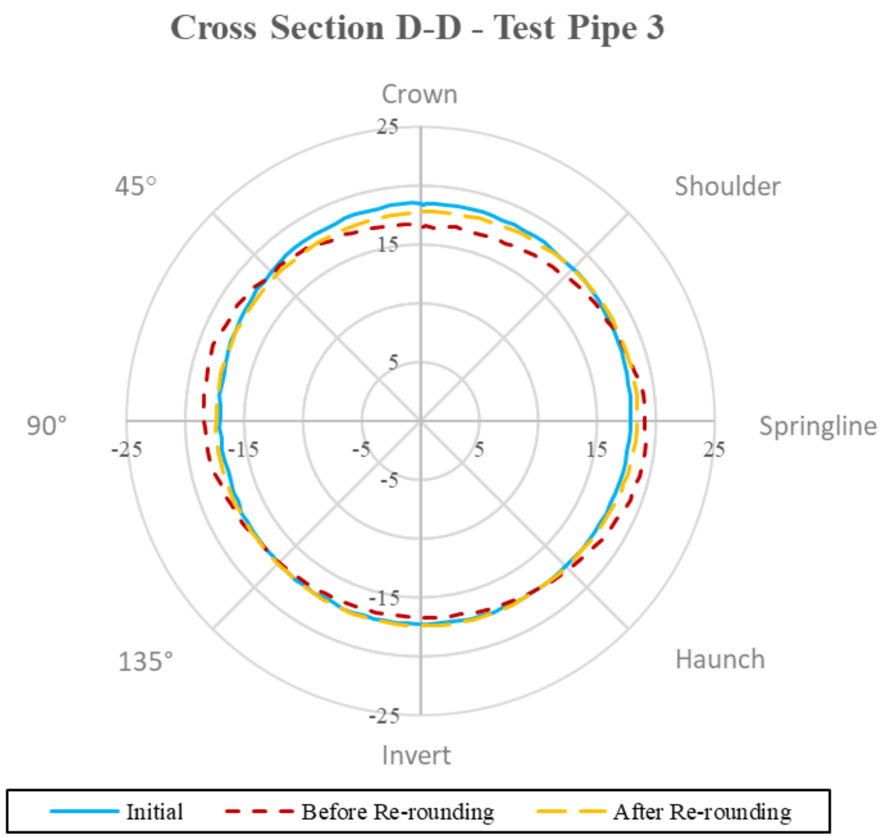

Figure 63. Deflected cross-section D-D of Test Pipe 3 (1 in = 25.4 mm).

Figure 64 shows the shape of the test pipe at cross-section E-E. This cross-section is located approximately 20 ft (6.1 m) from the inlet of the pipe which is the mid-point of the second pipe section. The vertical and horizontal diameters immediately before re-rounding were 34.16 in (867.7 mm) and 36.15 in (918.2 mm), respectively, with a vertical deflection of -4.20% and a horizontal deflection of +3.61%. After a single pass of the re-rounder the vertical and horizontal diameters were 35.34 in (897.6 mm) and 34.96 in (888.0 mm), respectively, yielding a final vertical deflection of -0.88% and a horizontal deflection of +0.20%. The re-rounding process resulted in a net change of +3.32% and -3.41% respectively in the vertical and horizontal directions.

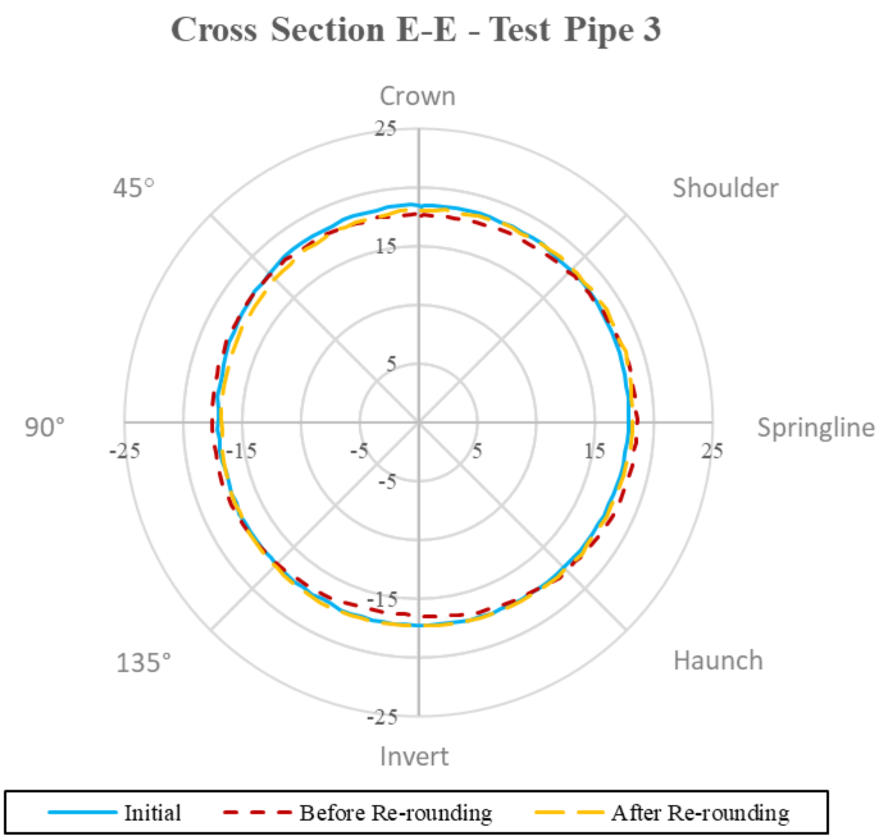

Figure 64. Deflected cross-section E-E of Test Pipe 3 (1 in = 25.4 mm).

Figure 65 shows the shape of the test pipe at cross-section F-F. This cross-section is located approximately 25 ft (7.6 m) from the inlet of the pipe or 5 ft (1.5 m) from the outlet end of the second pipe section. The vertical and horizontal diameters immediately before re-rounding were 32.02 in (813.3 mm) and 38.25 in (971.6 mm), respectively, with pre-re-rounding vertical deflection of -10.20% and a horizontal deflection of +9.62%. After a single pass of the re-rounder the vertical and horizontal diameters were measured as 34.75 in (882.6 mm) and 36.84 in (936.7 mm), respectively. This vertical deflection measured after re-rounding was -2.53% and the horizontal deflection was +5.58%. The re-rounding process resulted in a net change in vertical deflection of +7.68% and -4.05% in the horizontal deflection.

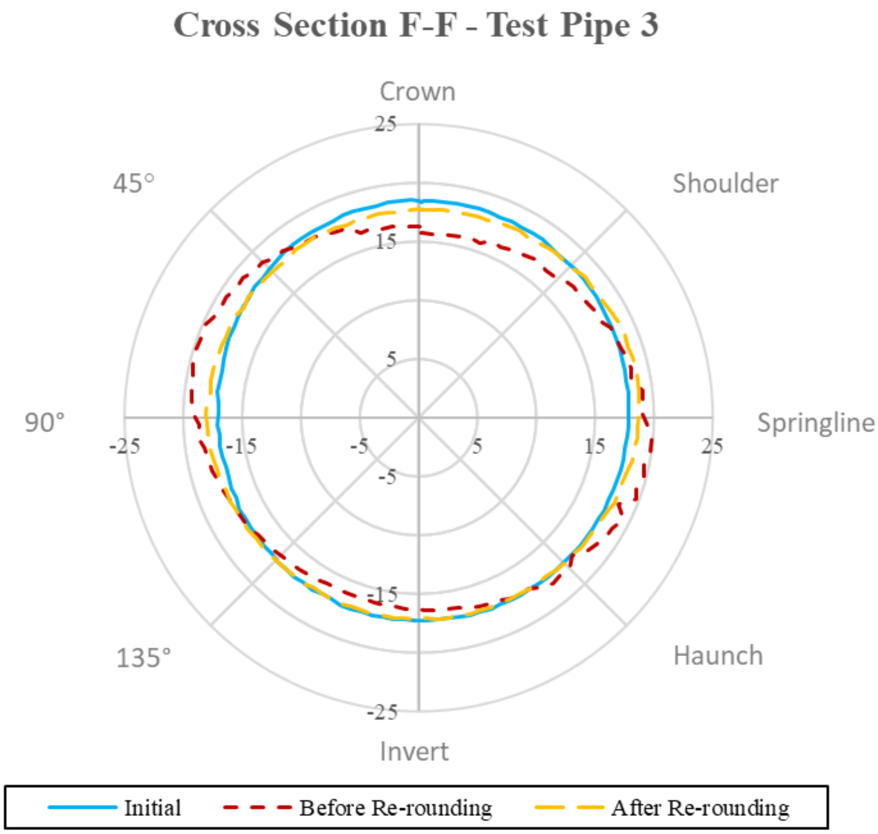

Figure 65. Deflected cross-section F-F of Test Pipe 3 (1 in = 25.4 mm).

A summary of the results of deflection measurements for Test Pipe 3 is provided in Table 8 and a summary of deflections is provided in Table 9.

Table 8. Summary of diameter measurements for Test Pipe 3.

Cross-Section	Initial Diameter				Diameter Before Re-rounding				Diameter After Re-rounding			
	Vertical		Horizontal		Vertical		Horizontal		Vertical		Horizontal	
	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)
A-A	35.65	0.9055	34.89	0.8862	34.23	0.8694	35.67	0.9060	36.11	0.9172	34.82	0.8844
B-B	*	*	*	*	33.38	0.8479	37.65	0.9563	35.18	0.8936	35.99	0.9141
C-C	*	*	*	*	32.82	0.8336	38.29	0.9726	35.39	0.8989	35.89	0.9116
D-D	*	*	*	*	33.28	0.8453	37.58	0.9545	35.17	0.8933	35.75	0.9081
E-E	*	*	*	*	34.16	0.8677	36.15	0.9182	35.34	0.8976	34.96	0.8880
F-F	*	*	*	*	32.02	0.8133	38.25	0.9716	34.75	0.8827	36.84	0.9357
G-G	*	*	*	*	34.23	0.8694	34.18	0.8682	35.44	0.9002	35.55	0.9030
H-H	*	*	*	*	35.28	0.8961	32.55	0.8268	**	**	36.09	0.9167
I-I	*	*	*	*	34.86	0.8854	35.21	0.8943	36.22	0.9200	34.62	0.8793
J-J	*	*	*	*	35.53	0.9025	34.88	0.8860	35.59	0.9040	35.64	0.9053

* Initial measurement made at cross-section A-A and assumed the same for all points

** Data unreliable due to measurement noise

Table 9. Summary of deflection percentages for Test Pipe 3.

Cross-Section	Before Re-rounding		After Re-rounding		Recovered Deflection	
	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)
A-A	-3.98%	2.24%	1.29%	-0.20%	5.27%	-2.44%
B-B	-6.37%	7.91%	-1.32%	3.15%	5.05%	-4.76%
C-C	-7.94%	9.74%	-0.73%	2.87%	7.21%	-6.88%
D-D	-6.65%	7.71%	-1.35%	2.46%	5.30%	-5.25%
E-E	-4.18%	3.61%	-0.87%	0.20%	3.31%	-3.41%
F-F	-10.18%	9.63%	-2.52%	5.59%	7.66%	-4.04%
G-G	-3.98%	-2.03%	-0.59%	1.89%	3.39%	3.93%
H-H	-1.04%	-6.71%	*	3.44%	*	10.15%
I-I	-2.22%	0.92%	1.60%	-0.77%	3.81%	-1.69%
J-J	-0.34%	-0.03%	-0.17%	2.15%	0.17%	2.18%

* Data unreliable due to measurement noise

Table 9 shows the vertical deflection of Test Pipe 3 before and after re-rounding at each of the named cross-sections. Cross-sections A-A, I-I, and J-J were under very minimal soil cover and thus never experienced significant vertical deformation. Cross-section H-H is excluded because of unreliable radial measurements due to signal noise. The vertical deflection of the other sections along the length of the pipe varied from -4.00% at G-G to -10.20% at F-F.

After a single pass of the re-rounder, the pipe deflections varied from -0.60% at G-G to -2.53% at cross-section F-F. Re-rounding was most effective at cross-section F-F with a reduction in vertical deflection of 7.68%. Re-rounding was least effective at cross-section E-E with a reduction in vertical deflection of 3.32%. Before re-rounding two of the six named cross-sections were deflected greater than the AASHTO 7.5% remediation/replacement limit. After re-rounding, all cross-sections were below 7.5%.

8.2.4 Discussion of Shape Data from Test Pipes 1, 2, and 3

The utility of the re-rounding process is dependent on the type of material used as structural backfill. A summary of vertical deflection results is provided in Figure 66. Of the three pipes tested, Test Pipe 3, backfilled with ODOT Structural Backfill Type 3, (open-graded aggregate) was by far the most amenable to the re-rounding process. At the cross-section with the greatest reduction in vertical deflection, the re-rounding process reduced the vertical deflection by 7.21% with a single pass of the re-rounder. This is explained by the large void ratio of the material which allows for the relatively easy movement of the aggregate particles during vibration. The Structural Backfill Type 1 used for Test Pipe 1 is a well-graded material with a much lower void ratio. More vibrational energy is required to move the soil particles. The average reduction in vertical deflection at the three central cross-sections (D-D, E-E, F-F), after three passes of the re-rounder, was 3.22%. This is an average of 1.07% per pass. The Type 2 Structural Backfill used for Test Pipe 2 is a uniformly graded sand that also has a lower void ratio. More vibrational energy is required to mobilize the soil particles. The average reduction in vertical deflection at the three central cross-sections (D-D, E-E, F-F), after two passes of the re-rounder, was 1.31%. This is an average of 0.66% per pass.

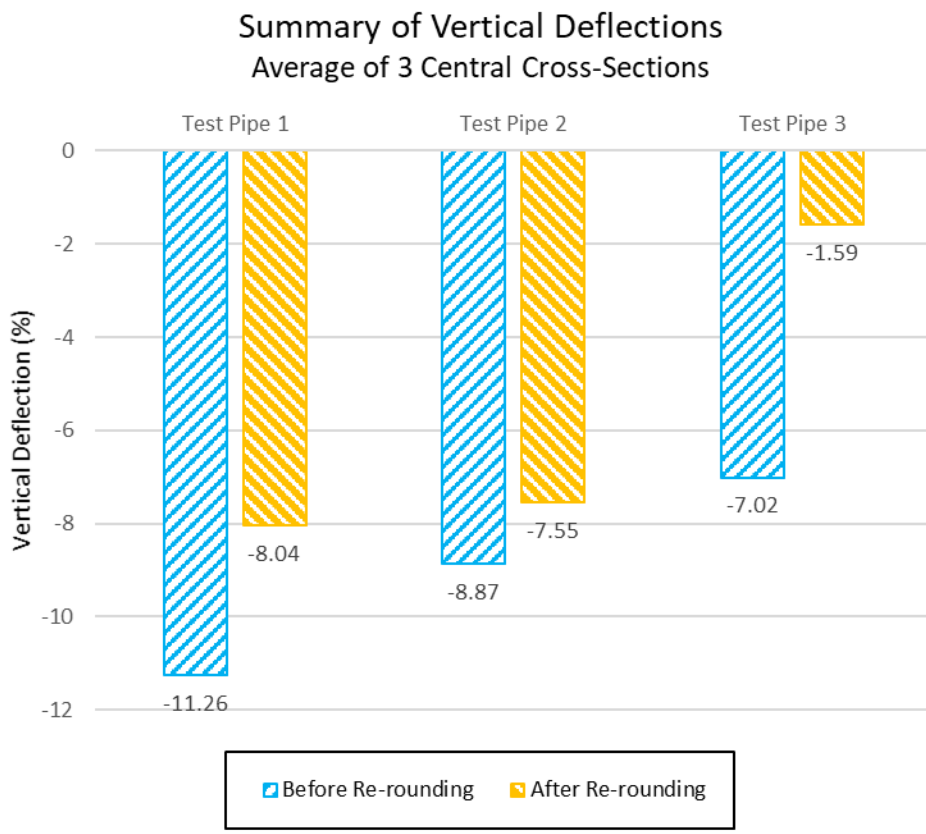

Figure 66. Summary of vertical deflections.

The long-term suitability of the re-rounding process was also considered. Shape measurements obtained with the laser profilometer show that the shape of the pipe remained essentially unchanged after 48 days for Test Pipe 1 and after 209 days for Test Pipe 2. This indicates re-rounded pipe will retain its shape over a long term.

8.2.5 Test Pipe 4 Shape Data

Table 10 summarizes the diameter measurements made on Test Pipe 4, which had a nominal diameter of 18 in (0.46 m) and which was installed in Structural Backfill Type 3 (AASHTO #57 aggregate). Table 11 is a summary of the deflection data corresponding to the diameter measurements. Note that the deflections before re-rounding are highest for sections B-B, C-C, G-G, and H-H, which is where the joints were, while sections D-D, E-E, and F-F were deflected only slightly. This is due to the placement of the deflector devices, which were approximately centered on the joints. The maximum deflections before re-rounding were 16.67% at G-G and H-H. The deflections collected after re-rounding at locations B-B, G-G, and H-H were compromised due to measurement device errors. However, the final profiles collected at exhumation show the reduction in deflection at all of these locations, with the maximum final deflection at -6.39% at location H-H.

Table 10. Summary of diameter measurements for Test Pipe 4 (Nominal diameter 18 in (0.46 m).

Cross-Section	Diameter Before Re-rounding				Diameter After Re-rounding				Diameter at Exhumation			
	Vertical		Horizontal		Vertical		Horizontal		Vertical		Horizontal	
	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)
A-A	17.16	0.4360	18.77	0.4766	16.61	0.4220	19.12	0.4858	17.48	0.4440	18.42	0.4678
B-B	15.08	0.3830	20.35	0.5169	*	*	*	*	16.89	0.4290	19.05	0.4838
C-C	15.04	0.3820	20.39	0.5180	17.44	0.4430	18.40	0.4673	17.80	0.4520	18.22	0.4628
D-D	17.84	0.4530	17.98	0.4566	17.75	0.4509	18.01	0.4574	17.72	0.4500	17.78	0.4516
E-E	17.68	0.4490	17.83	0.4528	17.71	0.4499	17.95	0.4558	17.72	0.4500	18.18	0.4617
F-F	17.36	0.4410	18.58	0.4719	17.17	0.4360	18.54	0.4709	17.52	0.4450	18.06	0.4587
G-G	15.00	0.3810	20.35	0.5170	*	*	*	*	16.97	0.4310	19.01	0.4829
H-H	15.00	0.3810	20.19	0.5129	*	*	*	*	16.85	0.4280	18.81	0.4777
I-I	17.91	0.4550	17.93	0.4555	17.71	0.4500	18.20	0.4624	17.95	0.4560	18.01	0.4574
J-J	17.40	0.4420	18.07	0.4589	16.97	0.4310	18.07	0.4589	17.17	0.4360	18.15	0.4609

*Suspect data found in profiles at joints.

Table 11. Summary of deflection percentages for Test Pipe 4.

Cross-Section	Before Re-rounding		After Re-rounding		Recovered Deflection		Final		Recovered Deflection	
	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)
A-A	-4.64%	4.25%	-7.70%	6.25%	-3.06%	2.00%	-2.89%	2.31%	1.75%	-1.94%
B-B	-16.23%	13.06%	*	*	*	*	-6.16%	5.82%	10.07%	-7.23%
C-C	-16.45%	13.30%	-3.12%	2.21%	13.34%	-11.09%	-1.14%	1.22%	15.31%	-12.08%
D-D	-0.92%	-0.13%	-1.37%	0.04%	-0.46%	0.18%	-1.58%	-1.22%	-0.66%	-1.09%
E-E	-1.79%	-0.97%	-1.59%	-0.30%	0.21%	0.66%	-1.58%	0.99%	0.22%	1.96%
F-F	-3.55%	3.23%	-4.63%	3.00%	-1.09%	-0.23%	-2.67%	0.33%	0.88%	-2.90%
G-G	-16.67%	13.08%	*	*	*	*	-5.73%	5.62%	10.94%	-7.46%
H-H	-16.67%	12.18%	*	*	*	*	-6.39%	4.49%	10.28%	-7.69%
I-I	-0.48%	-0.37%	-1.58%	1.13%	-5.90%	1.50%	-0.26%	0.05%	0.23%	0.42%
J-J	-3.33%	0.38%	-5.73%	0.38%	-2.40%	0.00%	-4.64%	0.81%	-1.30%	0.43%

*Suspect data found in profiles at joints.

8.2.6 Test Pipe 5 Shape Data

Table 12 shows the diameter data collected on Pipe 5, which had a nominal diameter of 18 in (0.46 m) and which was installed in Structural Backfill Type 2 (sand). The accompanying deflection data are in Table 13. Otherwise, the largest deflections were on cross-sections A-A, B-B, C-C, F-F, G-G, and H-H, between -12.38% and -14.50%. After re-rounding, these decreased to -5.39% to -7.47%, with a further slight reduction over the next month to -5.13% to -7.42%. Horizontal deflections were positive, slightly lower in magnitude, and followed the same trend in reduction, except for some slight increases during the month after re-rounding. The maximum horizontal deflection before re-rounding was

12.27% at cross-section H-H, which was reduced to a final deflection of 8.38%, which was also the maximum horizontal deflection at that time. This was the only location on Test Pipe 5 with a post-re-rounding deflection, horizontal or vertical, to exceed 7.5% in magnitude.

Table 12. Summary of diameter measurements for Test Pipe 5 (Nominal diameter 18 in (0.46 m).

Cross-Section	Diameter Before Re-rounding				Diameter After Re-rounding				Diameter at Exhumation			
	Vertical		Horizontal		Vertical		Horizontal		Vertical		Horizontal	
	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)	(in)	(m)
A-A	15.65	0.3975	19.08	0.4846	16.91	0.4295	18.71	0.4752	16.95	0.4306	18.54	0.4710
B-B	15.26	0.3877	19.80	0.5030	16.45	0.4179	18.96	0.4816	16.47	0.4183	18.69	0.4748
C-C	15.42	0.3917	19.87	0.5046	16.50	0.4190	18.83	0.4782	16.63	0.4225	18.70	0.4750
D-D	17.57	0.4463	17.49	0.4444	17.83	0.4528	17.74	0.4506	17.89	0.4544	17.76	0.4510
E-E	17.34	0.4404	17.70	0.4496	16.81	0.4269	18.74	0.4760	17.57	0.4463	17.91	0.4550
F-F	15.69	0.3986	19.47	0.4946	16.81	0.4269	18.74	0.4760	16.78	0.4261	18.74	0.4760
G-G	15.37	0.3904	19.90	0.5053	16.57	0.4210	18.74	0.4760	16.58	0.4212	18.74	0.4760
H-H	15.25	0.3873	19.97	0.5072	16.73	0.4249	18.82	0.4780	16.73	0.4250	18.94	0.4810
I-I	17.42	0.4425	17.63	0.4479	*	*	17.28	0.4389	17.92	0.4552	17.47	0.4437
J-J	17.15	0.4355	18.15	0.4611	17.08	0.4339	18.25	0.4636	17.27	0.4386	18.27	0.464

*Suspect data – profiler skipped over pipe invert.

Table 13. Summary of deflection percentages for Test Pipe 5.

Cross-Section	Before Re-rounding		After Re-rounding		Recovered Deflection		Final		Recovered Deflection	
	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical (%)	Horizontal (%)	Vertical Deflection (%)	Horizontal Deflection (%)	Vertical (%)	Horizontal (%)
A-A	-12.44%	6.77%	-5.39%	4.70%	7.05%	-2.06%	-5.13%	3.78%	7.31%	-2.99%
B-B	-13.27%	10.85%	-6.51%	6.15%	6.77%	-4.71%	-6.41%	4.65%	6.86%	-6.20%
C-C	-13.14%	11.44%	-7.08%	5.62%	6.06%	-5.82%	-6.31%	4.90%	6.83%	-6.54%
D-D	-1.46%	-2.08%	-0.03%	-0.71%	1.43%	1.37%	0.33%	-0.62%	1.79%	1.46%
E-E	-2.34%	-0.95%	-5.32%	4.86%	-2.98%	5.81%	-1.03%	0.24%	1.31%	1.19%
F-F	-12.38%	9.59%	-6.15%	5.47%	6.23%	-4.13%	-6.34%	5.48%	6.05%	-4.12%
G-G	-14.18%	11.60%	-7.47%	5.11%	6.71%	-6.49%	-7.42%	5.12%	6.76%	-6.48%
H-H	-14.50%	12.27%	-6.21%	5.81%	8.28%	-6.47%	-6.18%	6.47%	8.31%	-5.80%
I-I	-3.18%	-0.65%	*	*	*	*	-0.39%	-1.57%	2.79%	-0.92%
J-J	-2.99%	2.29%	-3.37%	2.84%	-0.38%	0.55%	-2.32%	2.92%	0.67%	0.63%

*Suspect data – profiler skipped over pipe invert.

8.3 Test Pipe Pressure Cell Data

Pressure cell readings were obtained before, during, and after the re-rounding process. Pressure cells were oriented radially to measure vertical pressure at the crown and horizontal pressure at both sides of the springline of each test pipe. Pressure cell readings obtained during each test pipe are provided in Table 14 through Table 16.

The pressure changes are consistent with soil particles moving from the crown and shoulders down to lower elevations near the haunches, and with pressure reduction at the springlines where the pipe surfaces move towards the center, leaving more room for the backfill. This visual observation was supported while exhuming Test Pipe 1 when the springline Pressure Cells P1R and P1L were found to have moved below the springline of the pipe as a result of the re-rounding process.

Table 14. Pressure cell readings for Test Pipe 1.

Date		Soil pressure					
		Left springline		Right springline		Crown	
		(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
5/15/2018	Installation	7.21	49.7	8.24	56.8	5.60	38.6
6/14/2018	Before	6.81	47.0	7.85	54.1	5.02	34.6
6/14/2018	After Pass 1	4.20	29.0	4.60	31.7	2.08	14.3
6/14/2018	After Pass 2	3.48	24.0	4.40	30.3	1.69	11.7
6/14/2018	After Pass 3	2.76	19.0	4.62	31.9	0.72	5.0

Table 15. Pressure cell readings for Test Pipe 2.

Date		Soil pressure					
		Left springline		Right springline		Crown	
		(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
9/29/2018	Installation	5.62	38.7	7.04	48.5	8.73	60.2
10/29/2018	Before	2.99	20.6	3.80	26.2	5.48	37.8
10/29/2018	After Pass 1	2.30	15.9	2.27	15.7	1.39	9.6
10/29/2018	After Pass 2	2.09	14.4	1.89	13.0	0.76	5.2

Table 16. Pressure cell readings for Test Pipe 3.

Date		Soil pressure					
		Left springline		Right springline		Crown	
		(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
1/29/2020	Before	2.69	18.5	0.66	4.6	4.08	28.1
1/29/2020	After Pass 1	2.23	15.4	2.25	15.5	5.20	35.9
1/30/2020	Next Day	2.26	15.6	2.03	14.0	5.12	35.3

The pressure cell readings for Test Pipes 1 and 2 showed a significant reduction in radial pressure when comparing the readings taken 30 days before re-rounding to readings taken after the completion of re-rounding. The measured values for Test Pipe 1 30 days prior to re-rounding were 7.21 psi (49.7 kPa); 8.24 psi (56.8 kPa); and 5.60 psi (38.6 kPa), at the left springline, right springline, and crown, respectively, and those measured after re-rounding were 2.76 psi 19.0 kPa); 4.62 psi (31.9 kPa); and 0.72 psi (5.0 kPa). These correspond to respective reductions of 61%, 44%, and 88% at the left springline, right springline, and crown. For Test Pipe 2, the measured values 30 days prior to re-rounding were 5.62 psi (38.7 kPa); 7.04 psi (48.5 kPa); and 8.73 psi (60.2 kPa), at the left springline, right springline, and crown, respectively, while those after re-rounding were 2.09 psi (14.4 kPa); 1.89 psi (13.0 kPa); and 0.76 psi (5.2 kPa). These corresponding to respective reductions of 63%, 73%, and 91%.

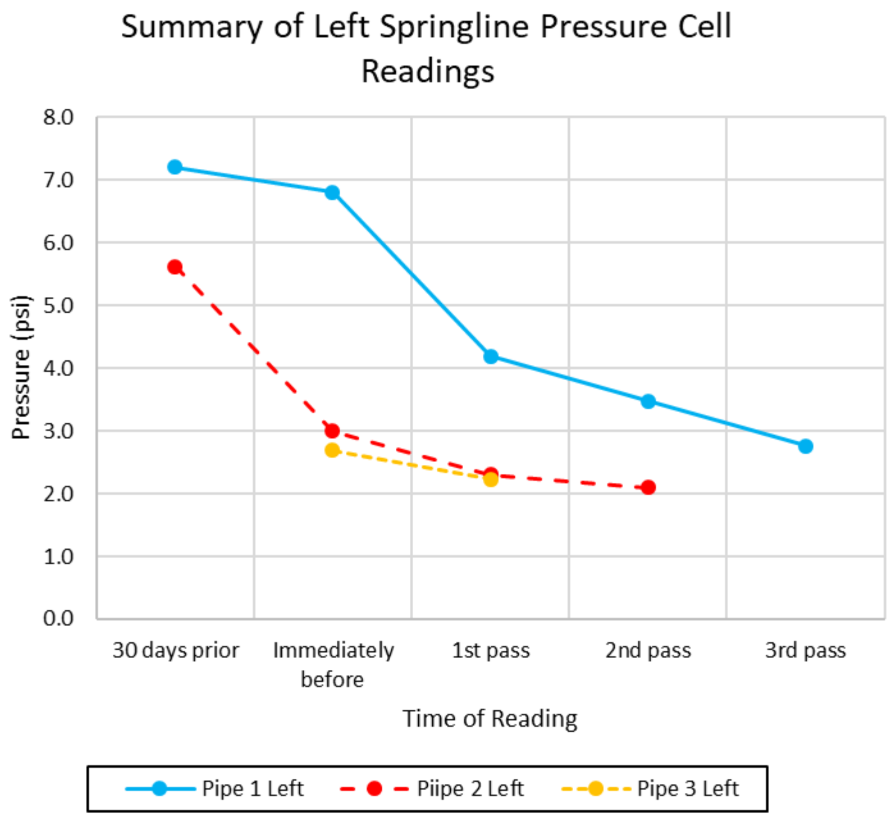

Figure 67. Summary of left springline pressure cell readings (1 psi = 6.89 kPa).

Test Pipe 3 did not follow a similar trend. Instead, there was a decrease in the left springline pressure, but an increase in pressure at the crown and right springline. The measured values for Test Pipe 3 immediately before re-rounding and re-rounding were 2.69 psi (18.5 kPa); 0.66 psi (4.6 kPa); and 4.08 psi (28.1 kPa), at the left springline, right springline, and crown, respectively, and those after re-rounding were 2.23 psi (15.6 kPa); 2.25 psi (15.5 kPa); and 5.20 psi (35.3 kPa). These correspond to an increase in pressure for Test Pipe 3 of 205% at the right springline and 25% at the crown, and a decrease in pressure of 16% at the left springline.

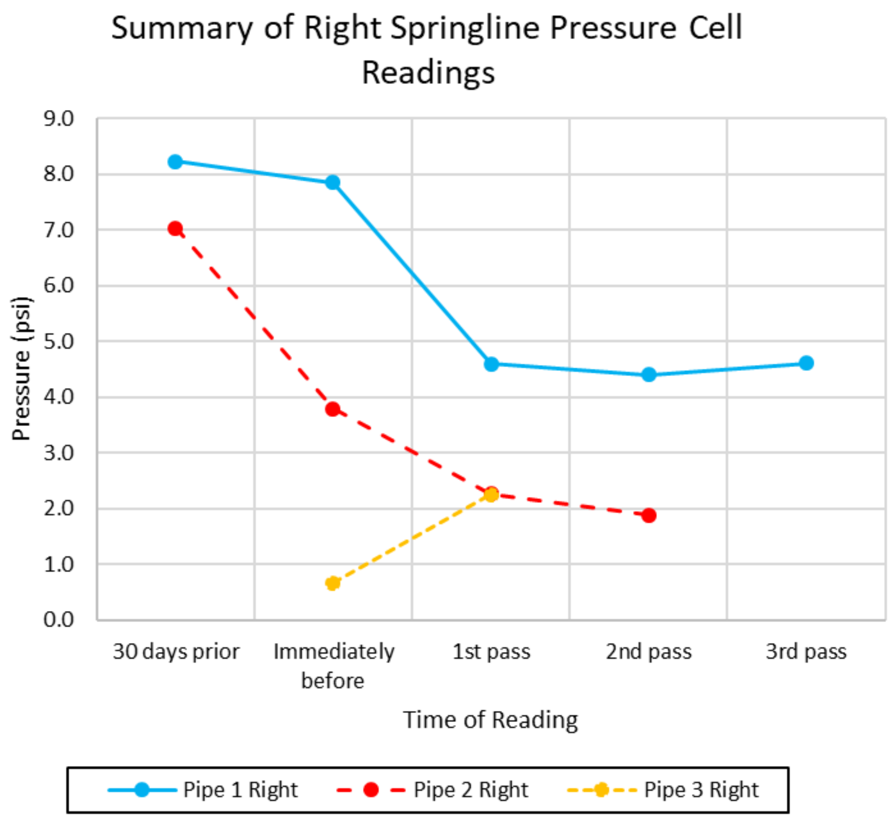

Figure 68. Summary of right springline pressure cell readings (1 psi = 6.89 kPa).

Both Test Pipe 1 and Test Pipe 2 show a reduction in radial pressure at each pressure cell. The change between the readings taken 30 days prior and immediately before reading is explained by the viscoelastic relaxation of the HDPE with time while under near-constant deformation. Over a 30 day period, the apparent modulus of the HDPE can decrease by as much as 60% [Pluimer, et al., 2018]. The result is positive soil arching and a reduction in the radial pressure. Additionally, the magnitude of the initial radial stress for Test Pipe 3 was significantly lower than for Test Pipes 1 and 2. Test Pipes 1 and 2 also saw a much greater reduction in radial pressures as a result of the re-rounding process.

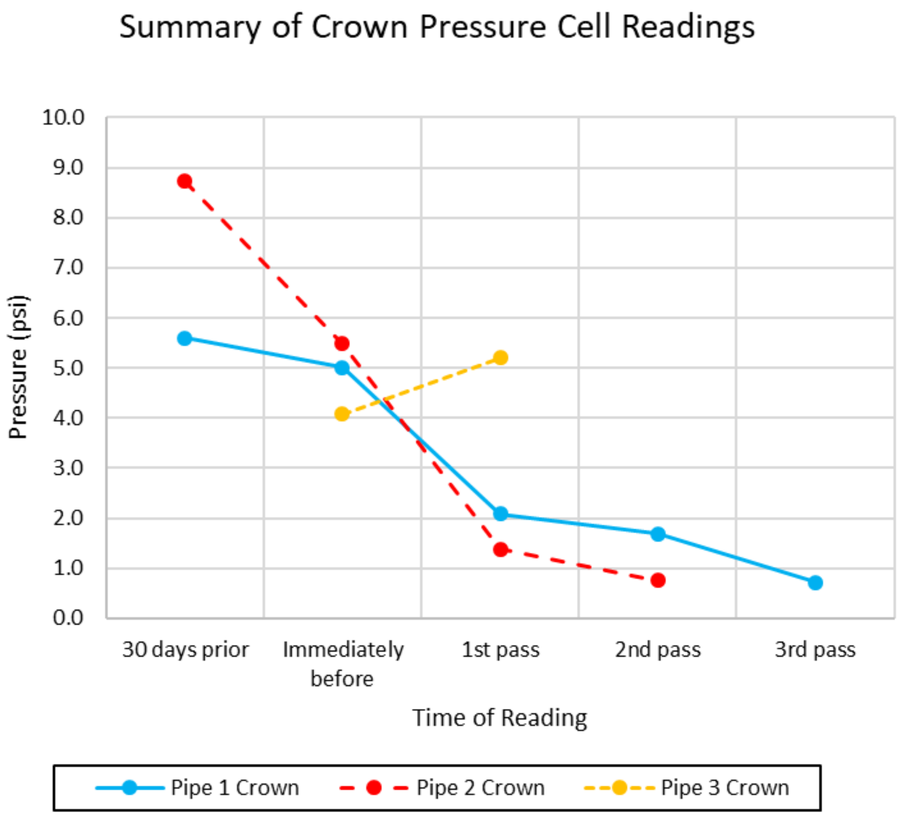

Figure 69. Summary of crown pressure cell readings (1 psi = 6.89 kPa).

Table 17 shows pressure cell readings for Test Pipe 4. One can see that after re-rounding, the pressure at all three cells has decreased, particularly at the springline. Table 18 shows pressure data from Test Pipe 5. Soil pressures around Test Pipe 5 generally follow the same trends as around Test Pipe 2, which has the same Type 2 backfill (sand), with the pressure decreasing with re-rounding. Test Pipes 4 and 3, which were both in Type 3 backfill (AASHTO # 57 aggregate) are less comparable, and this may be due to the fact that the 9 in (229 mm) wide pressure cell is half the diameter of Test Pipe 4, but only a quarter the diameter of Test Pipe 2, so the pressure conditions may vary more across the pressure cells on Test Pipe 4. Overall, the net result for Test Pipes 4 and 5 at exhumation as a decrease in soil pressure from the pre-re-rounding condition.

Table 17. Pressure cell readings for Test Pipe 4.

		Soil pressure					
		Left springline		Right springline		Crown	
Date		(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
6/24/2020	Installation	2.39	16.5	2.98	20.5	5.35	36.9
9/10/2020	Before re-rounding	2.58	17.8	2.93	20.2	4.55	31.4
9/10/2020	After re-rounding	1.12	7.7	0.82	5.7	4.09	28.2
10/21/2020	Final	1.12	7.8	0.93	6.4	3.42	23.6

Table 18. Pressure cell readings for Test Pipe 5.

		Soil pressure					
		Left springline		Right springline		Crown	
Date		(psi)	(kPa)	(psi)	(kPa)	(psi)	(kPa)
10/22/2020	Installation	3.42	23.6	3.99	27.5	8.46	58.3
2/23/2021	Before re-rounding	1.25	8.6	1.93	13.3	4.88	33.6
2/23/2021	After first pass	1.11	7.7	1.46	10.1	1.53	10.5
2/23/2021	After second pass	0.67	4.6	1.05	7.2	2.41	16.6
3/30/2021	Final	1.01	6.9	1.26	8.7	3.01	20.8

8.4 Test Pipe 1 Soil Analysis

Several soil analysis tests were performed on the backfill material utilized for Test Pipe 1. The density of the structural backfill was measured in place using a sand cone test. A total of three tests were performed at the left springline of the test pipe. The average density of the backfill material was determined to be 71.1%. Such a low value was expected because there was no compaction of the backfill material during the installation process. It is noted that the 71.1% measured is well below the 90% density required by the AASHTO Bridge Construction Specifications [AASHTO, 2017].

The optimum moisture content and maximum dry density of the backfill material were determined in the laboratory using the Standard Proctor Test. Table 19 provides the results of the proctor test for each of the three soil samples obtained and tested. The resulting moisture-density curve is provided in Figure 70. The optimum moisture content was determined to be 6.8% and the maximum dry density was determined to be 139.8 lb/ft^3 (2239 kg/m^3).

Table 19. Proctor test results.

		Sample 1	Sample 2	Sample 3	Average
Soil Wet Density	(lb/ft^3)	99.9	108.6	109.3	105.5
	(kg/m^3)	1600	1740	1751	1690
Soil Dry Density	(lb/ft^3)	94.3	101.8	102.4	99.9
	(kg/m^3)	1511	1631	1640	1600
Max Dry Density	(lb/ft^3)	139.8	139.8	139.8	139.8
	(kg/m^3)	2239	2239	2239	2239
Degree of Compaction	(%)	67.2	72.8	73.2	71.1
Moisture Content	(%)	5.7	6.8	8.4	6.9

Lastly, a sieve analysis was performed on the backfill material. Samples of the backfill material were collected before the installation of the test pipe. Material was also collected at both the crown and springline of the test pipe during removal of the pipe after testing was completed. Gradation curves of the three material samples are provided in Figure 71.

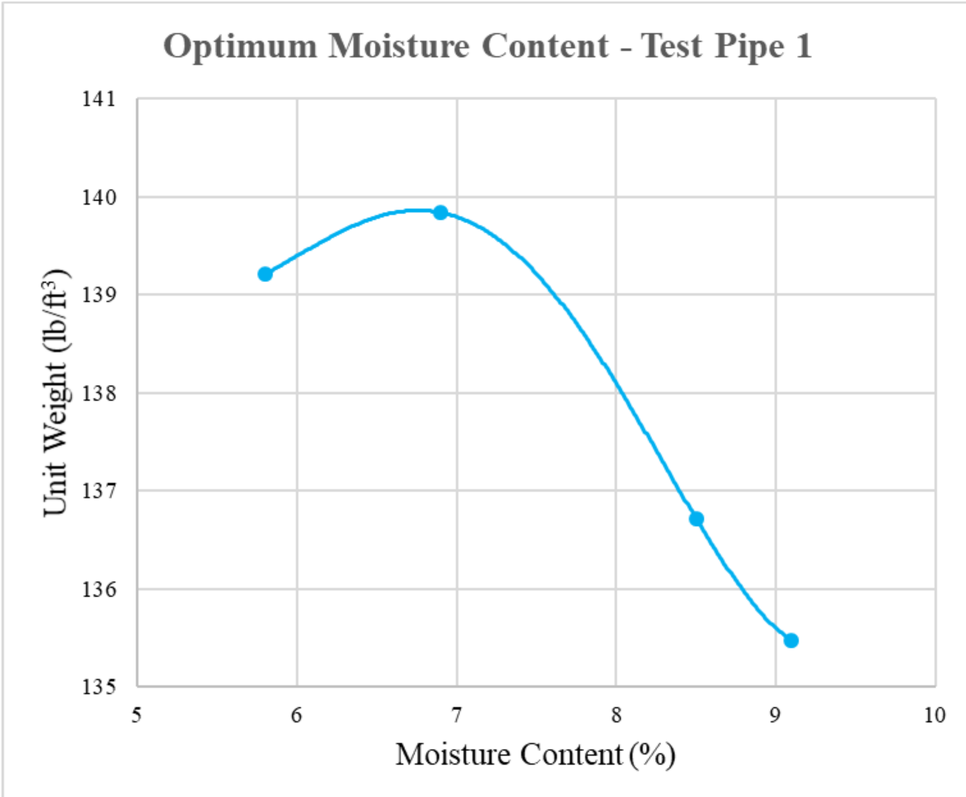

Figure 70. Moisture content - dry density relationship for Type 1 backfill used with Test Pipe 1 (1 lb/ft^3 = 16 kg/m^3).

The coefficient of uniformity, C_u, and coefficient of curvature, C_c, are measures of how well or poorly a soil is graded. They are defined as:

$$C_u = \frac{D_{60}}{D_{10}} \tag{1}$$

$$C_c = \frac{(D_{30})^2}{(D_{10})(D_{60})} \tag{2}$$

Where the D_{xx} is the grain size larger than that of XX% of the material by weight. Very low values of the coefficient of uniformity are indicative of poorly graded soils. Values above 4 for gravels and above 6 for sands are considered well-graded. Values of the coefficient of curvature between 1 and 3 are indicative of well-graded soils.

By visual inspection, the D_{60}, D_{30}, and D_{10} values for the backfill samples were obtained from Figure 71 and are provided in Table 20. Using these values, the coefficient of uniformity and coefficient of curvature were calculated and are presented in the same table. All three samples would be considered well-graded using the coefficient of uniformity. However, only the original sample, before re-rounding, is well-graded considering the coefficient of curvature criterion. Additionally, the gradation curves clearly show differences in the material gradation before and after re-rounding. There is less fine material in both the crown and springline samples. This can be attributed to the vibration of the re-rounder causing the fine material particles to settle further down towards the haunch area. The crown shows a greater degree of material segregation as would be expected since this is where the greatest vibrational energy was applied.

Table 20. Coefficient of uniformity and coefficient of curvature for Type 1 backfill for Test Pipe 1.

		Before Re-rounding	After Re-rounding (Crown)	After Re-rounding (Springline)
D_{60}	(mm)	6.8	13	7.9
	(in)	0.27	0.51	0.31
D_{30}	(mm)	1.5	2.1	4
	(in)	0.06	0.08	0.16
D_{10}	(mm)	0.1	1.2	0.4
	(in)	0.00	0.05	0.02
C_u		48.6	11.3	20.3
C_c		2.4	0.3	5.2

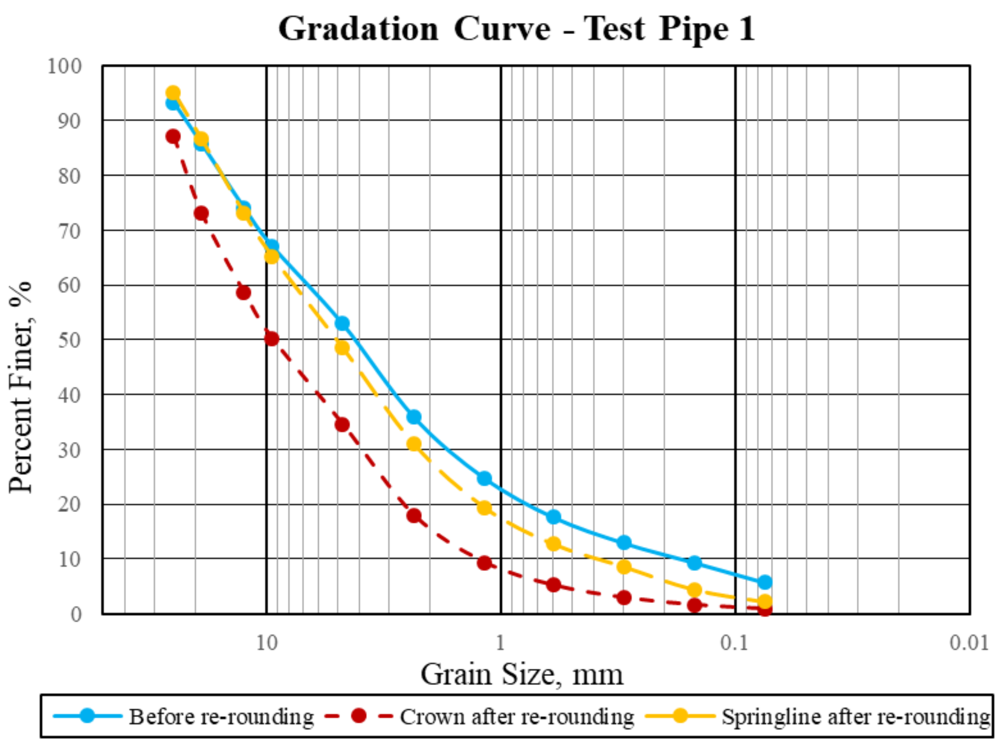

Figure 71. Gradation curve for Test Pipe 1 (1 mm = 0.039 in).

8.5 In-Situ Soil Stiffness Device

A device shown in Figure 35 and Figure 36, was placed at the shoulder and springline of Test Pipe 2 to measure the in-situ stiffness of the structural backfill material. An identical device was installed in the haunch region of Test Pipe 3. (A similar device in Test Pipe 1 did not work successfully.) The measurements obtained before and after re-rounding are provided in Table 21.

Table 21. In-situ soil stiffness measurements before and after re-rounding.

Location	Test Pipe 2 (Type 2 backfill) Before (psi/in)	Before (MPa/m)	After (psi/in)	After (MPa/m)	Change	Test Pipe 3 (Type 3 backfill) Before (psi/in)	Before (MPa/m)	After (psi/in)	After (MPa/m)	Change
Springline	325	88.2	212.5	57.7	-34.6%	-	-	-	-	-
Shoulder	325	88.2	250	67.9	-23.1%	-	-	-	-	-
Haunch	-	-	-	-	-	100	27.1	312.5	84.8	212%

The presented data show the in-situ soil stiffness at both the springline and shoulder of Test Pipe 2 experienced a reduction due to the re-rounding process, decreasing from 325 psi/in (88.2 MPa/m) to 212.5 psi/in (57.7 MPa/m) at the springline for a -34.6% change, and from 325 psi/in (88.2 MPa/m) to 250 psi/in (67.9 MPa/m) at the shoulder for a -23.1% change. On the other hand, Test Pipe 3 experienced a significant increase in the in-situ soil stiffness at the haunch of the pipe, from 100 psi/in (27.1 MPa/m) to 312.5 psi/in (84.8 MPa/m), and increase of +212%.

It is also noted that after re-rounding there was more uniformity to the stiffness measurements around the pipe circumference. The stiffening of the haunch material is beneficial and may result in a reduction in the vertical crown pressure.

These trends can be explained by the movement of the soil particles, predominantly fine particles moving from higher to lower, results in a higher soil density toward the bottom of the pipe resulting in a stiffening of the haunch. The exterior corrugation valley facilitates the particle movement by providing a low-friction pathway, as detailed by Sargand, Masada, and Hurd [1996]. The re-rounding process also results in the pipe wall at the springline moving inward toward the center. This movement reduces the confining pressure on the backfill outside the pipe springline which reduces the backfill density and allows the shoulder material to migrate downward more readily resulting in lower densities and lower stiffness at the shoulder and springline.

Test Pipe 2 was exhumed carefully to observe the layer of red-painted sand to identify any migration of the layer caused by the re-rounding. Despite the best efforts of the construction crew, no meaningful data could be obtained from the colored sand layer.

8.6 Burns and Richard Elastic Solution

Burns and Richard [1964] formulated a solution for an elastic shell (such as a pipe) embedded in an infinite elastic medium (soil) loaded with a surface pressure. The use of the elastic solution in a trench installation is erroneous because of the significant frictional interaction between the backfill soil and the in-situ soil. While the results of the method are typically not suitable for design purposes, they do provide significant insight into the trends of the stress state and deformations of the buried pipe problem. The equations are developed for two boundary conditions between the shell and the medium: full-slip interface and no-slip interface. The no-slip interface assumes continuity of the radial and tangential displacement between the pipe and the soil, whereas the full-slip interface assumes zero shear stress at the pipe-soil interface.

General parameters for the soil and pipe are the Poisson's ratio, v_s and v_p, and the elastic modulus, E_s and E_p. Other parameters utilized are the pipe radius, *R*, wall area, *A*, and wall moment of inertia, *I*.

From these basic parameters several quantities can be calculated:

$$M_s = \frac{E_s(1-\nu_s)}{(1+\nu_s)(1-2\nu_s)} \tag{3}$$

$$K = \frac{\nu_s}{1-\nu_s} \tag{4}$$

$$B = \frac{1}{2}(1+K) \tag{5}$$

$$C = \frac{1}{2}(1-K) \tag{6}$$

where:

M_s = constrained soil modulus

K = lateral stress ratio

Next, the ring stiffness ratio, *UF*, and bending stiffness ratio, *VF*, are defined as:

$$UF = (1 + K)\frac{M_s R}{EA} \tag{7}$$

$$VF = (1 - K)\frac{M_s R^3}{6EI} \tag{8}$$

For the no-slip interface, non-dimensional constants are introduced:

$$a_0 = \frac{UF - 1}{UF + {}^{B}/_{C}} \tag{9}$$

$$a_2^* = \frac{C(1 - UF)VF - \left({}^{C}/_{B}\right)UF + 2B}{(1 + B)VF + C\left(VF + {}^{1}/_{B}\right)UF + 2(1 + C)} \tag{10}$$

$$b_2^* = \frac{(B + CUF)VF - 2B}{(1 + B)VF + C\left(VF + {}^{1}/_{B}\right)UF + 2(1 + C)} \tag{11}$$

For the full-slip interface, similar non-dimensional constants are introduced:

$$a_2^{**} = \frac{\left(2VF - 1 + {}^{1}/_{B}\right)}{\left(2VF - 1 + {}^{3}/_{B}\right)} \tag{12}$$

$$b_2^{**} = \frac{(2VF - 1)}{\left(2VF - 1 + {}^{3}/_{B}\right)} \tag{13}$$

Utilizing the following five soil and pipe properties introduced above - M_s, K, R, EA, and EI - along with the non-dimensional parameters from Equations (5) through (8), and the constants from Equations (9) through (13) the radial stress in any point in the soil can be determined as:

$$\sigma_r = P\left\{B\left[1 - a_0\left({}^{R}/_{r}\right)^2\right] - C\left[1 - 3a_2^*\left({}^{R}/_{r}\right)^4 - 4b_2^*\left({}^{R}/_{r}\right)^2\right]\cos 2\theta\right\} \tag{14}$$

for the no-slip case, and

$$\sigma_r = P\left\{B\left[1 - a_0\left({}^{R}/_{r}\right)^2\right] - C\left[1 - 3a_2^{**}\left({}^{R}/_{r}\right)^4 - 4b_2^{**}\left({}^{R}/_{r}\right)^2\right]\cos 2\theta\right\} \tag{15}$$

for the full-slip case where:

r = radial distance to the point of solution. Set *r* = *R* to determine results for the ring.

θ = angle measured counterclockwise from the horizontal axis.

Equations (16) and (17) provide the relationship for determining the bending moment, M_n, and the radial deformation, w_n, of the pipe, respectively, for the no-slip case. Equations (18) and (19) provide the relationship for determining the bending moment, M_f, and the radial deformation, w_f, of the pipe, respectively, for the full-slip case.

$$M_n = PR^2\left\{\frac{C}{6}\frac{UF}{VF}[1-a_0] + \frac{C}{2}[1-a_2^* - 2b_2^*]\cos 2\theta\right\} \tag{16}$$

$$w_n = \frac{PR}{M_n}\frac{1}{2}\{UF[1-a_0] - VF[1-a_2^* - 2b_2^*]\cos 2\theta\} \tag{17}$$

$$M_f = PR^2\left\{\frac{C}{6}\frac{UF}{VF}[1-a_0] + \frac{C}{3}[1+3a_2^{**} - 4b_2^{**}]\cos 2\theta\right\} \tag{18}$$

$$w_f = \frac{PR}{M_f}\frac{1}{2}\left\{UF[1-a_0] - \frac{2}{3}VF[1+3a_2^{**} - 4b_2^{**}]\cos 2\theta\right\} \tag{19}$$

Of the five previously discussed pipe and soil parameters, three are material or geometric properties of the pipe (*EA*, *EI*, and *R)*. The lateral stress ratio, *K*, is a function of the Poisson's ratio of the soil which is essentially unchanging within the stress state and confinement of a buried pipe. The constrained soil modulus is a function of the soil elastic modulus and Poisson's ratio. Holding *EA*, *EI*, *R*, v_s, and *K* constant while varying the soil elastic modulus gives the relationship shown in Figure 72 between the soil elastic modulus and the pressure at the crown of a pipe and at a location 7 in (180 mm) above the crown (the location of the pressure cells installed for each of the pipe experiments). A similar graph for the springline is given in Figure 73.

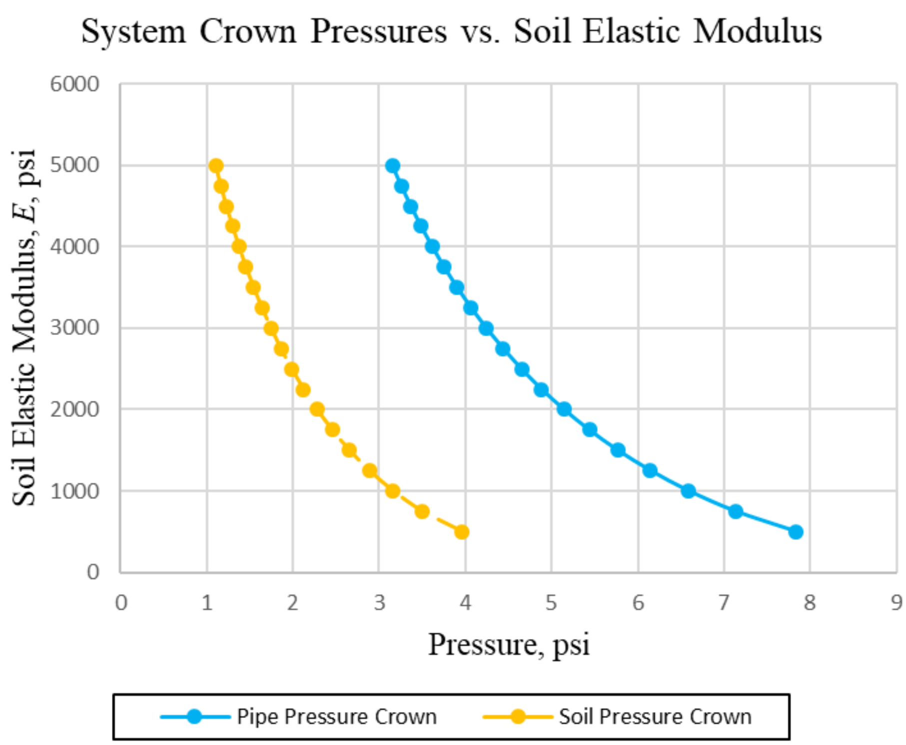

Figure 72. System Pressure vs. Soil Elastic Modulus at pipe crown (1000 psi = 6.89 MPa).

It is evident that for increasing modulus values there is a decrease in the pressure at the pipe and the soil pressure 7 in (180 mm) radially distant from the pipe. This is the opposite relationship of what was experienced in Test Pipes 1 and 2 when comparing the pipe-soil system before and after re-rounding. For each of these experiments, there was a decrease at the springline in both the pressure and the soil stiffness. For Test Pipe 3, there was a decrease in soil pressure at the crown and an increase in soil pressure at the springline. There was no measurement of the springline soil stiffness for Test Pipe 3. The conclusion drawn is that a fundamental assumption of the Burns and Richard elastic solution, namely, a homogeneous elastic medium, is not a suitable approximation of the pipe-soil stress state before and after re-rounding.

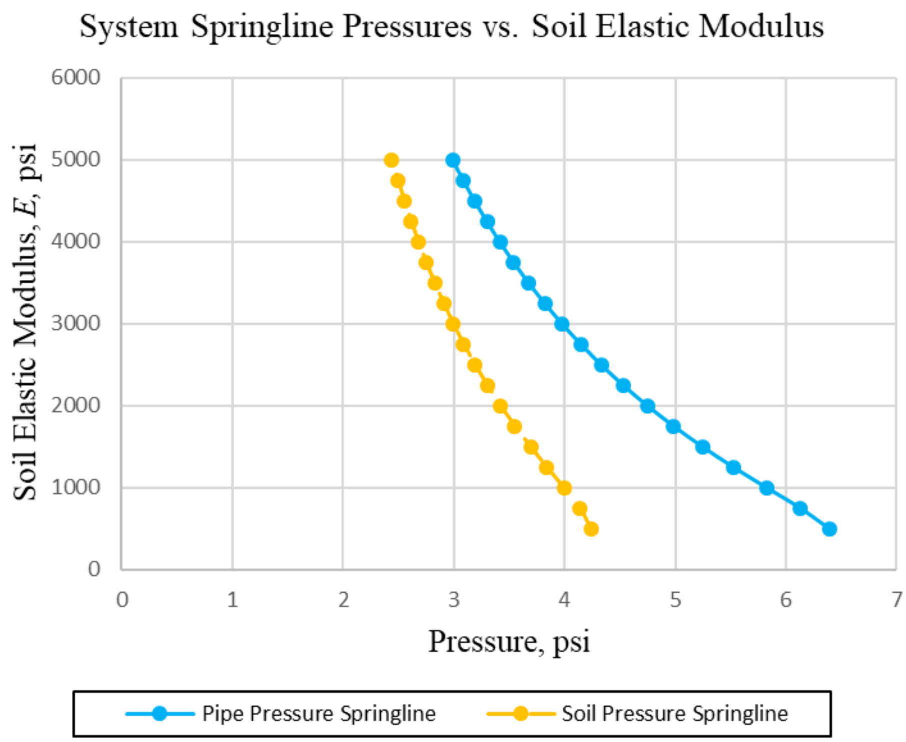

Figure 73. System Pressure vs. Soil Elastic Modulus at the springline (1000 psi = 6.89 MPa).

8.7 Analysis of Test Pipe Soil Pressure and Stiffness Measurements

The data presented in Sections 8.3 through 8.6 show the re-rounding process results in a complex interaction between the soil particles and the pipe. The vibrational energy imparted to the pipe wall during the re-rounding process moves the soil particles and allows for a significant redistribution of soil stresses.

For Test Pipes 1 and 2, with relatively low void ratios, the pressure cell readings indicate the re-rounding process results in a reduction in radial pressure and in the in-situ soil stiffness at the springline. This suggests the assumptions of the Burns and Richard elasticity solution are not satisfied, so presumably the backfill material is not homogeneous and/or not elastic.

A redistribution of soil particles was visually observed during the pipe experiments. Additionally, the analysis of the soil samples taken at the crown and springline of Test Pipe 1 show a reduction of fine particles. These materials were redistributed into the pipe haunch area, resulting in increased soil stiffening there. The increase in soil stiffness in the pipe haunch for Test Pipe 3 clearly shows the same phenomenon. This is also consistent with the conclusion drawn from the elasticity solution.

The long-term measurements of the pipe shape for Test Pipes 1 and 2 show that the pipe is in static equilibrium. Therefore, the reduction in crown pressure is a necessary outcome of the reduced vertical deflection. It is believed that the upward pressure applied during re-rounding will increase the confinement of the soil above the crown, increasing the elastic modulus of the soil and reducing the pressure by promoting positive soil arching. While there is movement of fine material from the crown which would tend to reduce the confining pressure, it is believed that the upward movement supersedes the soil migration. Likewise, material at the pipe shoulder is redistributed to the pipe springline and the pipe haunch. This may lead to the conclusion that there should also be a stiffening of the backfill at the springline. However, the re-rounding process reduces the horizontal diameter of the pipe, increasing the space available for the springline soil, thus reducing the material density and likewise the stiffness. This movement of the pipe wall away from the soil also results in the reduction of the radial pressure at the pipe springline.

The re-rounding of Test Pipe 3 backfilled with open-graded aggregate results in a completely different phenomenon. Note that the soil pressures before and after re-rounding are quite small in magnitude when compared to the geostatic stress. This can be explained by the interlocking of the aggregate particles with one another, essentially creating a soil arch and redistributing the stresses around the pipe. Another explanation is that the open-graded aggregate was making inconsistent contact with the pressure cells, thus exerting less pressure on the cell. The re-rounding process mobilizes the particles resulting in some settlement. This settlement stiffens the haunch area which is originally in a very poorly compacted state. However, the remaining backfill when vibrated also moves but returns to a state of arching when the vibration is complete.

8.8 Accelerometer Data

Two pairs of accelerometers, each with one aligned to measure horizontal accelerations and the other to measure vertical accelerations, were installed in the backfill material over Test Pipes 2 and 3 at heights of 6 in (152 mm) and 18 in (460 mm) above the crown at cross-section D-D, approximately 15 ft (4.6 m) from the inlet. The location and orientation for each accelerometer are provided in Figure 33 for Test Pipe 2 and in Figure 45 for Test Pipe 3.

8.8.1 Test Pipe 2 Accelerometer Data

Figure 74 and Figure 76 and show the response amplitude of the two vertical acceleration from accelerometers P2-1 and P2-3 as a function of time for the portion of the re-rounding of Test Pipe 2 when the re-rounding device was in Section D-D, directly below the accelerometers. Figure 75 and Figure 77 show a detail of the same plots to better show the waveform. The waveform approximately sinusoidal but not symmetric, suggesting that the soil did not respond symmetrically in tension and compression, as expected.

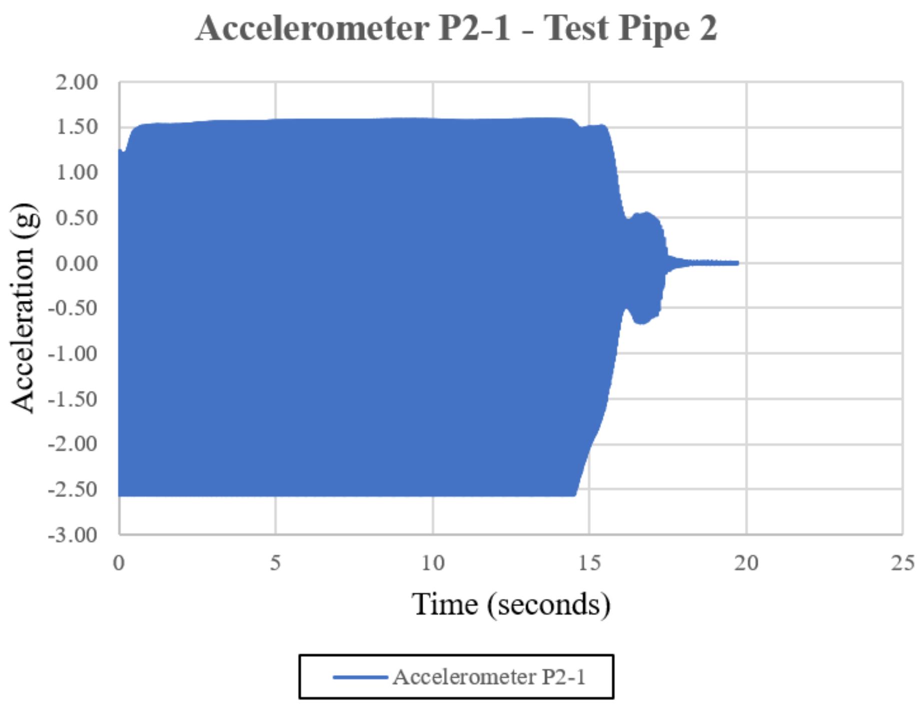

Figure 74. Vertical acceleration as a function of time for accelerometer P2-1 of Test Pipe 2 while the re-rounder was being pulled through Cross-section D-D (1 g = 32.2 ft/s^2 = 9.81 m/s^2).

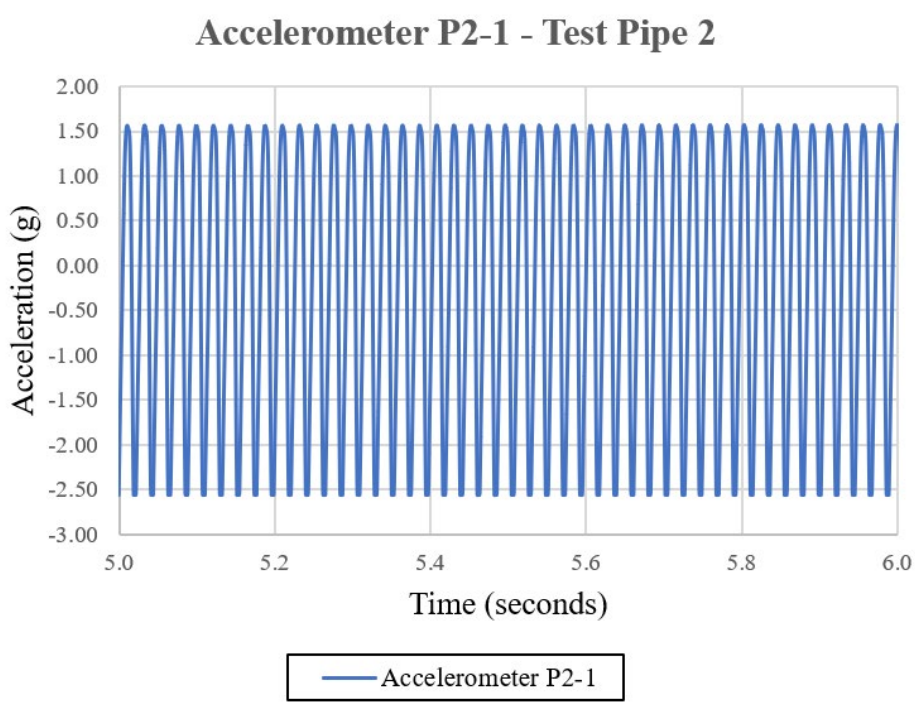

Figure 75. Detail of previous figure showing acceleration waveform at P2-1 for Test Pipe 2 (1 g = 32.2 ft/s^2 = 9.81 m/s^2).

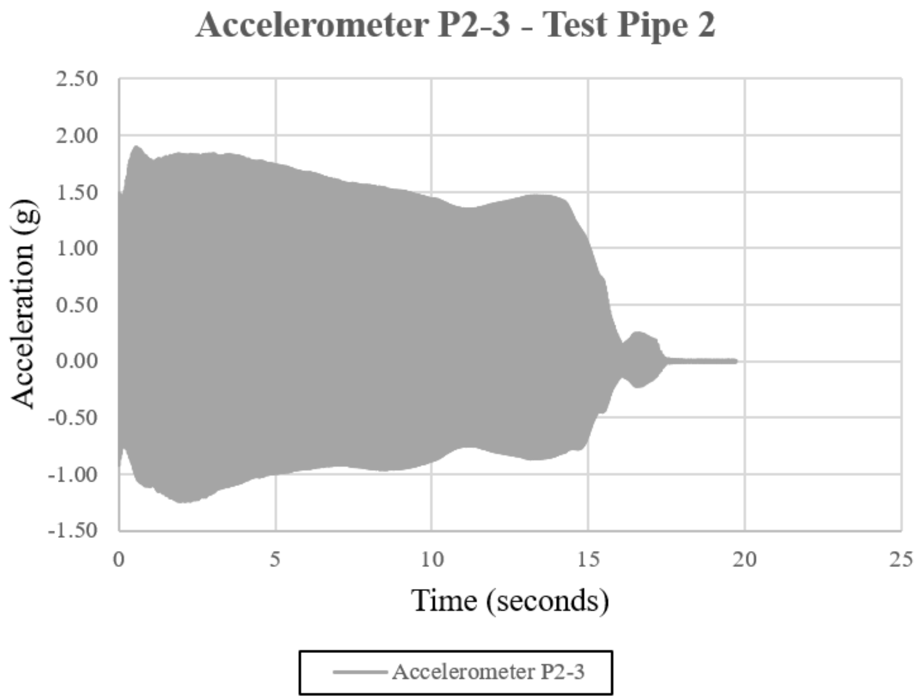

Figure 76. Vertical acceleration as a function of time for accelerometer P2-3 for Test Pipe 2 while the re-rounder was being pulled through Cross-section D-D (1 g = 32.2 ft/s^2 = 9.81 m/s^2).

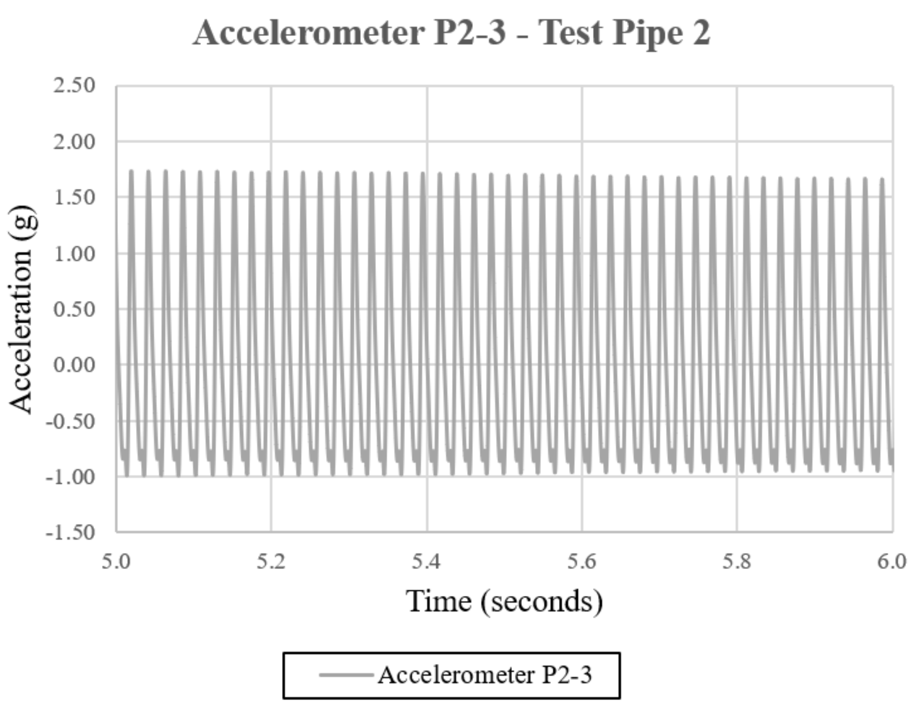

Figure 77. Detail of previous figure showing acceleration waveform at P2-3 for Test Pipe 2 (1 g = 32.2 ft/s^2 = 9.81 m/s^2).

A Fast Fourier Transformation (FFT) was performed on acceleration waveform data, converting the time domain representation into a frequency domain representation to determine the dominant frequency of the re-rounding. The results of the FFT are provided in Figure 78 and Figure 79. The dominant frequency for both accelerometers was approximately 46 Hz. The maximum measured accelerations, taken as one-half of the peak-to-trough height of the waveform, were calculated to be 2.07g (66.6 ft/s^2 or 20.3 m/s^2) and 1.57g (50.5 ft/s^2 or 15.4 m/s^2) for accelerometers P2-1 and P2-4, respectively. Since the acceleration is the derivative of the velocity, the maximum acceleration $\ddot{u}_{max}$ = $2\pi f\dot{u}_{max}$, where f is the frequency and $\dot{u}_{max}$ is the velocity amplitude, or peak particle velocity (PPV). The PPV at each accelerometer is calculated as: $PPV_{P2\text{-}1}$ = 2.77 in/s (70 mm/s) and $PPV_{P2\text{-}3}$ = 2.10 in/s (53 mm/s).

Assuming subsurface body waves (n=1) are predominant in the pipe backfill, the damping equation from Woods and Jodele [1985] with the peak particle velocity relationships in Andrews et al. [2013] becomes:

$$\dot{u}_2 = \dot{u}_1 \frac{X_1}{X_2} e^{-\alpha(X_2 - X_1)} \tag{20}$$

Where $\dot{u}_1$ and $\dot{u}_2$ are the peak particle velocities at positions X_1 and X_2, and α is the material damping coefficient. First taking X_1 and X_2 as the positions as the accelerometers and $\dot{u}_1$ and $\dot{u}_2$ as the PPV, α can be computed, yielding a value of 0.276 ft^{-1} (0.91 m^{-1}), substantially higher than the published values provided in Andrews et al. [2013]. Then changing $\dot{u}_2$ to the maximum PPV a pavement can tolerate (1 in/s (25 mm/s) based on the number given by Andrews et al. [2013] for a new residential structure) allows X_2 to be calculated to estimate the minimum backfill hieght for the pavement on the surface to avoid damage from re-rounding. The result is 50 in (4.2 ft or 1.2 m) minimum depth of fill required over a pipe in sand backfill to ensure the pavement layer above is not damaged by the re-rounding process.

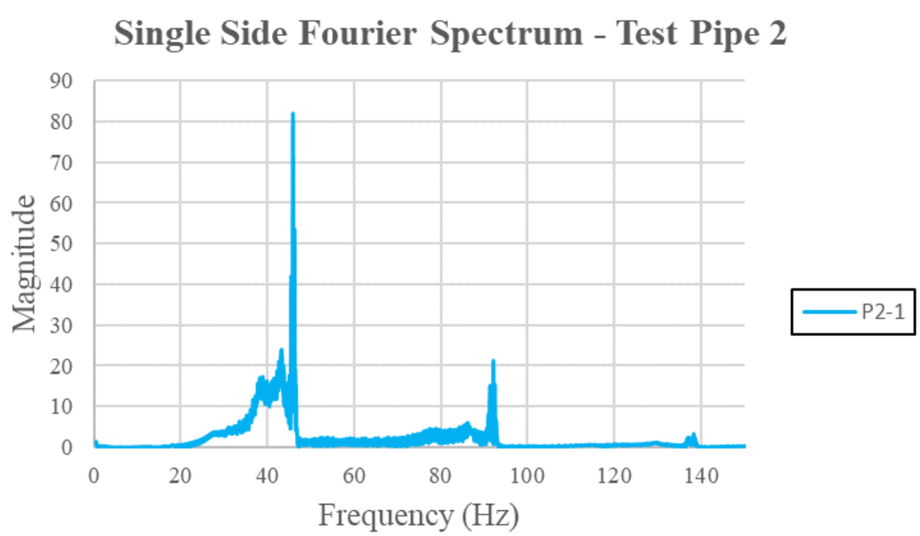

Figure 78. Single-side FFT spectrum for P2-1 of Test Pipe 2.

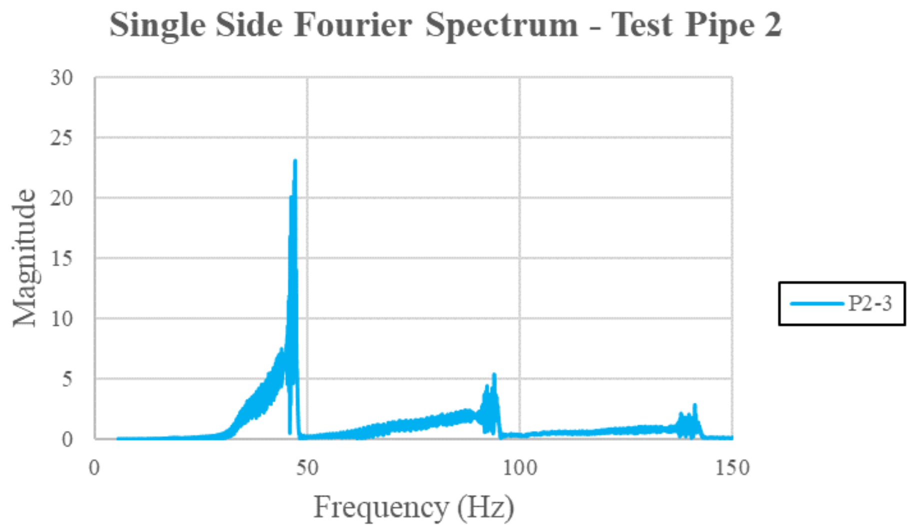

Figure 79. Single-side FFT spectrum for P2-3 of Test Pipe 2.

The required cover can also be determined considering the maximum allowable strain in the pavement. One widely used criterion for a strain limit (fatigue endurance limit) for asphalt concrete pavement to withstand bottom-up cracking is 70 με [Brown and Timm, 2006; Newcomb, 2002; Sargand, Figueroa, and Romanello, 2008; Witczak et al., 2013]. Dividing by a factor of safety of 3, the factored strain limit becomes 23.33 με. This is converted to a factored stress limit of 11.67 psi (80.5 kPa) using an elastic modulus for asphalt pavement of 500,000 psi (3.4 GPa). Additionally, an assumed soil elastic modulus, E, value of 1500 psi (10.3 MPa) and a mass density, ρ, of 3.73 lbm/ft^3 (120 lbf/ft^3/32.2ft/sec^2, 1920 kg/m^3) taken from AASHTO [2017] are inserted into the following equation:

$$\sigma = \rho \sqrt{\frac{E}{\rho}} \dot{u}_{max}$$

The result is a maximum allowable PPV of 127 in/s (3.23 m/s) at a stress of 11.67 psi (80.5 kPa). This PPV, along with the calculated $PPV_{P2\text{-}1}$ of 2.77 in/s (70 mm/s) at X_1 of 6 in (0.15 m) and the material damping coefficient, a, of 0.276 ft^{-1} (1.10 m^{-1}) are inserted into the Woods and Jodele [1985] equation and solved for the distance X_2. This yields a distance X_2 of less than 1 in (25.4 mm). This is an indicator that the re-rounding process does not produce vibrational strains capable of damaging an asphalt pavement.

8.8.2 Liquefaction of Sand Backfill Under Vibratory Re-Rounding

There was an initial belief that the vibration could result in the liquefaction of the sand backfill material. However, this appears unlikely because liquefaction is believed to occur predominantly in loose sands with high moisture content subjected to shear waves [Handy and Spangler, 2007]. The re-rounding process generally produces compression waves and except for deep cut installations, the free-draining properties of the granular backfill materials would limit their degree of saturation and potential for liquefaction.

8.8.3 Test Pipe 3 Accelerometer Data

Figure 80 and Figure 82 show the response amplitude of the two vertical acceleration accelerometers (P3-1 and P3-3) as a function of time for the portion of the re-rounding process where the re-rounding device was in cross-section D-D directly below the accelerometers. Figure 81 and Figure 83 show a detail of the same plots to better show the waveform. The waveform is roughly sinusoidal but not symmetric, suggesting the soil did not respond symmetrically in tension and compression, as expected.

Following the method used on the Pipe 2 data, an FFT was performed to convert the data to the frequency domain and determine dominant frequency of the re-rounding. The results of the FFT are provided in Figure 84 and Figure 85. The dominant frequency for accelerometer P3-1 was approximately 82 Hz. However, by inspecting Figure 81 it is evident that the actual frequency is approximately 41 Hz and the 82 Hz given by the FFT is the harmonic of the actual frequency. The dominant frequency for accelerometer P3-3 was approximately 41 Hz. The maximum measured accelerations, taken as one-half of the amplitude of the waveform, were calculated to be 0.64g (20.6 ft/s^2 and 6.3 m/s^2) and 0.50g (16.1 ft/s^2 and 4.9 m/s^2) for accelerometers P3-1 and P3-3, respectively.

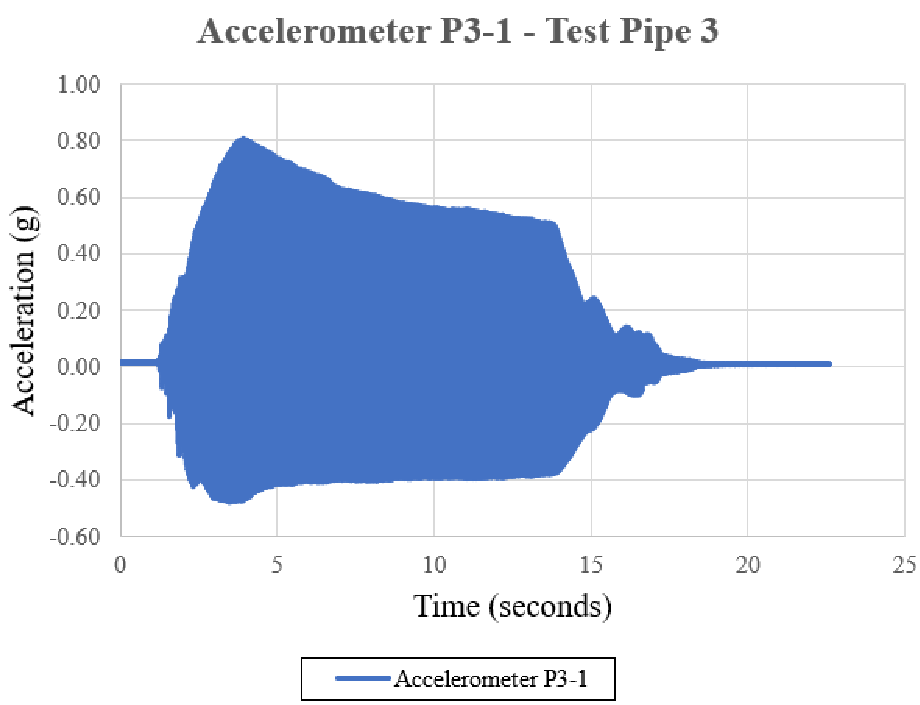

Figure 80. Vertical acceleration as a function of time for accelerometer P3-1 for Test Pipe 3 while the re-rounder was being pulled through cross-section D-D (1 g = 32.2 ft/s^2 = 9.81 m/s^2).

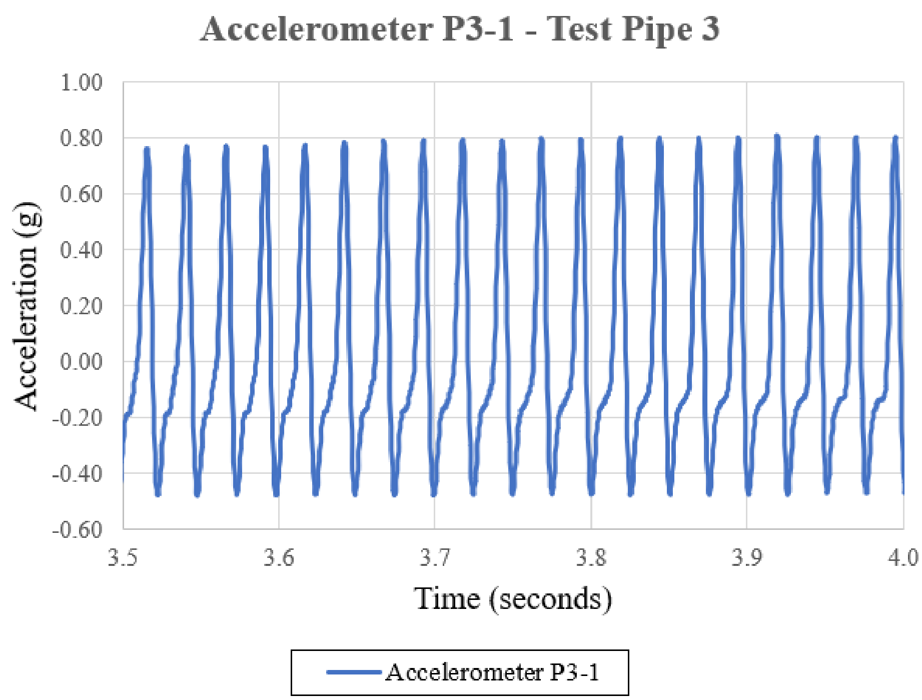

Figure 81. Detail of previous figure showing acceleration waveform at P3-1 for Test Pipe 3 (1 g = 32.2 ft/s^2 = 9.81 m/s^2).

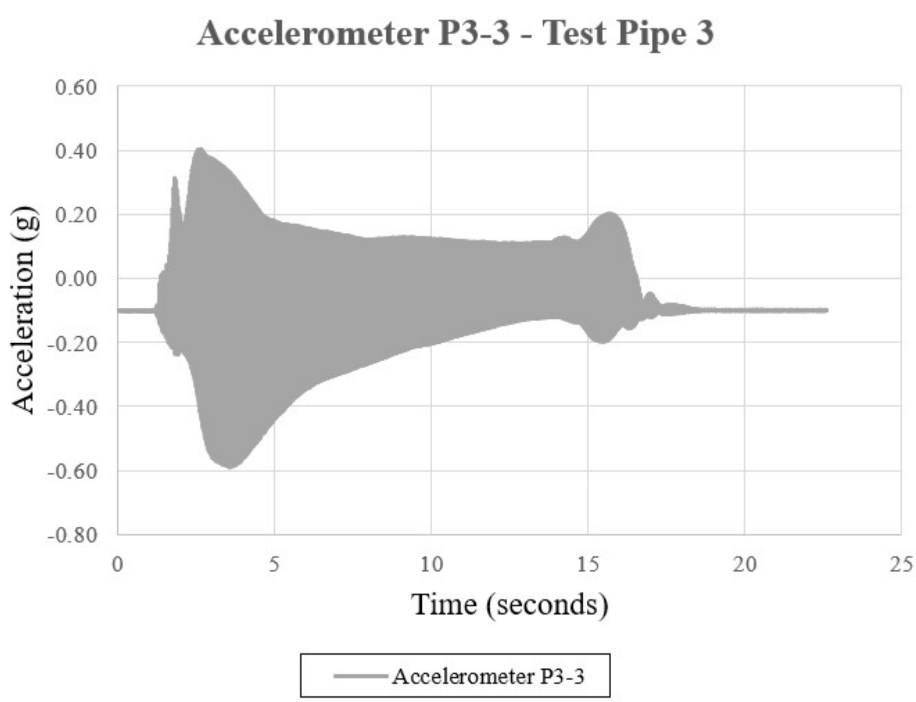

Figure 82. Vertical acceleration as a function of time for accelerometer P3-3 for Test Pipe 3 while the re-rounder was being pulled through Cross-section D-D (1 g = 32.2 ft/s^2 = 9.81 m/s^2).

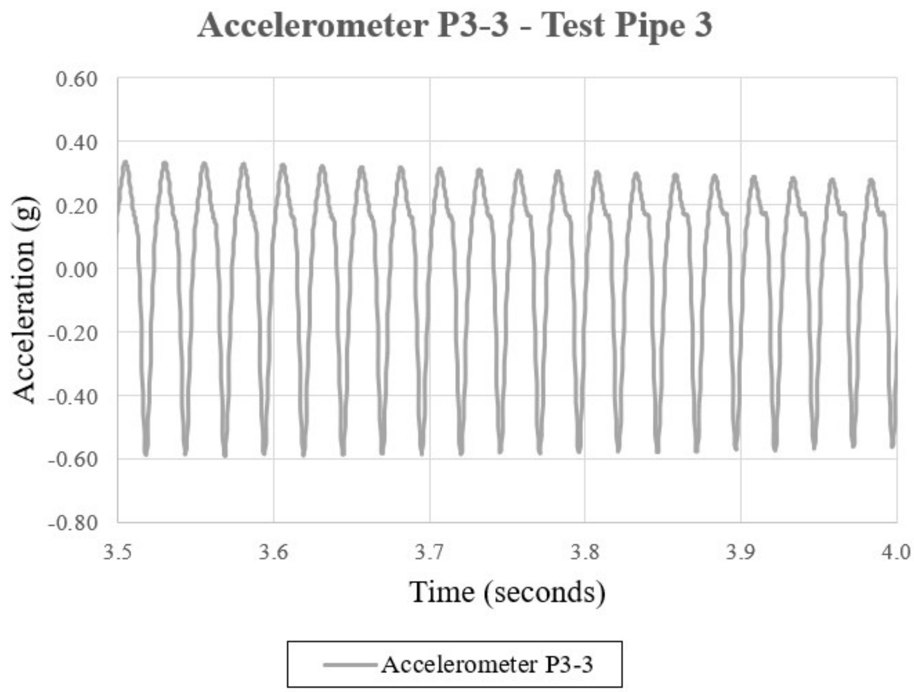

Figure 83. Detail of previous figure showing acceleration waveform at P3-3 for Test Pipe 3 (1 g = 32.2 ft/s^2 = 9.81 m/s^2).

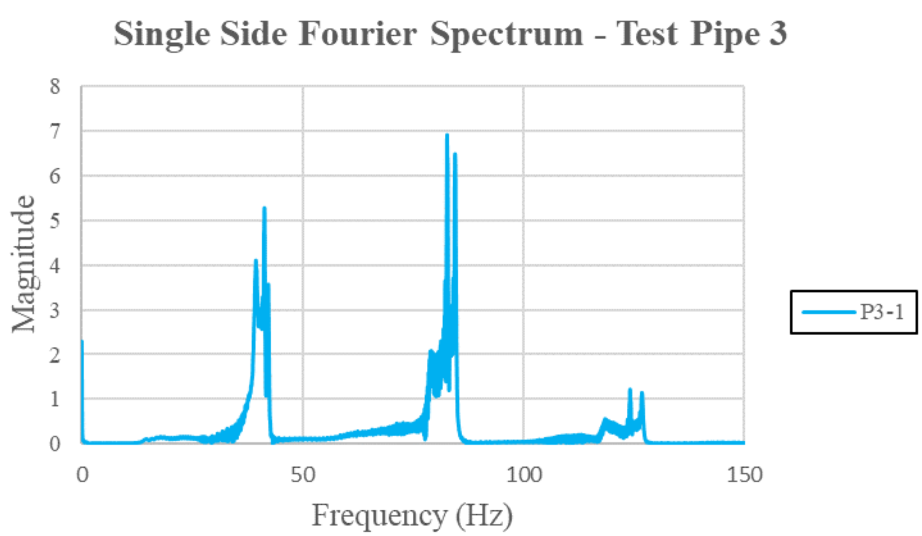

Figure 84. Single-sided Fourier spectrum for accelerometer P3-1 for Test Pipe 3.

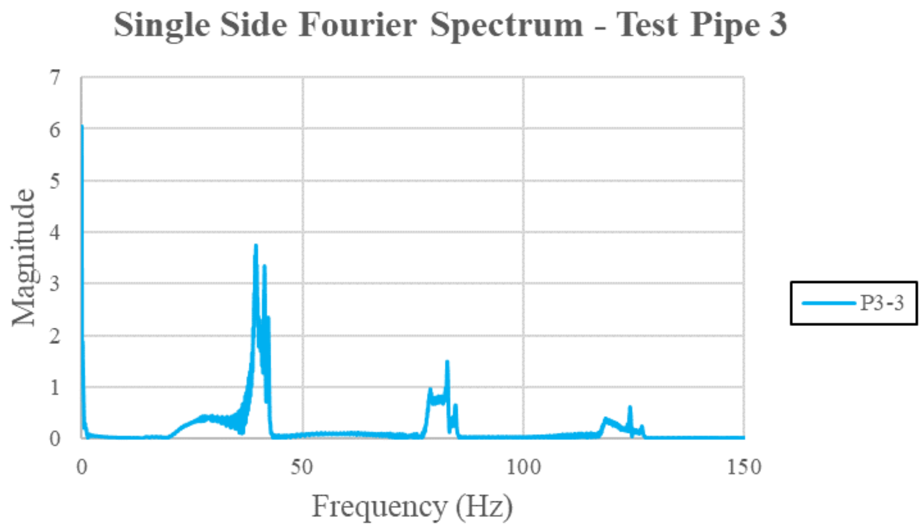

Figure 85. Single-sided Fourier spectrum for accelerometer P3-3 for Test Pipe 3.

A similar process as that described for Test Pipe 2 was utilized to determine the PPV at each accelerometer. The results are: $PPV_{P3\text{-}1}$ = 0.959 in/s (24 mm/s). and $PPV_{P3\text{-}3}$ = 0.749 in/s (19 mm/s). The wave energy decays with distance. Since the actual PPV is already less than the allowable pavement damage threshold value of 1.0 in/s (25 mm/s)., the distance at which a PPV of 1.0 in/s (25 mm/s). is obtained will be less than 6 in (0.15 m) (the height of accelerometer P3-1 above the crown). While this may be acceptable from a vibratory damage standpoint, the potential for settlement of the open-graded aggregate would necessitate a reasonable cover depth.

A summary of the results obtained from the accelerometer data is provided in Table 22.

Table 22. Summary of accelerometer data.

Backfill material		Test Pipe 2 Structural Backfill Type 2		Test Pipe 3 Structural Backfill Type 3	
Dominant frequency	(hz)	46		41	
Accelerometer		P2-1	P 2-4	P3-1	P3-3
Maximum acceleration	(g)	2.07	1.57	0.64	0.50
	(ft/s^2)	66.6	50.5	20.6	16.1
	(m/s^2)	20.3	15.4	6.3	4.9
Peak particle velocity	(in/s)	2.77	2.10	0.96	0.75
	(mm/s)	70.4	53.3	24.4	19.1

8.9 Test Pipe Corrugation Depth Measurements

The depths of the pipe corrugations were measured for Test Pipes 1, 2, and 3. The measurements were obtained to determine how the impulse and pressure exerted on the interior wall of the pipe by the re-rounder impacts the corrugation profile of the pipe. For Test Pipe 1, measurements were obtained at the left and right springlines and crown for cross-sections A-A through F-F; and at the crown only, for cross-sections G-G though J-J. The measurements obtained are presented in Table 23. For Test Pipes 2 and 3, measurements were obtained at the crown of the pipe at cross-sections D-D and E-E and are presented in Table 24 and Table 25, respectively.

The results show very little change in the corrugation height. For Test Pipe 1 the maximum magnitude change in corrugation height was 5.50%. The mean value was 2.21% with a standard deviation of 1.48%. Test Pipe 2 saw no change in corrugation depth. For Test Pipe 3 the maximum change in corrugation height was 5.11%. The mean value was 1.48% with a standard deviation of 2.08%. However, Test Pipes 2 and 3 had extremely limited data sets each comprising only four values.

There does not appear to be any clear correlation between the measurement location, pipe cross-section, and resulting corrugation height.

Table 23. Corrugation depth measurements for Test Pipe 1.

Cross-section		A-A			B-B			C-C		
position		Crown	Right	Left	Crown	Right	Left	Crown	Right	Left
Before re-rounding	(in)	2.196	2.183	2.166	2.358	2.164	2.188	2.245	2.325	2.192
	(mm)	55.78	55.45	55.02	59.89	54.97	55.58	57.02	59.06	55.68
After re-rounding	(in)	2.135	2.091	2.149	2.386	2.045	2.215	2.233	2.301	2.128
	(mm)	54.23	53.11	54.58	60.60	51.94	56.26	56.72	58.45	54.05
Change	(%)	-2.78	-4.21	-0.78	1.19	-5.5	1.23	-0.53	-1.03	-2.92
Cross-section		D-D			E-E			F-F		
position		Crown	Right	Left	Crown	Right	Left	Crown	Right	Left
Before re-rounding	(in)	2.275	2.215	2.234	2.152	1.945	1.905	2.246	2.044	2.066
	(mm)	57.79	56.26	56.74	54.66	49.40	48.39	57.05	51.92	52.48
After re-rounding	(in)	2.348	2.312	2.302	2.099	2.001	1.899	2.244	1.998	2.121
	(mm)	59.64	58.72	58.47	53.31	50.83	48.23	57.00	50.75	53.87
Change	(%)	3.21	4.38	3.04	-2.46	2.88	-0.31	-0.09	-2.25	2.66

Cross-section		G-G	H-H	I-I	J-J
position		Crown	Crown	Crown	Crown
Before re-rounding	(in)	2.269	2.254	2.296	2.172
	(mm)	57.63	57.25	58.32	55.17
After re-rounding	(in)	2.245	2.301	2.303	2.094
	(mm)	57.02	58.45	58.50	53.19
Change	(%)	-1.06	2.09	0.3	-3.59

Table 24. Corrugation depth measurements for Test Pipe 2.

Cross-section		D-D		E-E	
position		Crown	Right	Crown	Right
Before re-rounding	(in)	2.206	2.213	2.176	2.294
	(mm)	56.03	56.21	55.27	58.27
After re-rounding	(in)	2.206	2.213	2.176	2.294
	(mm)	56.03	56.21	55.27	58.27
Change	(%)	0	0	0	0

Table 25. Corrugation depth measurements for Test Pipe 3.

Cross-section		D-D		E-E	
position		Crown	Right	Crown	Right
Before re-rounding	(in)	2.28	2.27	2.265	2.132
	(mm)	57.91	57.66	57.53	54.15
After re-rounding	(in)	2.26	2.258	2.218	2.241
	(mm)	57.40	57.35	56.34	56.92
Change	(%)	-0.88	-0.53	-2.08	5.11

9 Summary and Conclusions

9.1 Summary

Flexible pipes, such as high-density polyethylene (HDPE) pipe, require proper installation for long-term function. The pipe is reliant upon the backfill material and compaction for structural stability. The pipe and backfill comprise the soil-structure system. When backfill material is not compacted in accordance with governing specifications, the pipe performance can suffer. Distress, such as excessive deflection, is observed in pipes with poorly compacted backfill.

A method of remediating excessive deflection, called "re-rounding", has been used throughout the mid-western United States. The re-rounding process utilizes an eccentric pneumatic compactor with expanding curved plates which vibrate and exert pressure against the pipe interior. The device investigated in this project oscillated on the vertical axis against the crown and invert. Despite the existence of the technology for over 30 years there is a lack of comprehensive mechanistic data on the re-rounding process and little is known about the impacts of re-rounding on the installed thermoplastic pipe.

To close this knowledge gap, ORITE conducted a full-scale controlled field study on the impacts of re-rounding on deflected thermoplastic pipe. The main objective of the field evaluation is to validate re-rounding as a viable remediation technique for HDPE pipe exceeding maximum allowable deflection and examine the long-term service of re-rounded pipe. The viability was assessed by investigating the reduction in deflection after re-rounding, and the effect of installation variables including type of backfill and magnitude of deflection on the resulting performance of re-rounding as determined by the following measures of success: the reduction in deflection of the pipe, damage to pipe structure or corrugation, pavement damage, and whether the improvements are likely to be long-lasting. In short, is the change in diameter sustainable?

Five HDPE pipes, two of diameter 18 in (0.45 m) and three of diameter 36 in (0.9 m), were instrumented with various sensors and purposely installed to induce deflection. A horizontal expansion device was used to ensure adequate deflection for some installations. Different backfill materials (ODOT Structural Backfill Types 1, 2, and 3) were used for the test pipes, and the backfill was characterized in terms of gradation and uniformity before and after re-rounding operations.

Pipe 1 was a 36 in (0.9 m) HDPE pipe installed in Structural Backfill Type 1 (well-graded ODOT Item 304 crushed aggregate). During the installation, aggregate was dumped but not compacted on both sides of the pipe and over the crown. A backhoe then pressed on the crown to ensure sufficient deflection while more aggregate was added. The aggregate interlock helped ensure the deflection was maintained throughout the installation process.

Pipe 2 was a 36 in (0.9 m) HDPE pipe installed in Structural Backfill Type 2 (sand). The installation process was similar to that for Pipe 1. While a reasonable degree of deflection was obtained, the lack of aggregate interlock made it hard to prevent the pipe from recovering its shape to some extent, and the final installed deflection was less than intended.

Pipe 3 was a 36 in (0.9 m) HDPE pipe installed in Structural Backfill Type 3 (open-graded AASHTO #57 crushed stone aggregate). It proved impossible to maintain the pipe deflection during installation by pressing down with a backhoe. The pipe was damaged in the attempt and had to be replaced. A pipe deflector device was designed and fabricated for use during installation of the replacement pipe to ensure adequate deflection during installation.

Pipe 4 was an 18 in (0.45 m) HDPE pipe installed in Structural Backfill Type 3 (AASHTO #57 open-graded crushed-stone aggregate). Deflection was maintained during installation using the pipe deflector.

Pipe 5 was an 18 in (0.45 m) HDPE pipe installed in Structural Backfill Type 2 (sand). Deflection was maintained during installation using the pipe deflector.

To characterize the pipe shape and determine deflection for Pipes 1, 2, and 3, a laser-based pipe profiler was used to measure the radius at approximately 3° intervals. Due to the smaller diameter of Pipes 4 and 5, the profiler was replaced with a LiDAR unit which recorded radius readings at intervals of approximately 1.1°. The data were used to generate shape profiles of the pipes at ten locations spaced at approximately 5 ft (1.5 m) intervals along the length of the pipe; these profiles were used to determine deflection and to compare the shape changes caused by the re-rounding.

The installed sensors also measured crown and springline soil pressures, soil stiffness (except Pipes 4, and 5, which were too small to admit a person to make the measurements), acceleration of backfill/peak particle velocity (Pipes 2-5), and pipe corrugation height (Pipes 2 and 3). A forensic excavation was performed at the end of each experiment to determine the movement of backfill material in response to the re-rounding and visually observe the final condition of the pipe.

Analysis of the data from the full-scale controlled field study test pipes leads to several conclusions regarding the impacts of re-rounding on installed HDPE pipe.

9.2 Conclusions

A comprehensive investigation was undertaken to validate re-rounding as a viable remediation technique for HDPE pipes exceeding maximum allowable deflection and examine the long-term serviceability of the re-rounded pipe. The viability of the procedure was assessed by investigating the reduction in deflection after re-rounding, and the subsequent performance of the pipe over time and whether there was an impact from the magnitude of deflection or type of backfill material. In short, could the deflection in the pipe be brought to an acceptable level, and then is the pipe able to continue service for a long time. The results of the investigation are summarized as follows:

9.2.1 Deflections

Here is a table summarizing the deflection data in this experiment. Underlined deflection values exceed ODOT 7.50% criterion for repair or replacement.

Test Pipe	1	2	3	4	5
Structural backfill material (ODOT Type)	Item 304 (1)	Sand (2)	#57 (3)	#57 (3)	Sand (2)
Nominal diameter	36 in (0.9 m)			18 in (0.45 m)	
Re-rounder passes	3	2	1	1	2
Maximum vertical deflection before re-rounding	-13.91%	-9.89%	-10.18%	-16.67%	-14.50%
Deflection of above after re-rounding	-7.20%	-8.57%	-2.52%	-6.17%	-6.21%
Maximum deflection in pipe after re-rounding	-8.62%	-8.57%	-2.52%	-6.17%	-7.47%

- Test Pipe 1 was a 36 in (0.9 m) diameter pipe installed with ODOT Structural Backfill Type 1 (ODOT Item 304 well-graded crushed stone aggregate) with a maximum initial vertical deflection of -13.91%. After three passes with the re-rounder, the deflection was reduced to -7.20%. However, the maximum deflection after re-rounding at another location in the pipe was -8.62%, and some other sections were above the -7.5% criterion for repair or replacement. In the third pass, the re-rounder became so hot, the vendor said further use would permanently damage their device, so the re-rounding was stopped after three passes. Thus, while the deflection of the pipe was substantially reduced, the pipe still exceeded the -7.5% limit in multiple locations.
- Test Pipe 2 was a 36 in (0.9 m) diameter pipe installed with ODOT Structural Backfill Type 2 (sand) with a maximum initial vertical deflection of -9.89%. After two passes of the re-rounder, the deflection was reduced to -8.57%, still exceeding the -7.5% criterion.
- Test Pipe 3 was a 36 in (0.9 m) diameter pipe installed with ODOT Structural Backfill Type 3 (AASHTO #57 open-graded crushed stone aggregate) with a maximum initial vertical deflection of -10.18%. One pass of the re-rounder reduced this deflection to -2.52%, and as this was the maximum in the pipe, the re-rounded pipe was well within the -7.5% criterion.
- Test Pipe 4 was an 18 in (0.45 m) diameter pipe installed with ODOT Structural Backfill Type 3 (AASHTO #57 open-graded crushed stone aggregate) with a maximum initial vertical deflection of -16.67%. Only one pass of the re-rounder was used for the pipe to pass the vendor's mandrel test. While the profile data collected immediately after re-rounding was problematic, the deflection at that location was reduced to -6.17% at the end of the experiment; this was also the maximum along the pipe, satisfying the -7.5% criterion.

- Test Pipe 5 was an 18 in (0.45 m) diameter pipe installed with ODOT Structural Backfill Type 2 (sand) with a maximum initial vertical deflection of -14.50%. After two passes of the re-rounder the deflection was -6.21%, holding fairly steady for the next 40 days at 6.18% before exhumation of the pipe. The maximum vertical deflection along the pipe after re-rounding was -7.47%, -7.42% at exhumation; both barely within the -7.5% criterion.
- From the deflection results from Test Pipes 1, 2, and 3, it is clear that re-rounding had the best success in reshaping the pipe to acceptable levels in the open-graded aggregate Type 3 backfill. However, during the first installation of Pipe 3, it was observed the ODOT Structural Backfill Type 3 (AASHTO #57 open-graded aggregate) did not provide sufficient resistance, and the pipe recovered from the induced deflection after installation. Hence it was necessary to use the pipe deflector device to maintain the desired level of initial deflection during the second installation of Pipe 3. Both the difficulty in maintaining the intended deflection during construction and the ease with which the pipe was re-rounded can be attributed to a lack of aggregate interlock in the AASHTO #57 aggregate used as Structural Backfill Type 3.
- Re-rounding had an intermediate success in the ODOT Structural Backfill Type 2 (sand), requiring two passes of the re-rounder in both sizes of pipe, 36 in (0.9 m) (Pipe 1) and 18 in (0.45 m) (Pipe 5) but the re-rounding did not completely restore the pipe shape to meet operational criteria.
- The well-graded Item 304 aggregate used as ODOT Structural Backfill Type 1 proved highly resistant to re-rounding due to aggregate interlock. This backfill required the least amount of added effort to maintain initial deflection during construction.

9.2.2 In-situ Soil Stiffness

- A device to measure in-situ soil-stiffness was placed at shoulder and springline of Pipe 1, but the device moved and it could not be located after re-rounding.
- A device to measure in-situ soil-stiffness was placed at various locations about the circumference of Test Pipes 2 and 3 to measure the in-situ stiffness of the structural backfill material. The soil at both the springline and shoulder of Test Pipe 2 experienced a reduction in stiffness after re-rounding. The measured value decreased from 325 psi/in (88.2 MPa/m) to 212.5 psi/in (57.7 MPa/m) at the springline and from 325 psi/in (88.2 MPa/m) to 250 psi (67.9 MPa/m) at the shoulder. Test Pipe 3 experienced a significant increase in the soil stiffness at the haunch of the pipe after re-rounding, from 100 psi/in (27.1 MPa/m) to 312.5 psi/in (84.8 MPa/m).

9.2.3 Soil Pressure

- For Test Pipe 1 in ODOT Structural Backfill Type 1 (Item 304 well-graded aggregate), the soil pressure at the left and right springline decreased from 6.81 psi (47.0 kPa) and 7.85 psi (54.1 kPa) to 4.20 (29.0 kPa) and 4.60 psi (31.7 kPa) after the first pass, 3.48 (24.0 kPa) and 4.40 psi (30.3 kPa) after the second pass, and 2.76 (19.0 kPa) and 4.62 psi (31.9 kPa) after the third pass, showing some consistent reduction on the left side with each pass, and a reduction after one pass then a nearly constant pressure after succeeding passes on the other side. At the crown, there was a consistent reduction pattern, from 5.02 psi (34.6 kPa) before re-rounding to 2.08 psi (14.3 kPa) after one pass, 1.69 psi (11.7 kPa) after two passes, and 0.72 psi (5.0 kPa) after three passes.
- For Test Pipe 2 in ODOT Structural Backfill Type 2 (sand), the soil pressure at the left and right springline decreased from 2.99 psi (20.6 kPa) and 3.80 psi (26.2 kPa) to 2.30 (15.9 kPa) and 2.27 psi (15.7 kPa) after the first pass, and 2.09 (14.4 kPa) and 1.89 psi (13.0 kPa) after the second pass. At the crown the pressures went from 5.48 psi (37.8 kPa) before re-rounding to 1.39 psi (9.6 kPa) after one pass and 0.76 psi (5.4 kPa) after two passes. At all sensors there was a reduction in pressure with each pass of the re-rounder.
- For Test Pipe 3 in ODOT Structural Backfill Type 3 (AASHTO #57 aggregate), the soil pressure at the left and right springline went from 2.69 psi (18.5 kPa) and 0.66 psi (4.6 kPa) to 2.23 (15.4 kPa) and 2.25 psi (15.5 kPa) after the first pass; the pressure decreased on the left and increased significantly on the right so that the pressures at both sides were close after re-

rounding. At the crown the pressure went from 4.08 psi (28.1 kPa) before re-rounding to 5.20 psi (35.9 kPa) after the pass of the re-rounder, a significant increase.
- The pressure cell and stiffness data are consistent with the theory that fine materials in ODOT Structural Backfill Type 1 (Item 304 aggregate) move down from the crown and springline and settle in the haunch area around the pipe. This was verified by gradation data collected before and after re-rounding at different locations in the backfill. In addition, the re-rounder pushed the crown up and the invert down, and the springline regions responded by contracting and reducing the horizontal diameter, creating room for smaller particles to move.
- There may be similar particle movement in the ODOT Structural Backfill Type 2 (sand) and ODOT Structural Backfill Type 3 (AASHTO #57 aggregate), and the pressure cell and stiffness data from Pipe 3 were consistent with that hypothesis (Pipe 2 did not have a stiffness measurement device). However, because ODOT Structural Backfill Type 2 (sand) and ODOT Structural Backfill Type 3 (AASHTO # 57 aggregate) material have uniform gradations, the only way to verify movement of material is by measuring density, and the density of the material could not be measured in place without disturbing the backfill.
- Test Pipe 1 was exhumed 48 days after re-rounding and Test Pipe 2 was exhumed 209 days after re-rounding. For both pipes, the shape and pressure cell readings obtained just before exhumation indicate the pipe shape had not changed since re-rounding and the pressure in the soil around the pipe had decreased, indicating the system had been experiencing relaxation. The presence of relaxation indicates Pipes 1 and 2 were suitable for long-term continued service after re-rounding.

9.2.4 Acceleration

- Accelerometers were installed 6 in (0.15 m) and 18 in (0.45 m) above the crowns of Test Pipes 2 and 3. The acceleration data were analyzed to assess the likelihood of re-rounding to damage a pavement layer above the re-rounded pipe. Obtaining a limiting peak particle velocity value for pavement and other transportation infrastructure proved a challenge and presents a need for future research. However, a conservative minimum height of cover with ODOT Structural Backfill Type 2 (sand) 50 in (1.27 m) above the pipe appears sufficient to ensure the pavement is not damaged. Applying the same approach, the computed minimum cover height for ODOT Structural Backfill Type 3 (AASHTO #57 aggregate) was 6 in (0.15 m). Other design considerations, such as the settlement typical of vibrated open-graded aggregate, would probably require the cover height for HDPE pipes installed in ODOT Structural Backfill Type 3 (AASHTO #57 aggregate) be greater than this.

9.2.5 Corrugation

- Test Pipes 1, 2, and 3 were carefully examined for any signs of visible damage after they were exhumed from the test installation. There was no significant damage noted to any pipe. Thus, it is concluded that the re-rounding process did not damage the pipe.
- Corrugation depth measurements were obtained on Pipes 1, 2, and 3 before and after re-rounding, and no significant changes were found. For Test Pipe 1 the maximum change in corrugation height was -5.50%, with a mean value of 2.21% and a standard deviation of 1.48%. Test Pipe 2 experienced no measurable changes in corrugation depth. For Test Pipe 3 the maximum change in corrugation height was +5.11% with a mean value of -1.48%. The change in height of the corrugation is relatively greater on Pipe 1 than on Pipe 3, which confirms that the ODOT Structural Backfill Type 1 (Item 304 aggregate) around Pipe 1 was stiffer than the ODOT Structural Backfill Type 3 (AASHTO #57 aggregate).

9.2.6 General conclusions

The data from the deflection, soil stiffness, corrugation, and soil pressure measurements confirm the following conclusions:

- During the re-rounding operation, soil particles migrated, and pressure was redistributed; fine material from crown and springline moved down toward the haunch area, at least in ODOT Structural Backfill Type 1 (ODOT Item 304 well-graded aggregate). The movement of the particles was enhanced by the re-rounder pushing the crown and invert out, allowing the sides to move in. These factors also reduced the soil pressure at the crown and springline. Direct measurement of the redistribution of the more uniformly graded backfill material was not possible.

- It is difficult to successfully reduce deflection in HDPE pipes in ODOT Structural Backfill Type 1 (Item 304 aggregate) by re-rounding. The amount of energy involved is extreme and ability to move ODOT Structural Backfill Type 1 (Item 304 aggregate) appears limited. Based on evaluation of the gradation measurements during exhumation, only the fine materials appear to move vertically during re-rounding. However, the extreme energy required to mobilize the backfill material can be seen as a benefit to the long-term suitability of re-rounded HDPE pipes installed in ODOT Structural Backfill Type 1 (Item 304 aggregate).
- The research findings indicate HDPE pipes installed in the field with Item 304 (ODOT Structural Backfill Type 1) may still perform long-term without major distresses under deflections greater in magnitude than -7.5%; deflections up to -10% may be acceptable, assuming the backfill material was adequately compacted. In Item 304 (ODOT Structural Backfill Type 1), if the initial deflection before re-rounding is more than -7.5%, the pipe installation may still be safe and durable. However, typical strain limit states must also be verified.
- Installing the pipes with excess deflection proved a significant challenge, as all the pipes required significant deliberate effort to reach sufficient deflection. It proved necessary to resort to creating a device to hold the pipe in a deflected state during backfilling.
- Re-rounding may be successful at reducing deflections to acceptable levels for pipes in ODOT Structural Backfill Type 2 (sand). However, it is well established that the sand must be sufficiently confined. Sand which is open and exposed will migrate, particularly under pressure of water.
- Pipes in ODOT Structural Backfill Type 3 (AASHTO #57 aggregate) were easy to re-round. However, it is possible a change in environmental conditions and/or dynamic loading may create a change in the stress path leading to excessive deflection and reversing the effects of re-rounding. Consolidation in the embankment may be problematic, creating a loss of backfill height. This may be due to re-rounding or by service conditions.
- The 18 in (0.45 m) pipes generally followed the same general trends as the 36 in (0.9 m) pipes, including having the same number of re-rounder passes in each type of backfill.
- As the re-rounding device vibrates along the vertical axis to act on the inner crown and invert of the pipe, the effectiveness of re-rounding in cases with racking is not known.

9.3 Recommendations

- Re-rounding can be used as a mechanism for reducing vertical deflection in thermoplastic pipe exceeding minimum acceptable deflection requirements. However, since the re-rounding machine used operates on the vertical axis, its effectiveness against racked pipes is unknown.
- When pipe is backfilled using AASHTO #57 aggregate backfill, the re-rounding is very effective at reducing vertical deflection. However, this is because the backfill material was easily mobilized under the dynamic loading of the re-rounder. Further study is needed to confirm if condition changes or dynamic loads during service after re-rounding, particularly in shallow cover, could reverse the re-rounding and create deflection problems.
- If #57 is used as backfill, the use of fine material above the backfill should be used with caution as this can result in voids above the pipe crown.
- Further evaluation is needed to determine whether the re-rounding process and associated migration of material above the pipe leads to cracking in pavement, particularly when there is shallow cover.
- It remains to be determined what are the limit states (maximum peak particle velocity) to ensure the stresses from re-rounding vibrations do not cause any negative impacts to pavements or surrounding underground structures.

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Appendix A: Survey of state departments of transportation

A survey questionnaire for state department of transportation (DOT) professionals in the area of thermoplastic pipes was drawn up by the research team in consultation with the ODOT subject matter experts. The ODOT research office set up an online form via Formstack and disseminated the link via their contacts across the United States on November 1. As of the final response on November 15, seventeen responses had been gathered from sixteen states: AL, CA, CT, DE, GA, IL, ME, MI (two responses), MN, MT, NE, ND, TN, UT, VA, WA. The two responses from Michigan were essentially duplicates, so responses were compiled based on sixteen states (N=16). The questions are given in Figure 86.

forms

Formstack Submission for Research Survey – Re-rounding of Deflected Thermoplastic Conduit

Submitted at 11/01/16 2:30 PM

1. Is deflection measured as a quality control check for new thermoplastic pipe installations?:

1a. How is it measured?:

1b. Who performs the deflection measuring?:

1c. When is the deflection measured?:

2. What is the maximum deflection permitted during the installation of thermoplastic pipes in your state?:

3. When the deflection value is exceeded, is the pipe replaced?:

3a. If pipe is not replaced, what other options can be considered?:

4. Does your Department re-round thermoplastic pipes to reduce their maximum deflection?:

4a. If the re-rounding technique proved to be viable, would your state's DOT consider using it?:

5. Does your Department have guidelines regarding re-rounding of thermoplastic pipes?:

5a. Please include a copy of, or link to, the relevant guidelines or specifications.:

6. Identify any specific companies your agency has employed to perform re-rounding work?:

7. What successes or failures has your state's DOT had with re-rounding?:

Name:

Title:

Title - Copy:

State:

Phone:

Email:

Figure 86. Survey on re-rounding completed by state DOTs.

Figure 87 compiles responses to the first question of the survey, which asked if the state used deflection as a quality control check on thermoplastic pipe installations. Three quarters (75%, 12 states: DE, IL, ME, MI, MN, MT, NE, ND, TN, UT, VA, WA) said that they did, and the rest (AL, CA, CT, GA) said they did not.

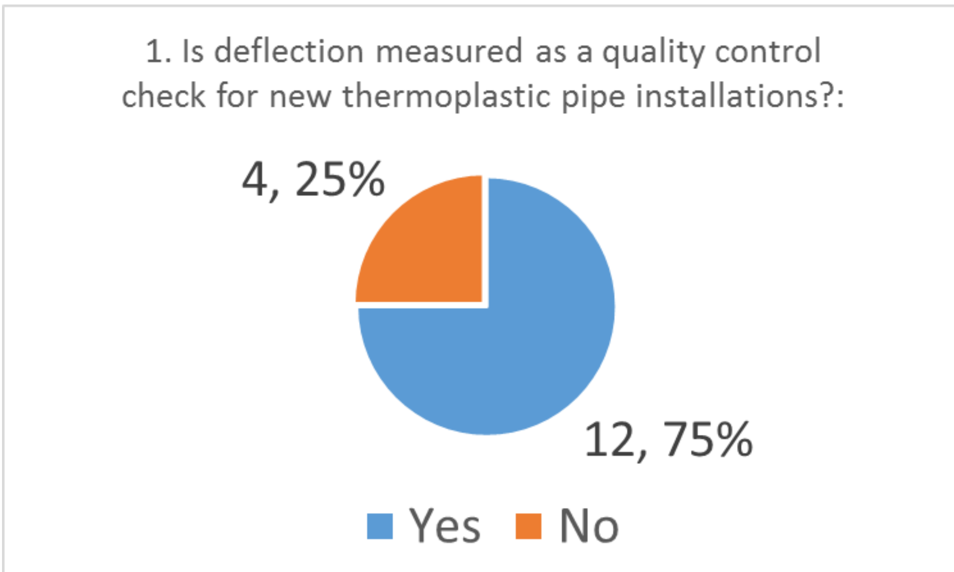


Figure 87. Responses to Question 1 of the survey.

The next question asked what was the maximum deflection permitted in thermoplastic pipe installations. Of the sixteen states, two thirds (69%, 11 states) indicated 5% deflection was the maximum. One of these (IL) stated “the mandrel is 95% of the base inside diameter”, which was interpreted to mean the same thing, while another (GA) stated “When pipe deflection exceeds 5% of the nominal diameter, Engineer reviews installation. GDOT remediates or replaces pipe when pipe deflection exceeds 7.5% of the nominal diameter”, which could be interpreted as 5% or 7.5%. Utah (UT) made a similar statement in amplifying their response: “Between 5% and less than 7.5% the contractor can propose corrective action.” One state (6.67% of responses, MT) specified 7%, and another (VA) specified 7.4%, with reduced payments for deflections “up to 7.4%”. Another state (CT) was counted at 6%, though they actually do not allow installation of thermoplastic pipe under the travelway; visual inspections and mandrel tests are used to determine acceptance, and if a maximum deflection criteria were used, the agency would follow the AASHTO LRFD specification of 6%. Another state (CA) had no specified maximum, but added “Obviously, if the pipe deflection is substantial that would be considered a failure. We do have leakage requirements. Deflections at the joints would be a failure.” One state (AL) provided the response “123” to several questions, indicating a lack of engagement with the questionnaire, and that response was categorized as “N/A” in this analysis.

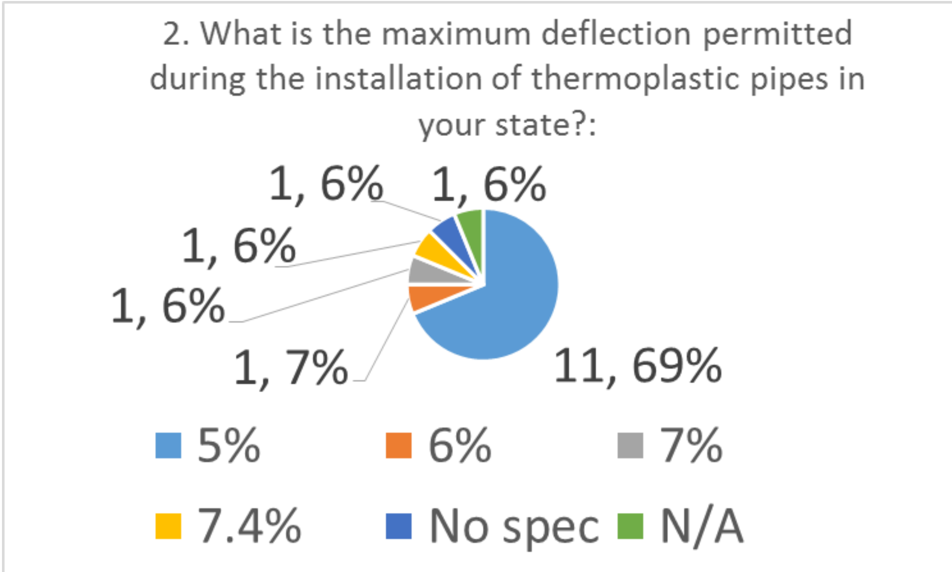


Figure 88. Responses to Question 2 of the survey.

Responses to Question 3, regarding action taken when maximum deflection is exceeded, are charted in Figure 89. Three quarters (75%, 12 states) indicated the pipe was replaced when the maximum deflection was exceeded. One state (6.25%, WA) answered "No", but with qualifications: "Normally no, depending on severity of deflection, and results of air test". Another state (AL) answered "No", but this was recategorized as "N/A" given the problematic response given Question 2 ("123"). That leaves two states (12.5%, MN, NE) had qualified repsonses categorized as "sometimes" – MN indicated the decision was made on a case-by-case basis, and NE indicated the decision was "At the discretion of the Engineer". Some of the Yes responses could be construed as sometimes, as for DE, GA, and UT, where pipes deflected between 5% and 7.5% are subject to an engineering evaluation and possible deduction.

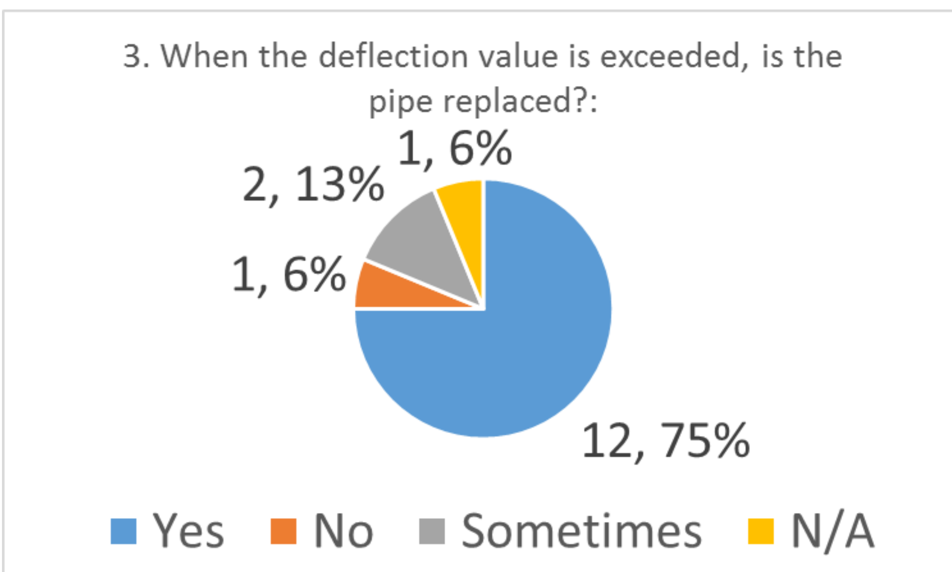


Figure 89. Responses to Question 3 of the survey.

Question 4 responses are presented in Figure 90, which indicates 94% of states (15) do not use re-rounding. The one state (6.25%, AL) that answered the question, did not provide any further useful information; for example when asked to identify companies that the agency had employed, the response was “123” and when asked about successes or failures with the technique, the response was also “123”.

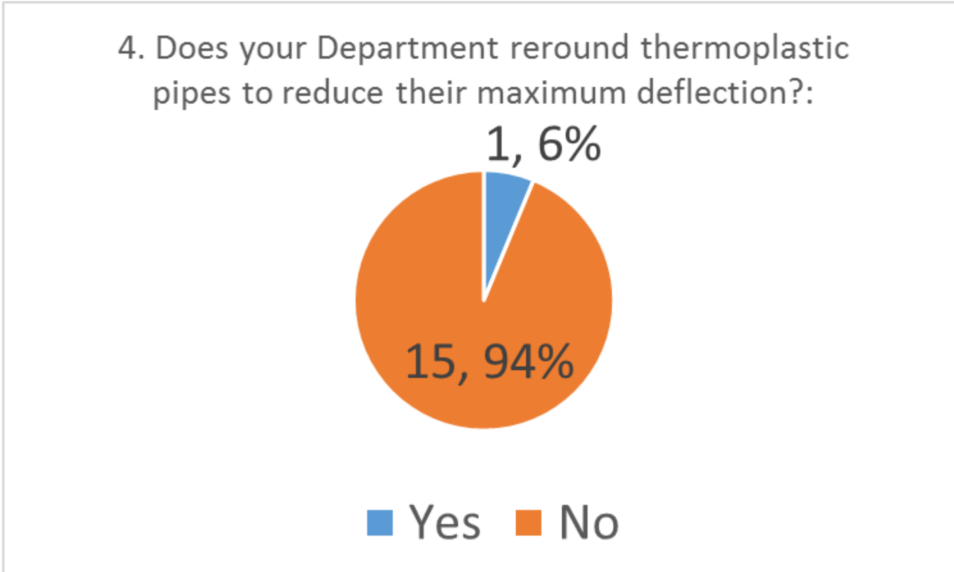


Figure 90. Responses to Question 4 of the survey.

Question 5, asking about guidelines, also got one yes response, again from AL, but they did not provide any further information, link, or copy of any documents. The other 15 states (94%) did not have any guidelines.

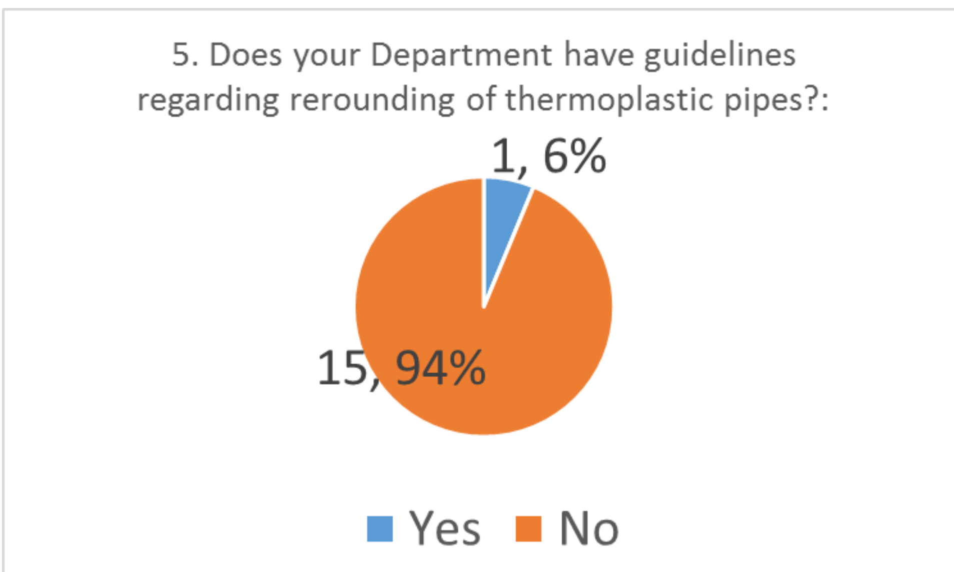
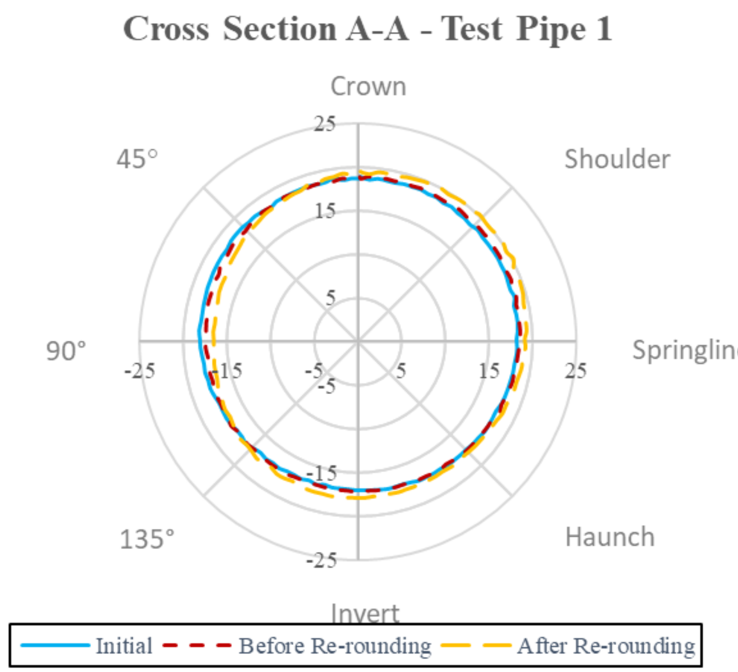
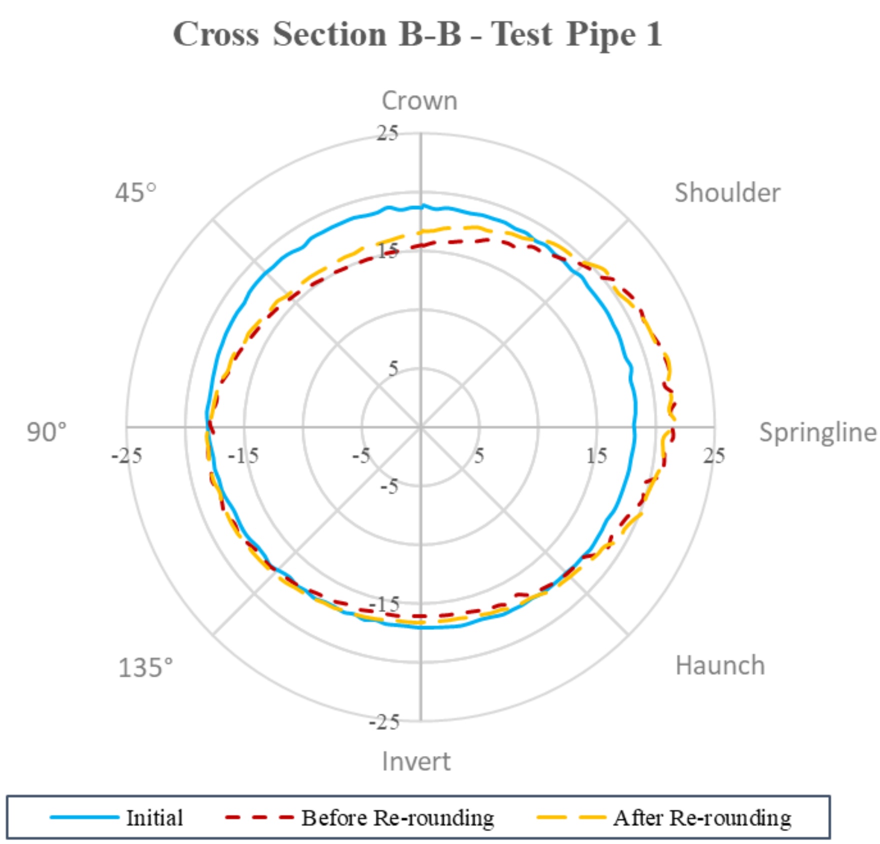


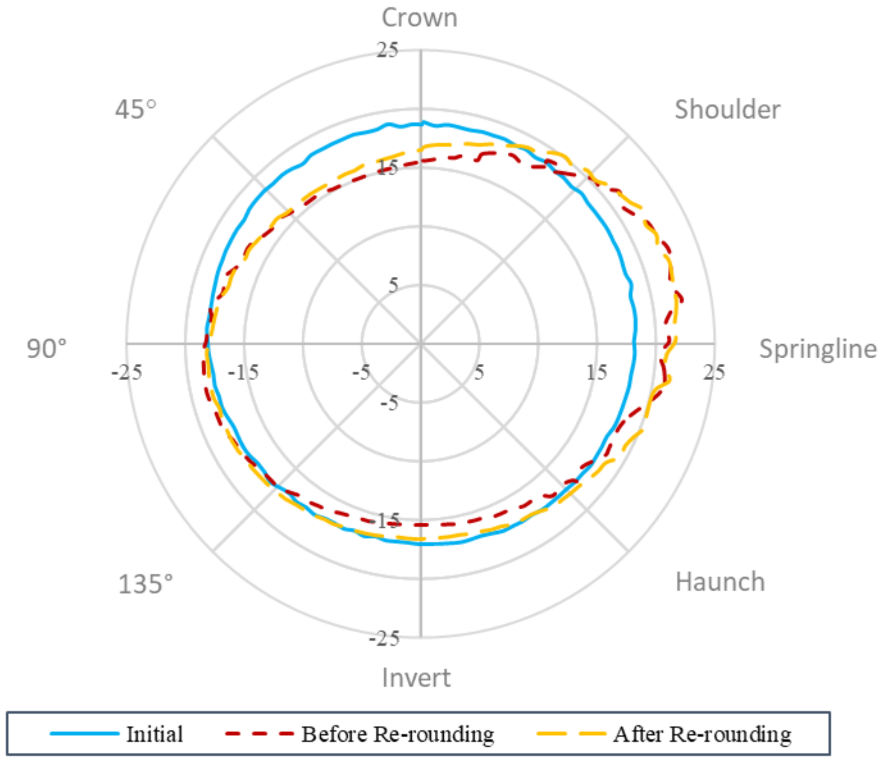
Figure 91. Responses to Question 5 of the survey.

Appendix B: Test pipe profiles.

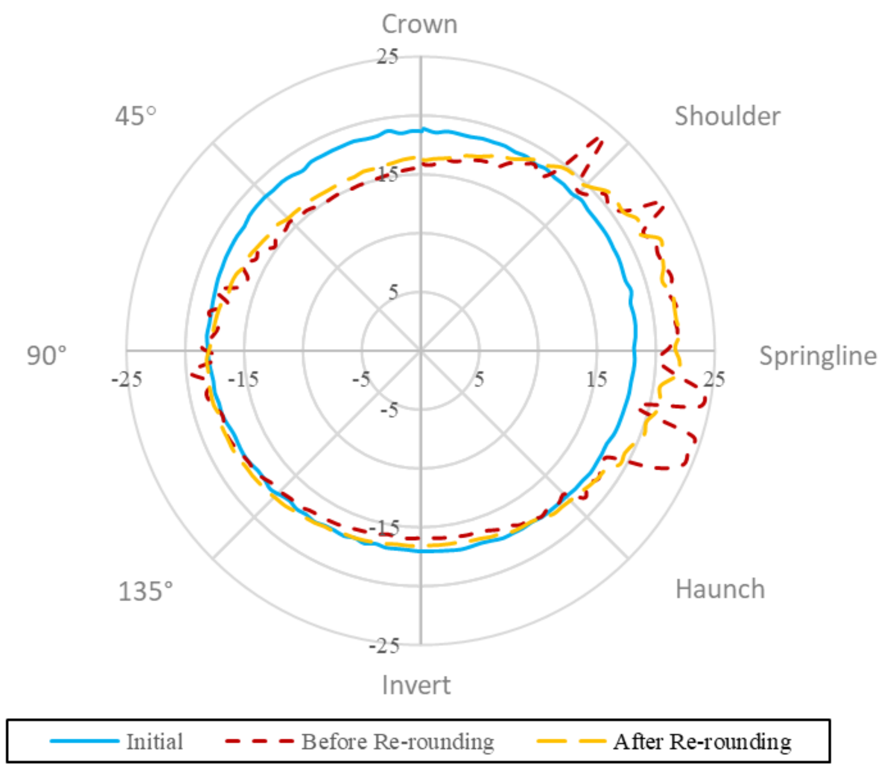




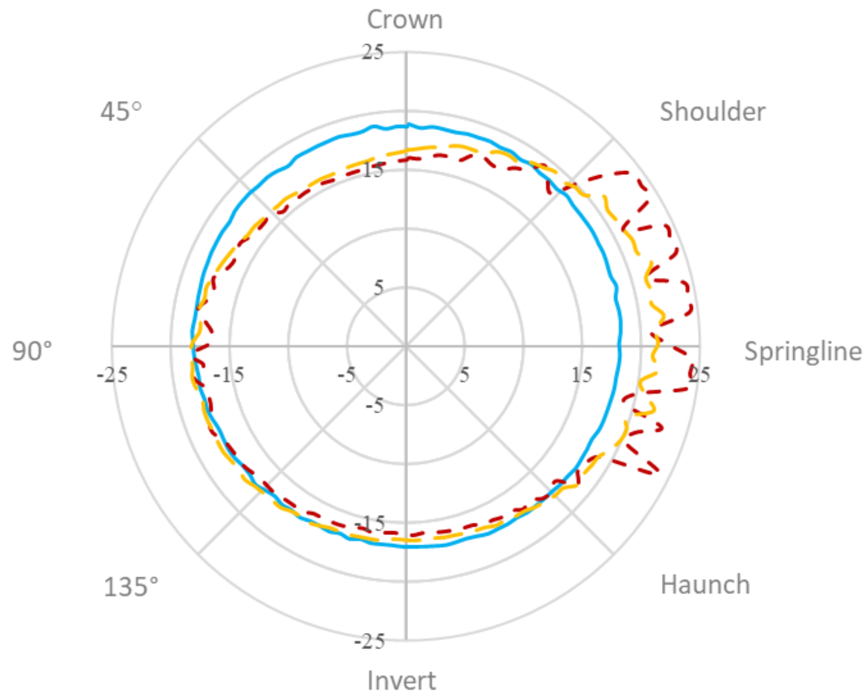
Cross Section C-C - Test Pipe 1



Cross Section D-D - Test Pipe 1

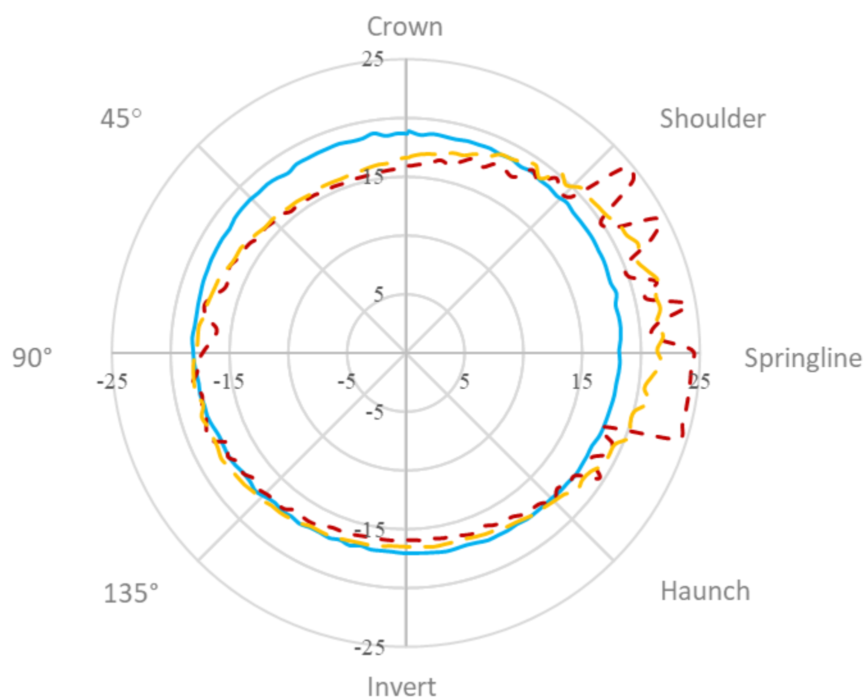


Cross Section E-E - Test Pipe 1

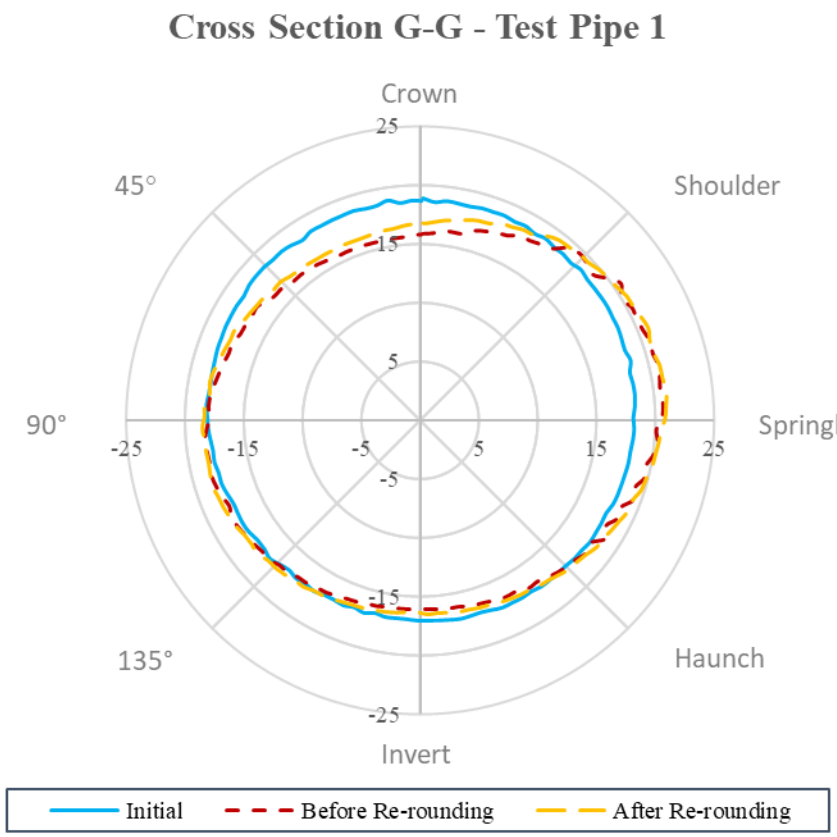


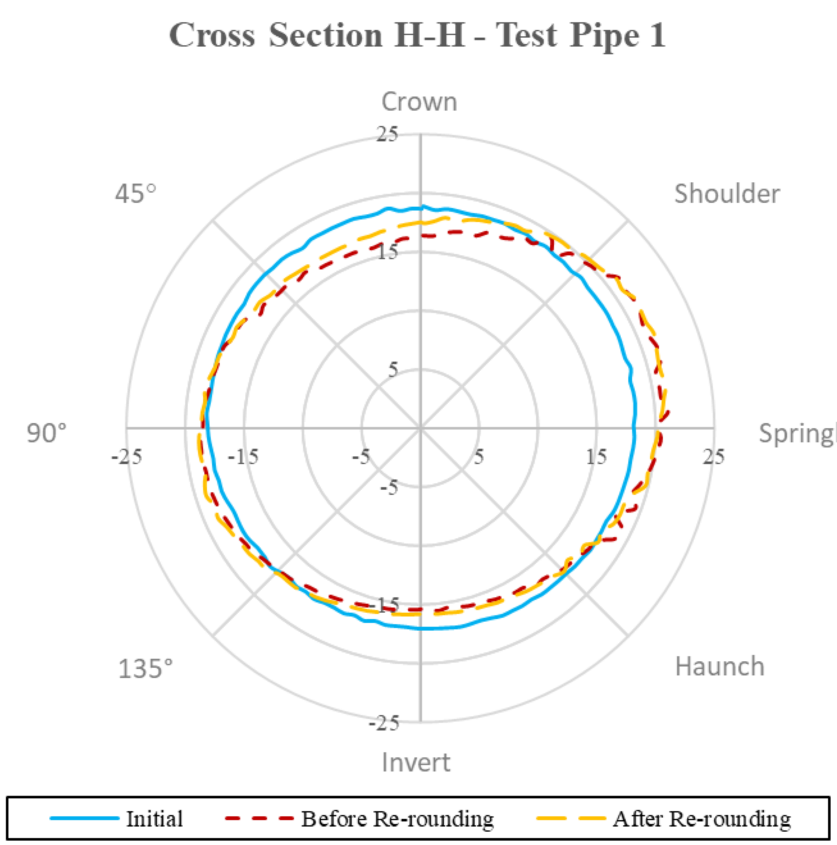
Initial — Before Re-rounding — After Re-rounding

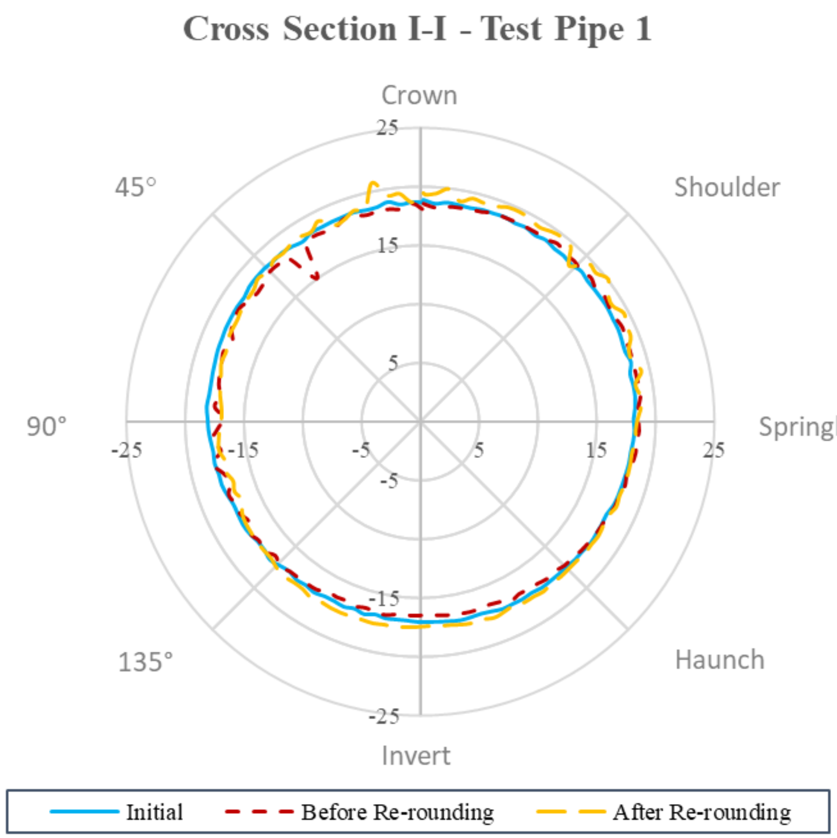
Cross Section F-F - Test Pipe 1

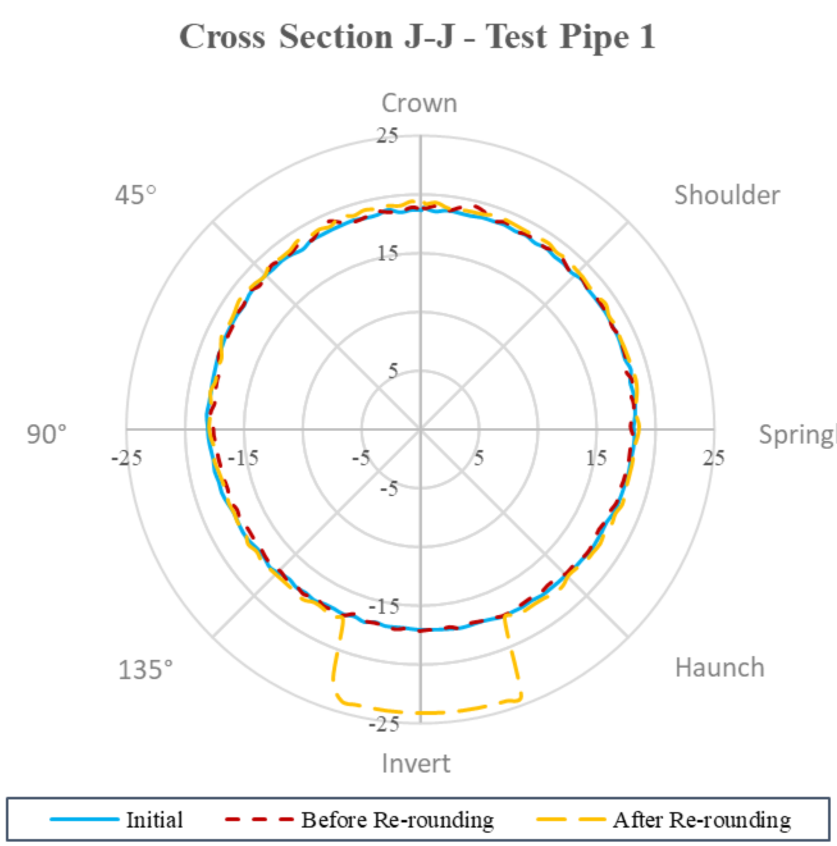


Initial — Before Re-rounding — After Re-rounding

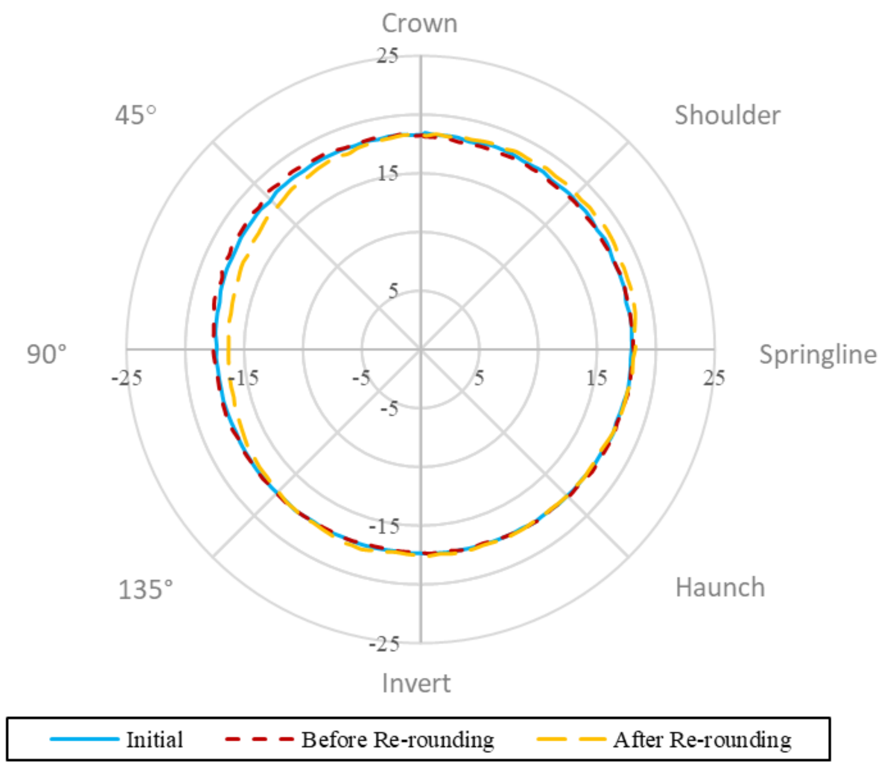

Cross Section G-G - Test Pipe 1
Crown
Shoulder
45°
Springline
90°
Haunch
135°
Invert
25
15
5
-5
-15
-25
Initial
Before Re-rounding
After Re-rounding


Cross Section H-H - Test Pipe 1
Crown
Shoulder
45°
Springline
90°
Haunch
135°
Invert
25
15
5
-5
-15
-25
Initial
Before Re-rounding
After Re-rounding

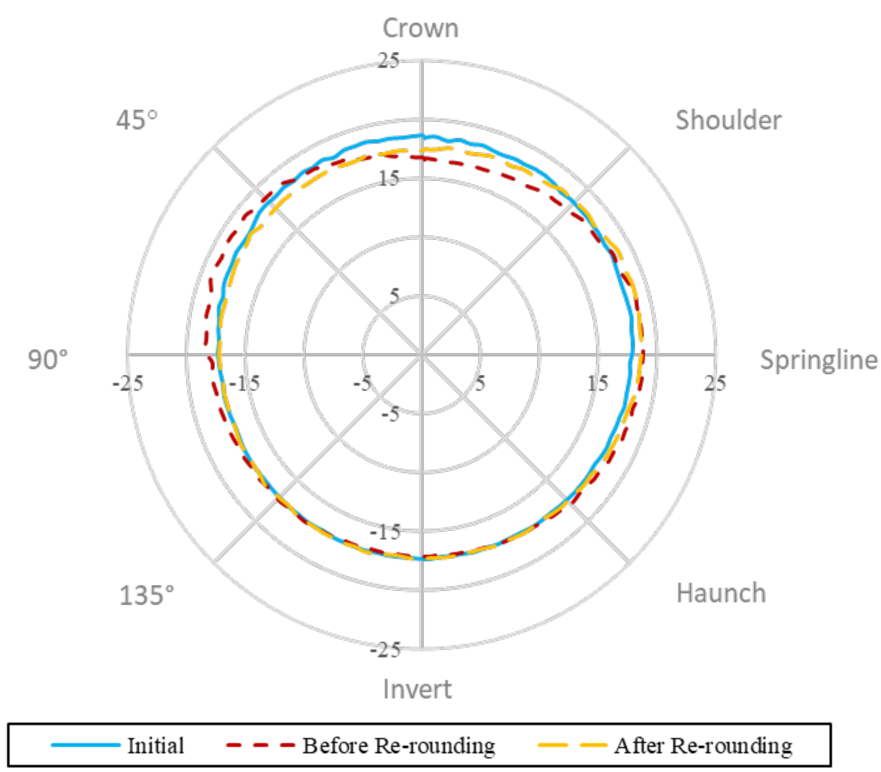

Cross Section I-I - Test Pipe 1
Crown
Shoulder
Springline
Haunch
Invert
135°
90°
45°
25
15
5
-5
-15
-25
Initial
Before Re-rounding
After Re-rounding


Cross Section J-J - Test Pipe 1
Crown
Shoulder
Springline
Haunch
Invert
135°
90°
45°
25
15
5
-5
-15
-25
Initial
Before Re-rounding
After Re-rounding

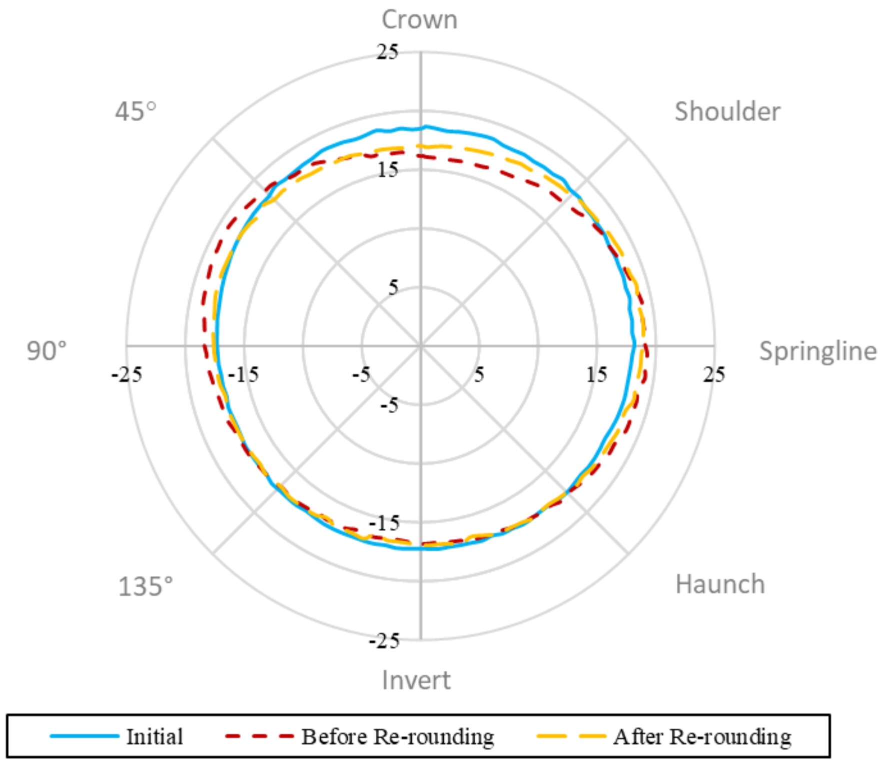
Cross Section A-A - Test Pipe 2



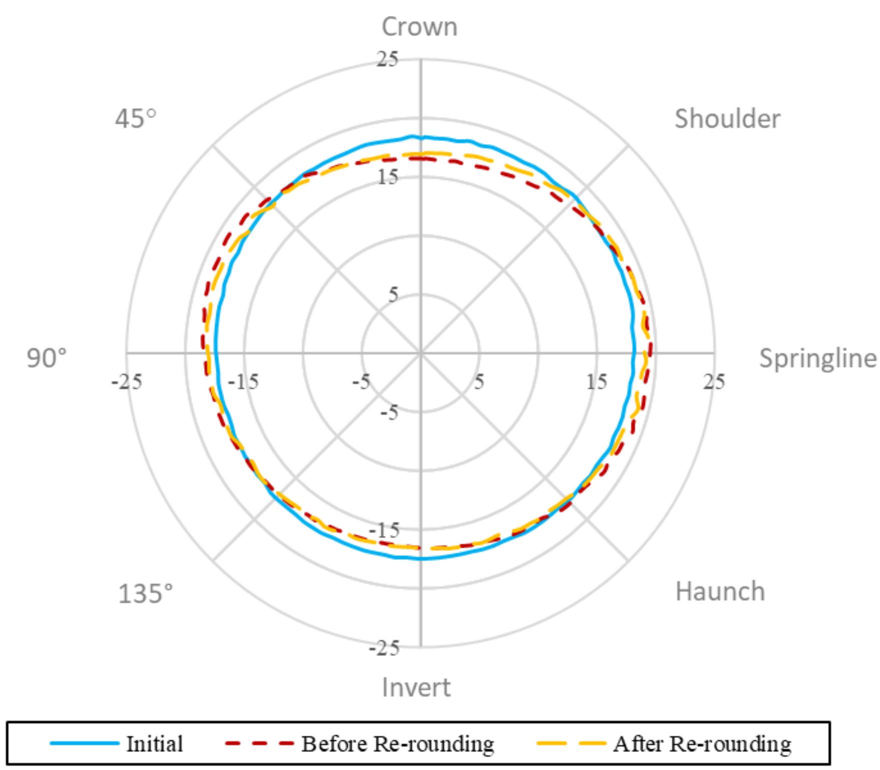
Cross Section B-B - Test Pipe 2



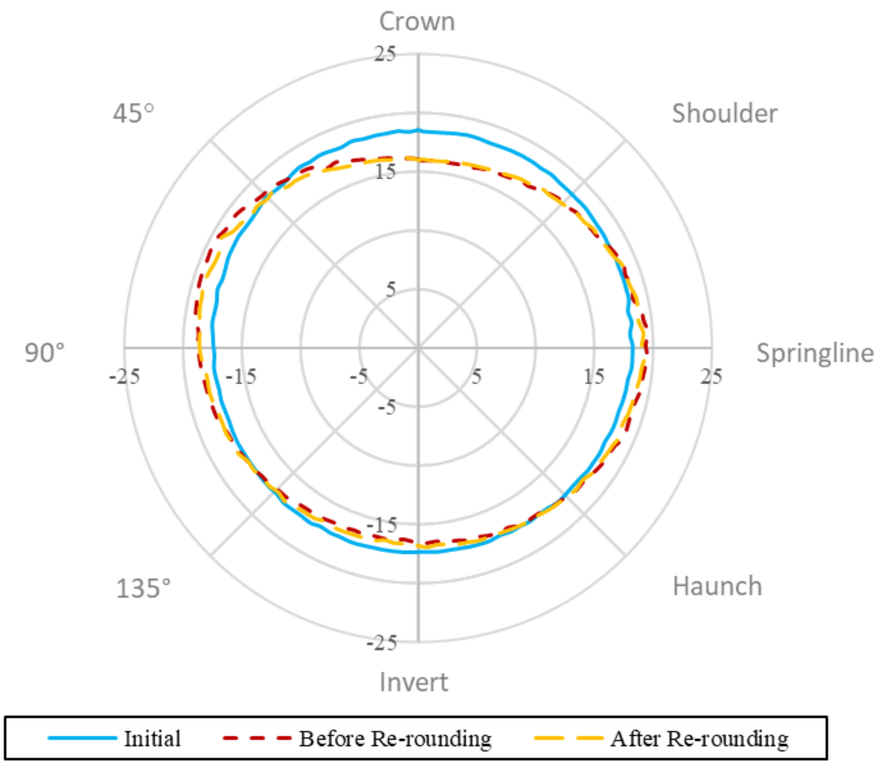
Cross Section C-C - Test Pipe 2



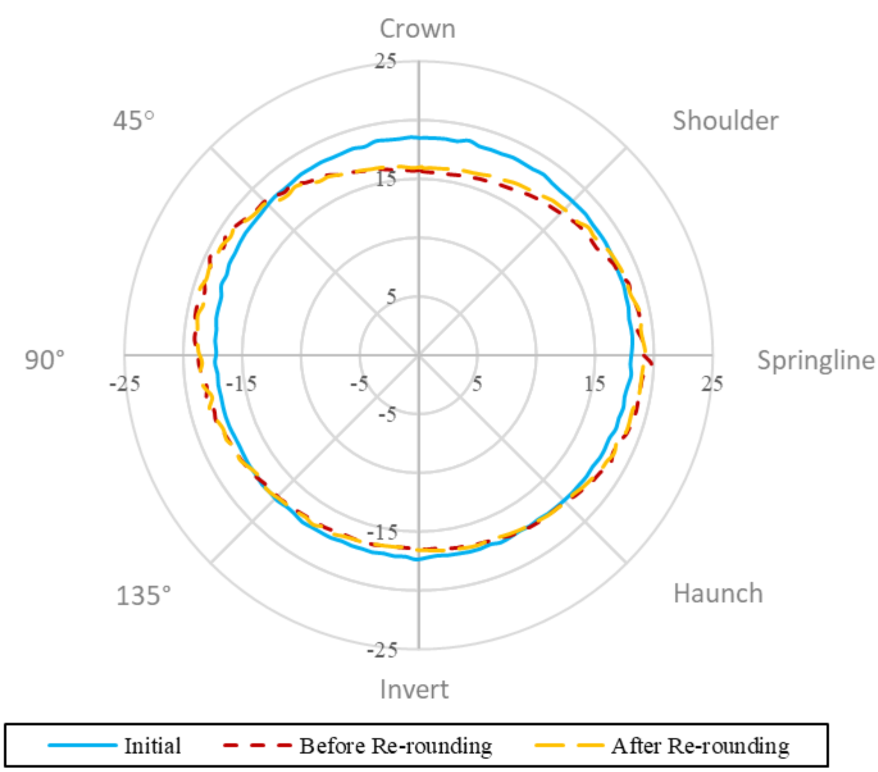
Cross Section D-D - Test Pipe 2



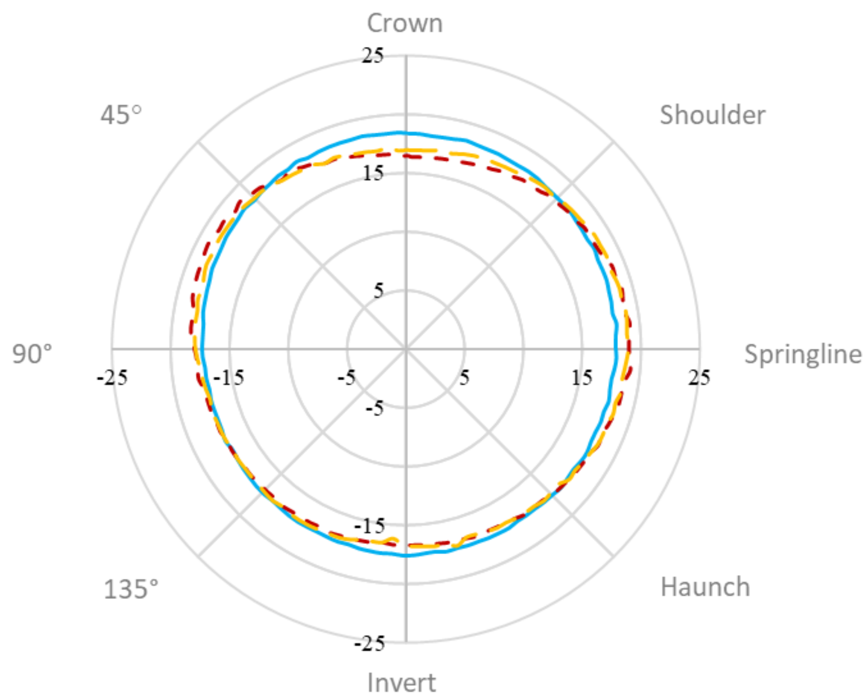
Cross Section E-E - Test Pipe 2



Cross Section F-F - Test Pipe 2

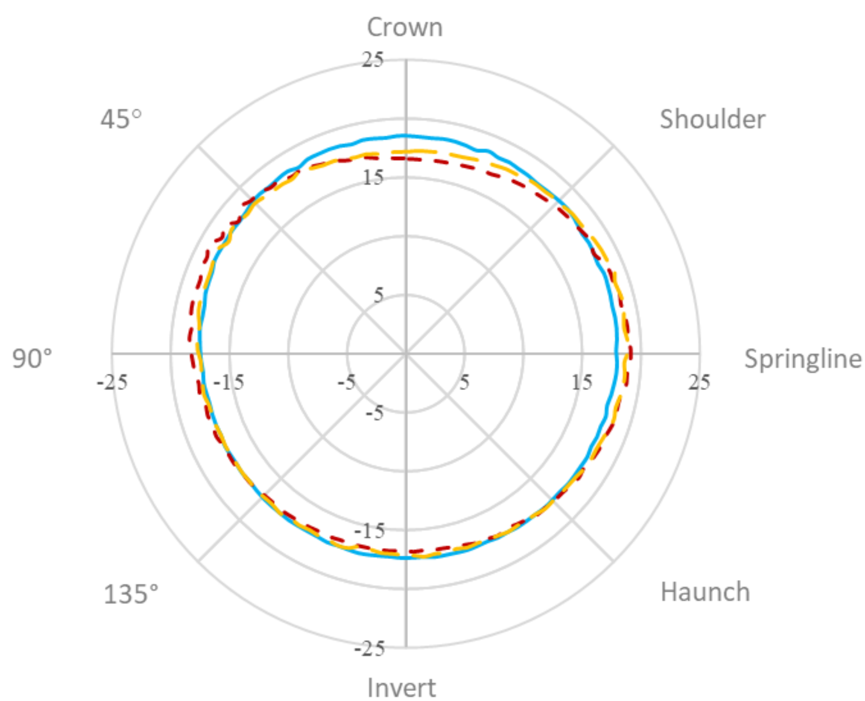


Cross Section G-G - Test Pipe 2



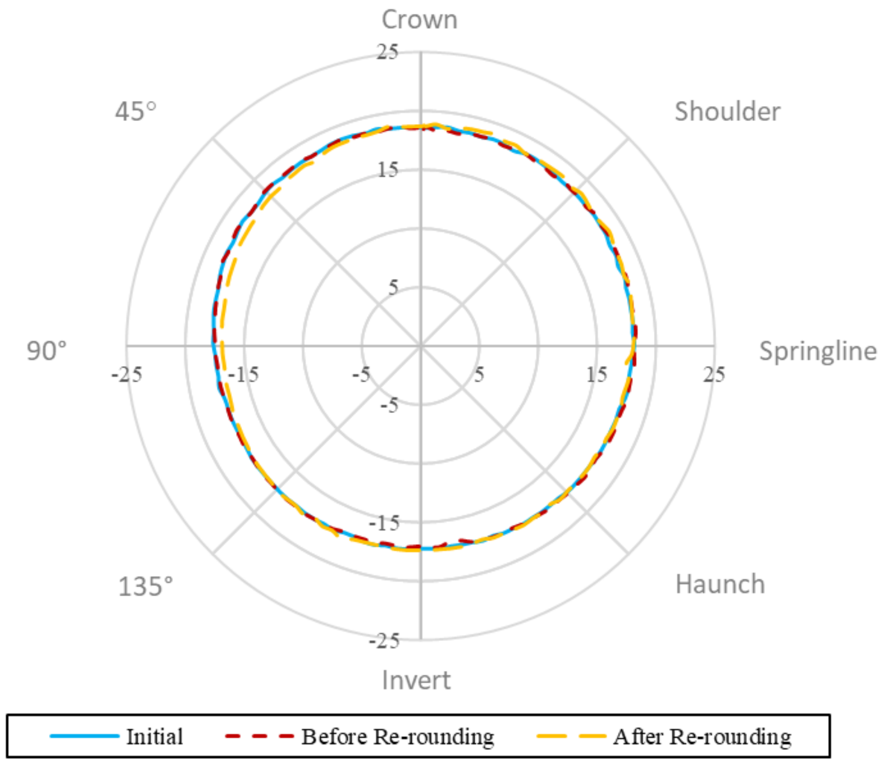
Initial — Before Re-rounding — After Re-rounding

Cross Section H-H - Test Pipe 2

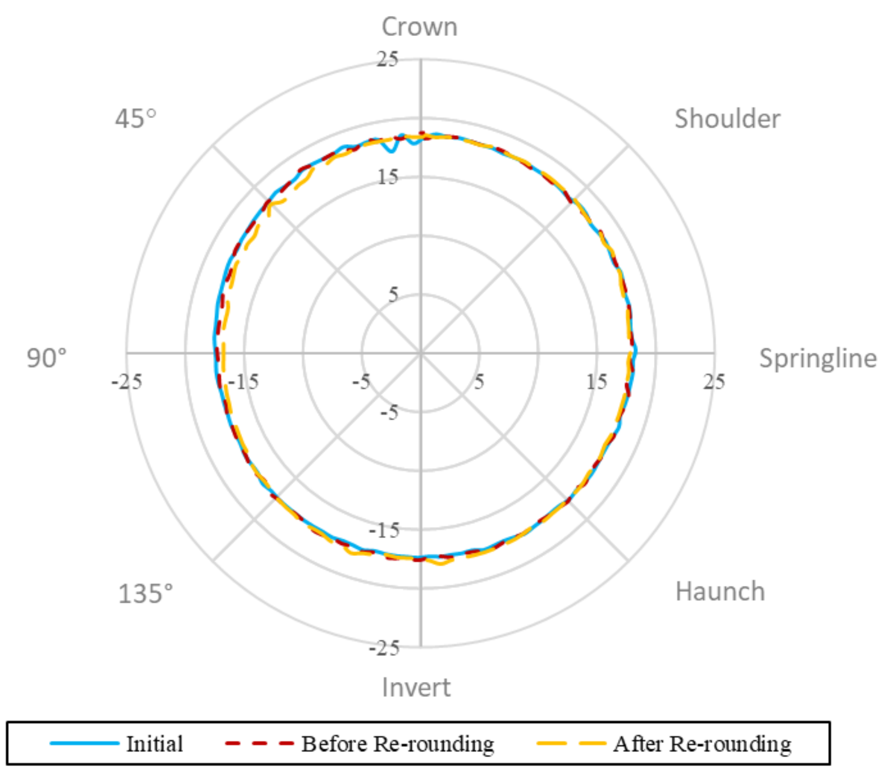


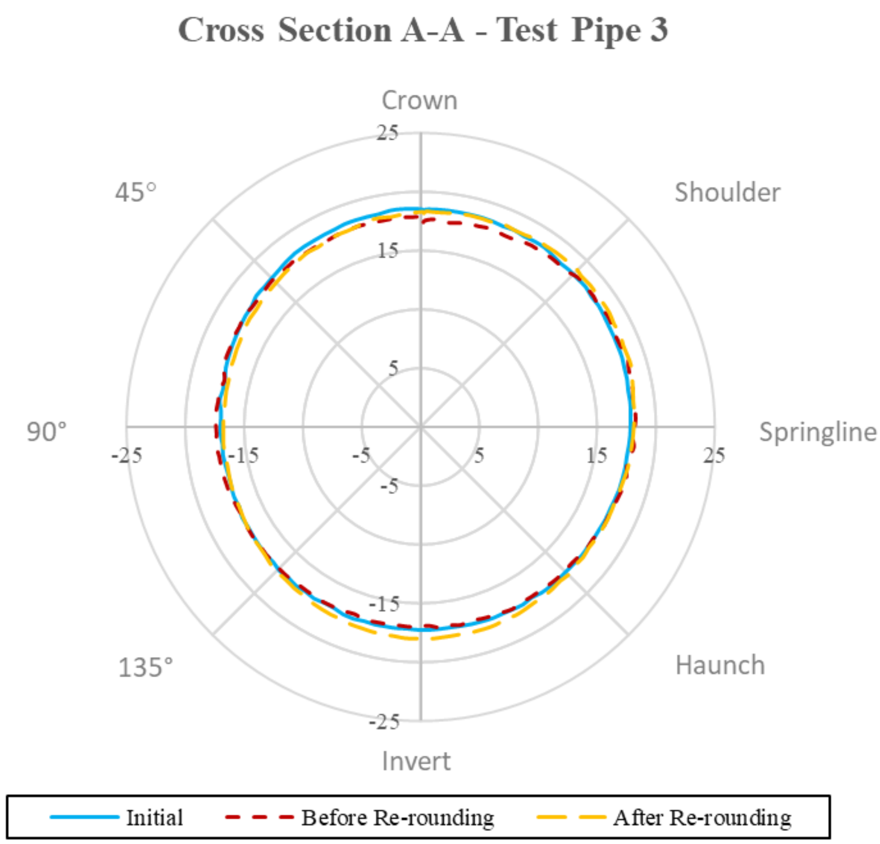
Initial — Before Re-rounding — After Re-rounding

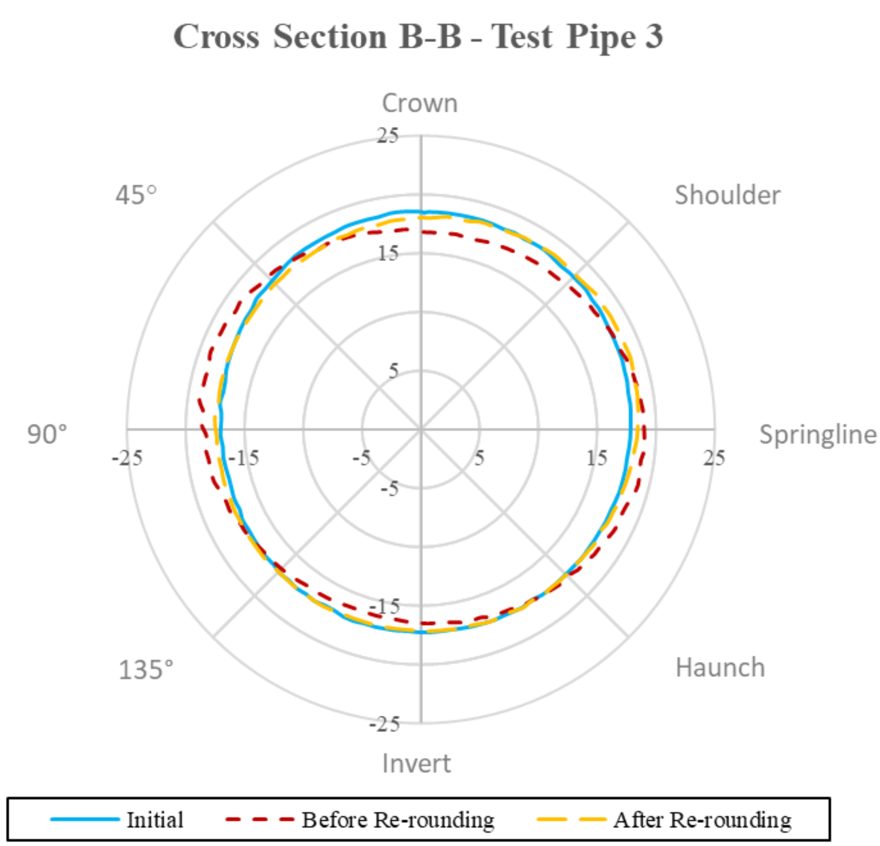
Cross Section I-I - Test Pipe 2



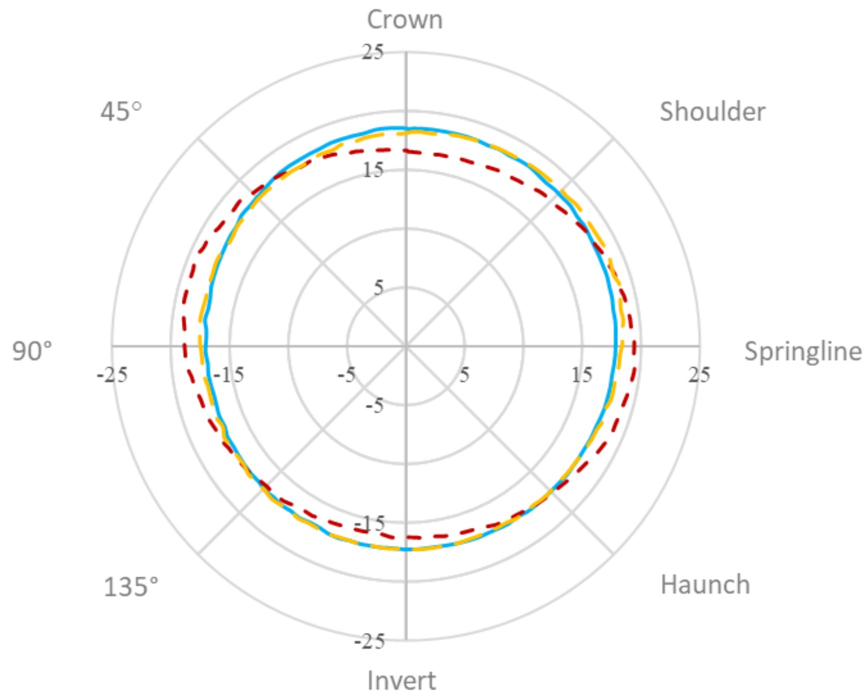
Cross Section J-J - Test Pipe 2




Cross Section A-A - Test Pipe 3
Crown
Shoulder
Springline
Haunch
Invert
135°
90°
45°
25
15
5
-5
-15
-25
Initial
Before Re-rounding
After Re-rounding

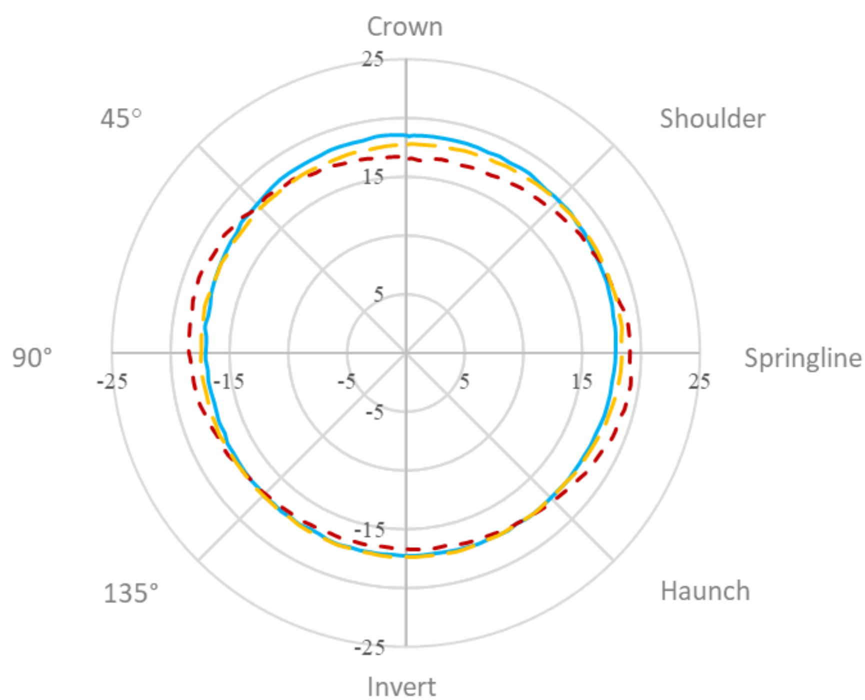

Cross Section B-B - Test Pipe 3
Crown
Shoulder
Springline
Haunch
Invert
135°
90°
45°
25
15
5
-5
-15
-25
Initial
Before Re-rounding
After Re-rounding

Cross Section C-C - Test Pipe 3

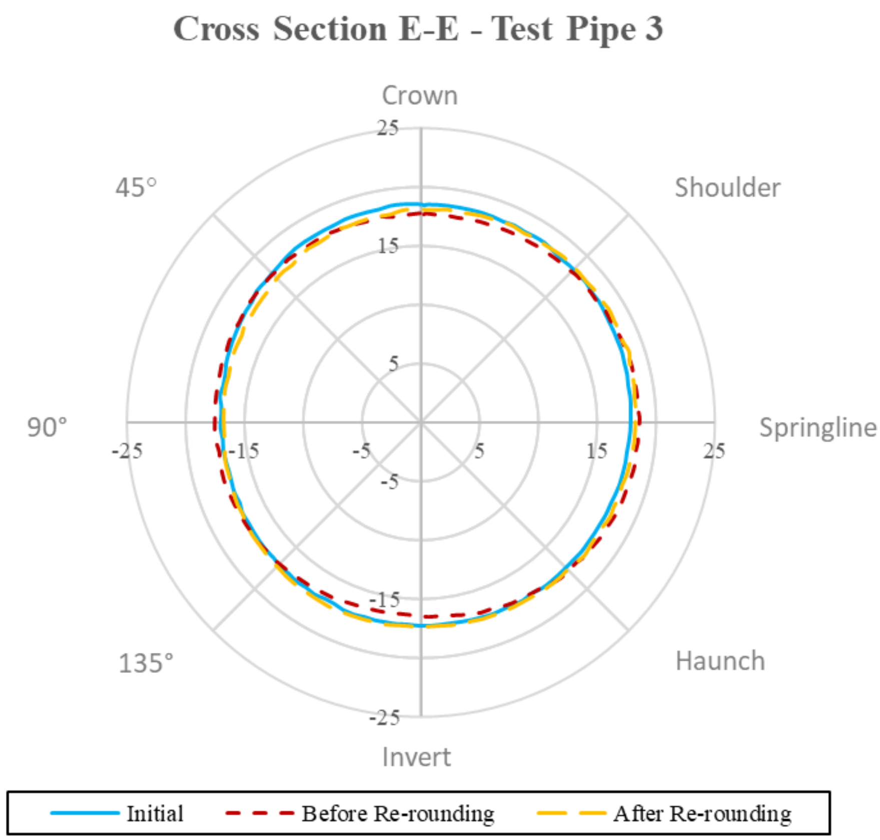


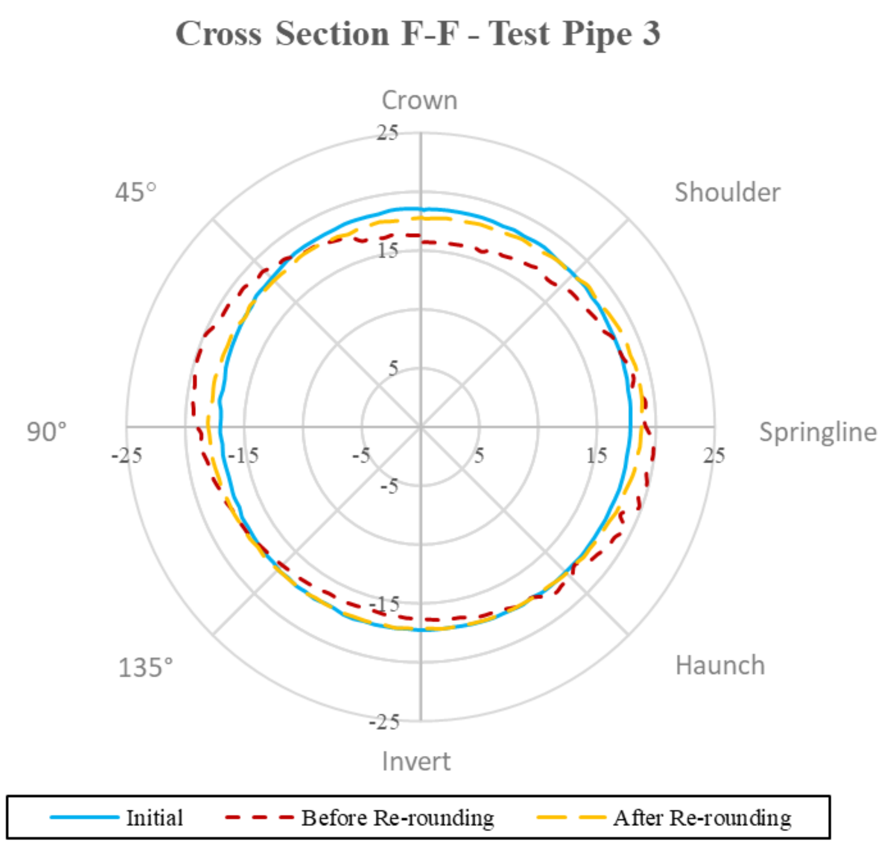
Initial — Before Re-rounding — After Re-rounding

Cross Section D-D - Test Pipe 3

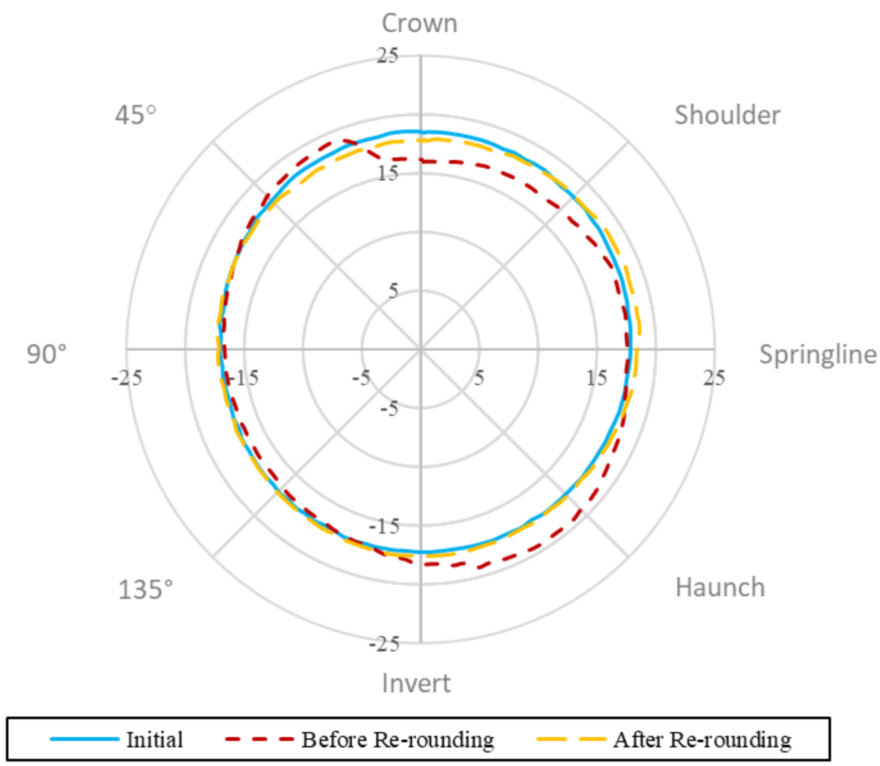


Initial — Before Re-rounding — After Re-rounding

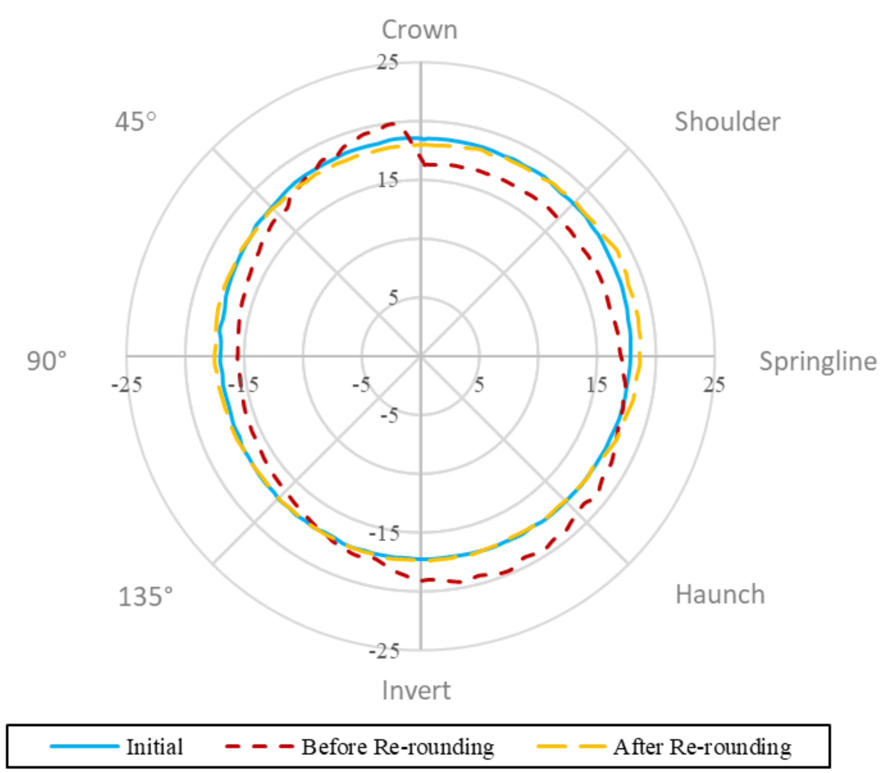

Cross Section E-E - Test Pipe 3
Crown
Shoulder
Springline
Haunch
Invert
135°
90°
45°
25
15
5
-5
-15
-25
Initial
Before Re-rounding
After Re-rounding


Cross Section F-F - Test Pipe 3
Crown
Shoulder
Springline
Haunch
Invert
135°
90°
45°
25
15
5
-5
-15
-25
Initial
Before Re-rounding
After Re-rounding

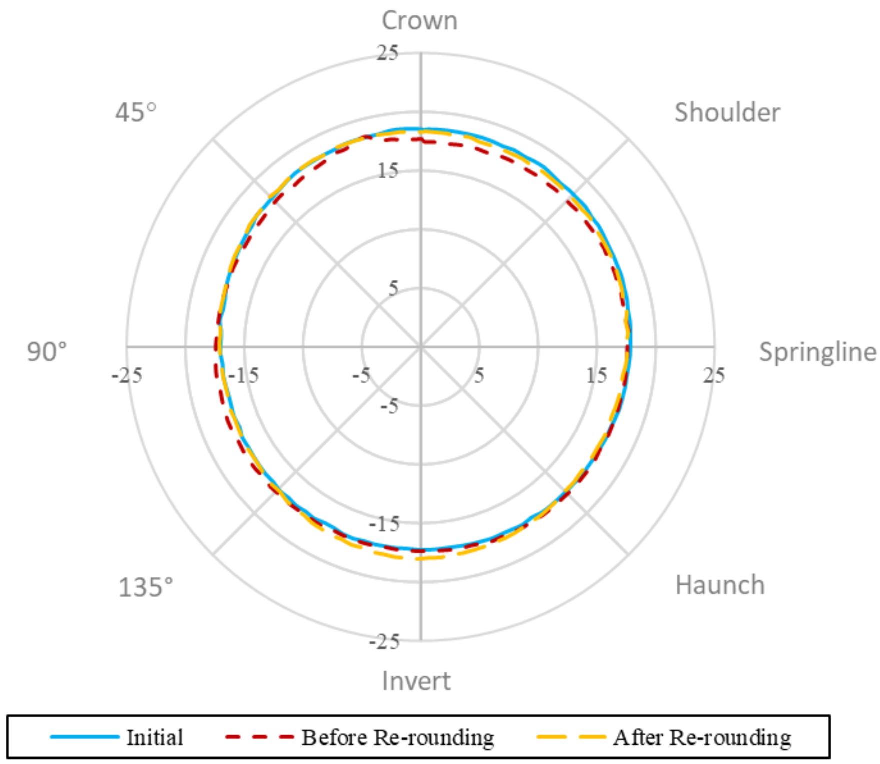
Cross Section G-G - Test Pipe 3



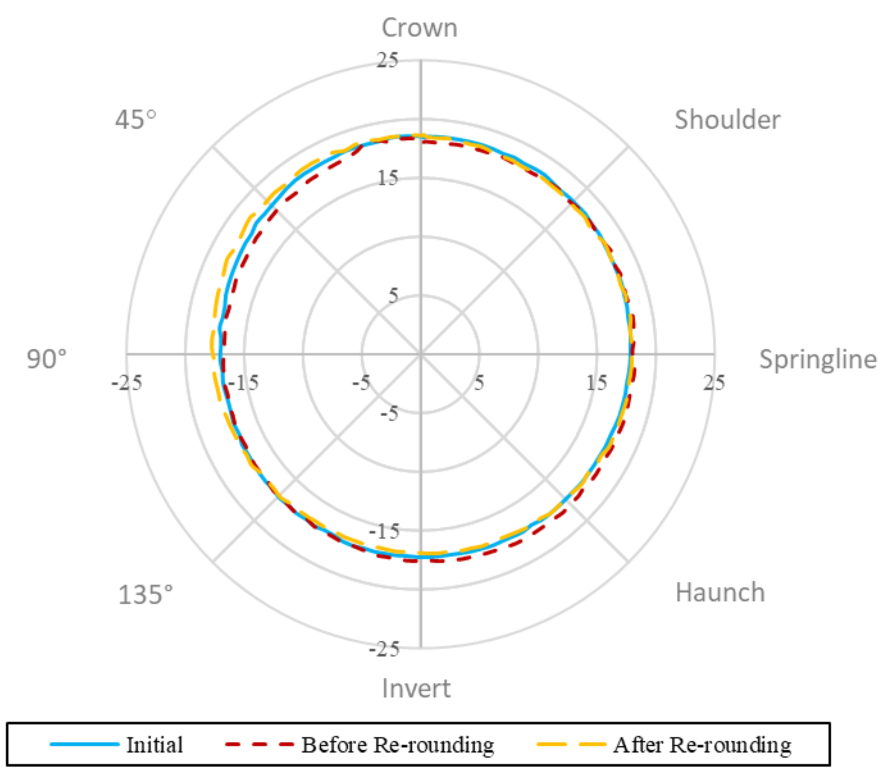
Cross Section H-H - Test Pipe 3

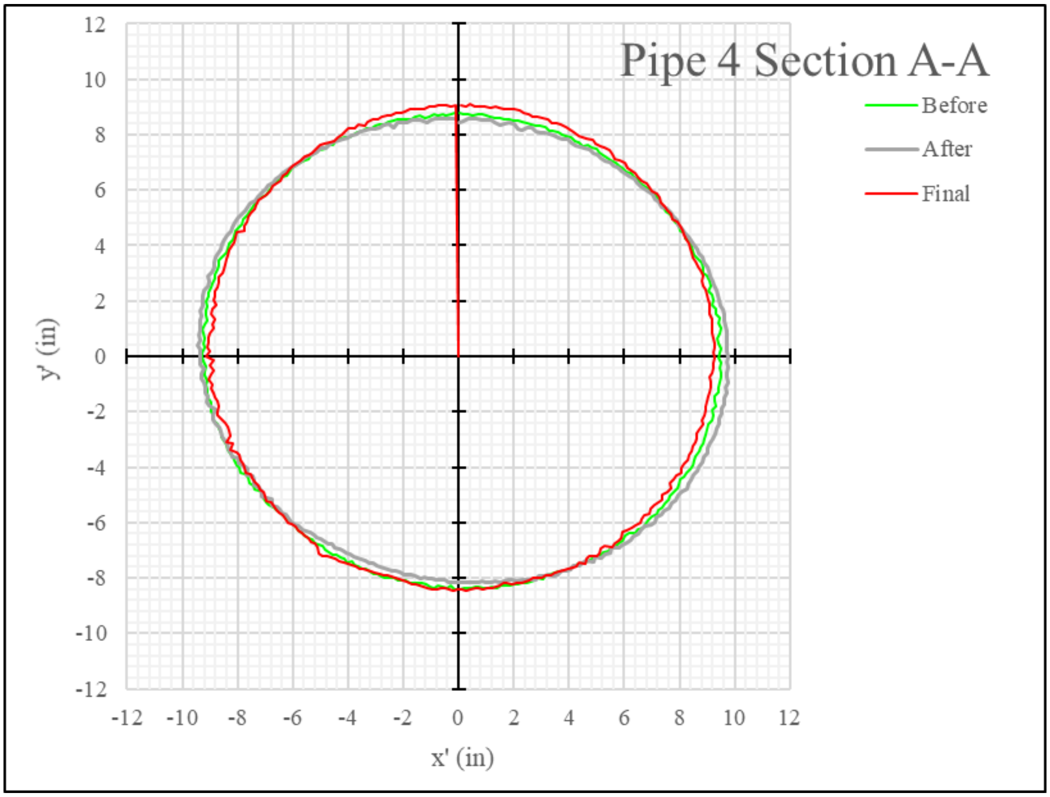


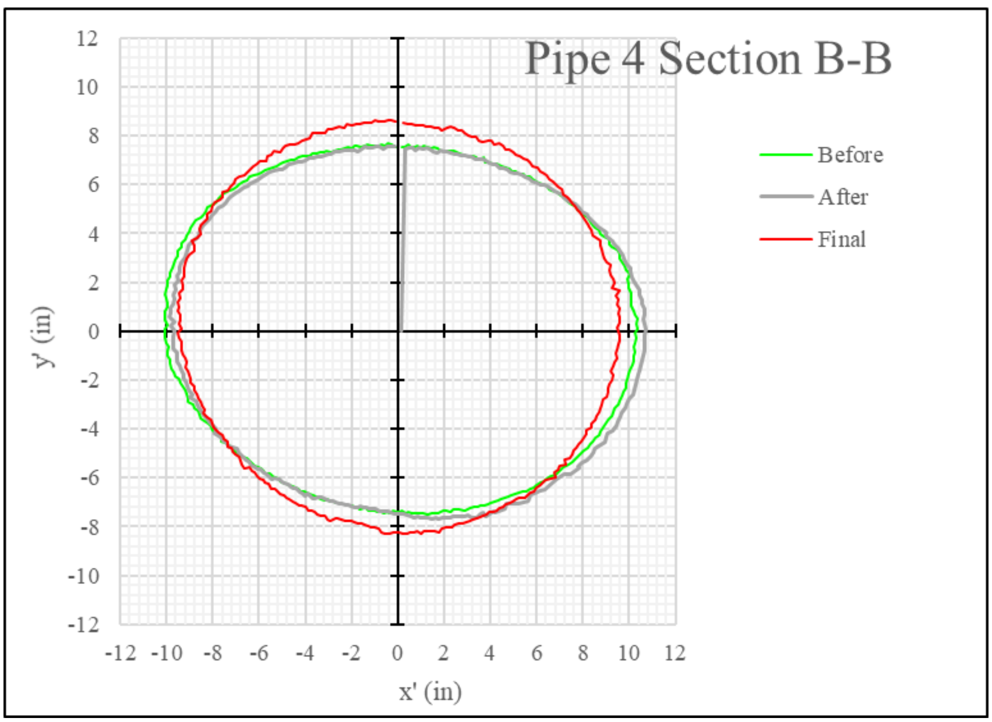
Cross Section I-I - Test Pipe 3

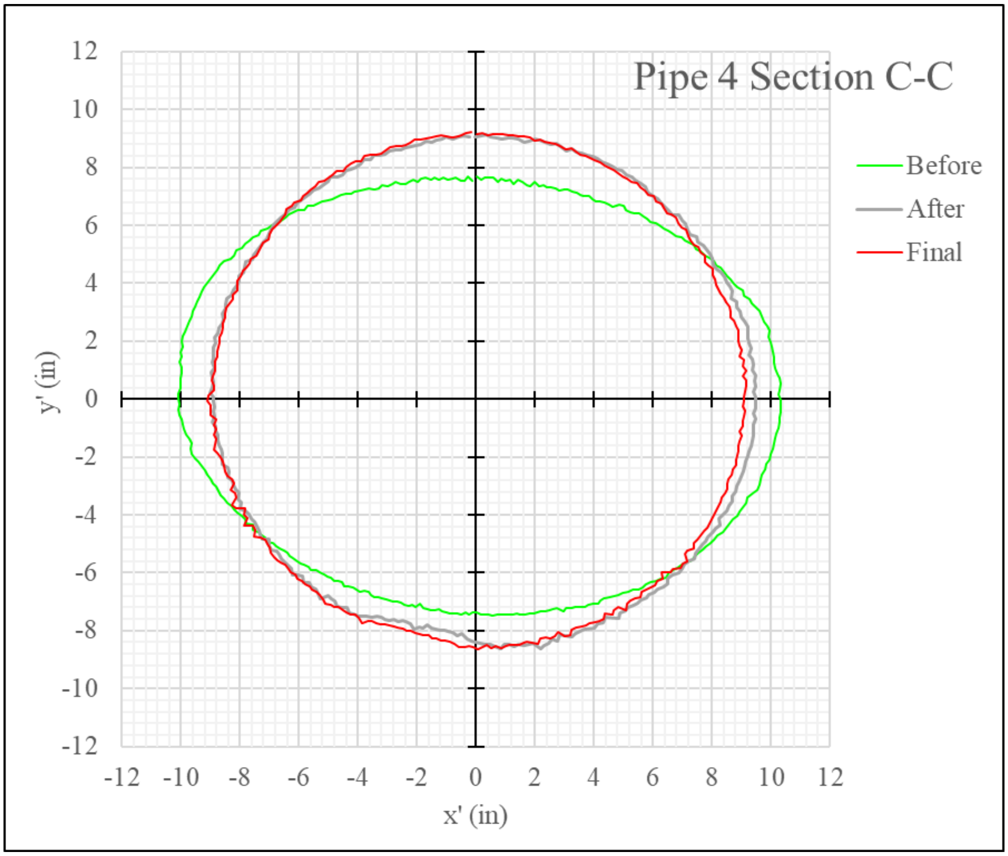


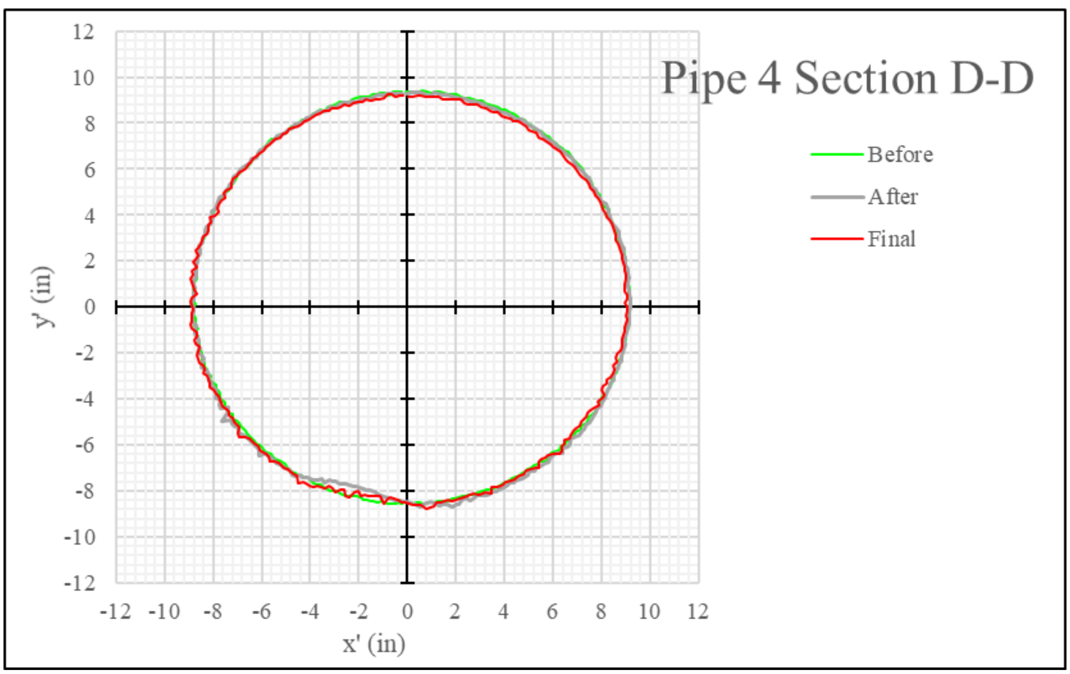
Cross Section J-J - Test Pipe 3

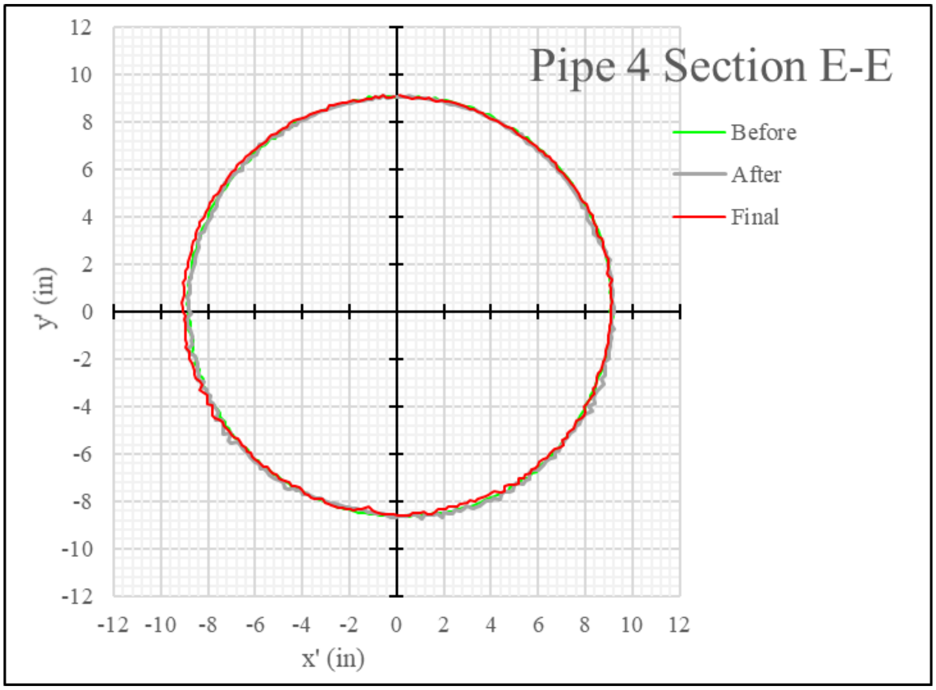



Pipe 4 Section A-A
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12


Pipe 4 Section B-B
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12


Pipe 4 Section C-C
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12


Pipe 4 Section D-D
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12


Pipe 4 Section E-E
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
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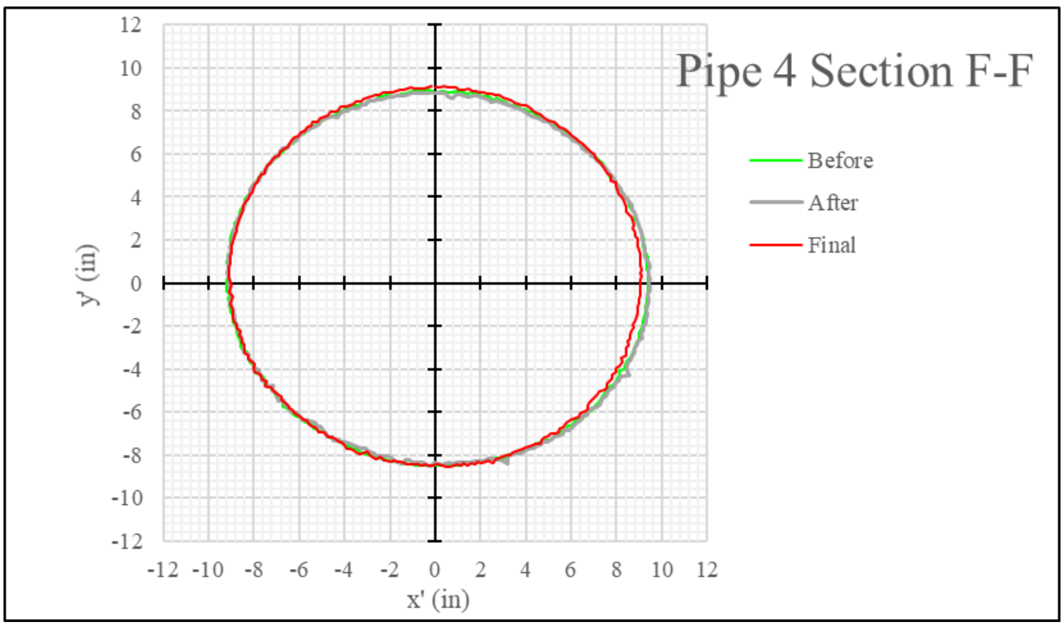
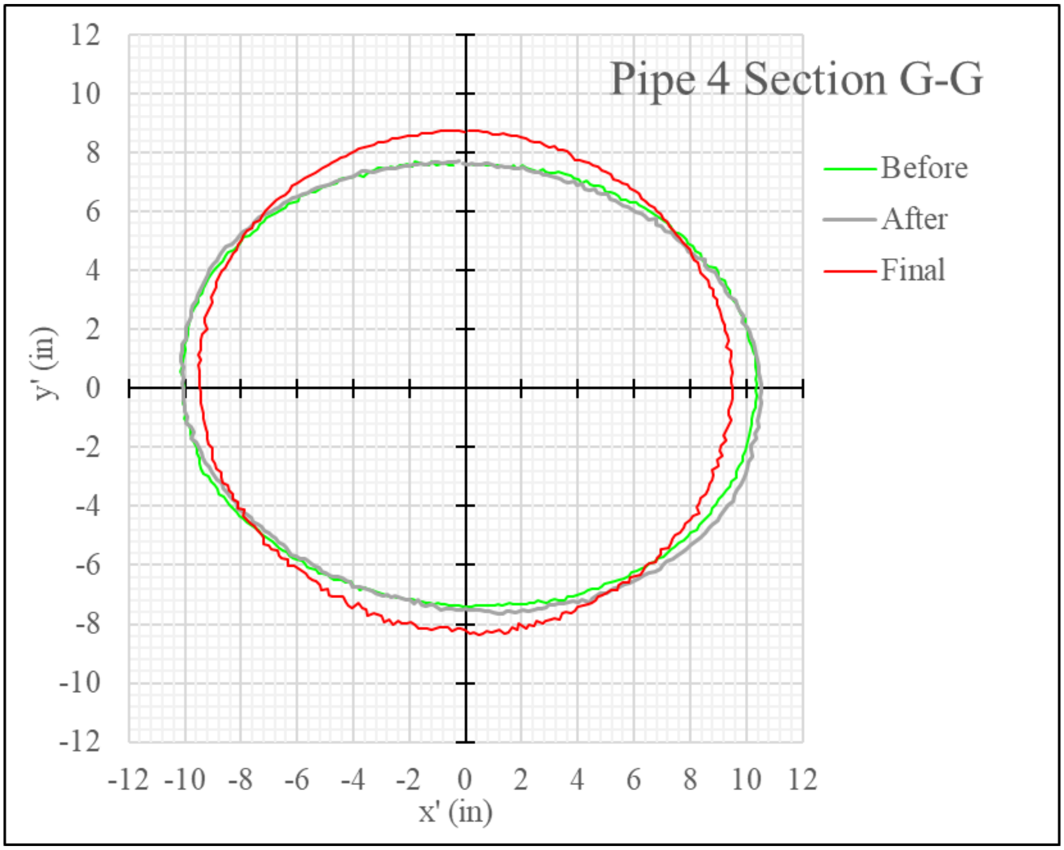
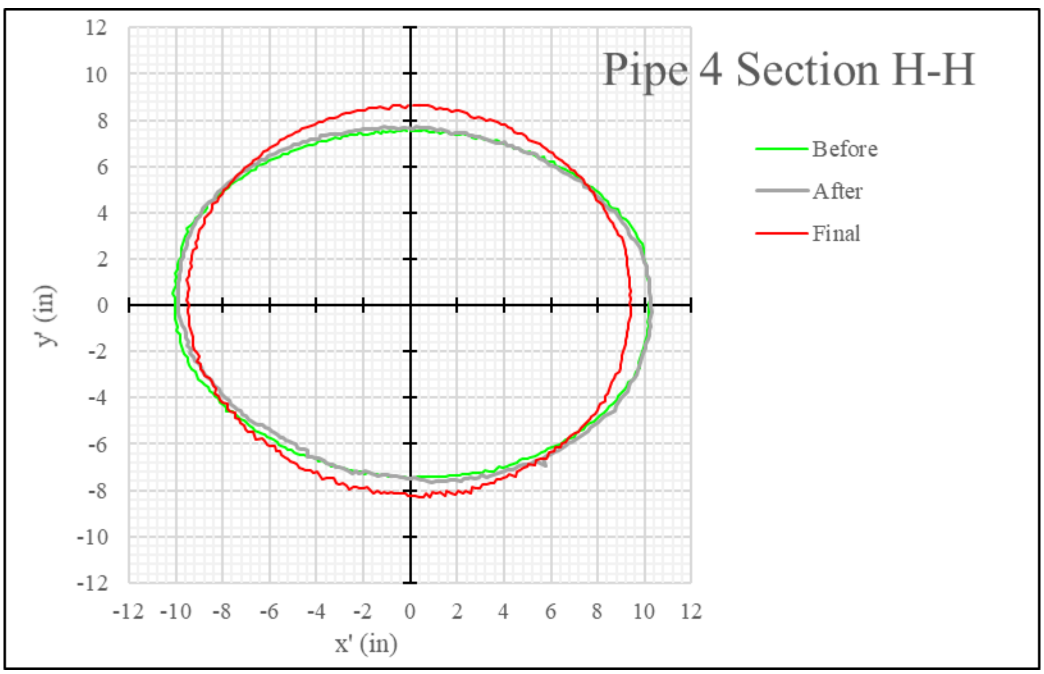
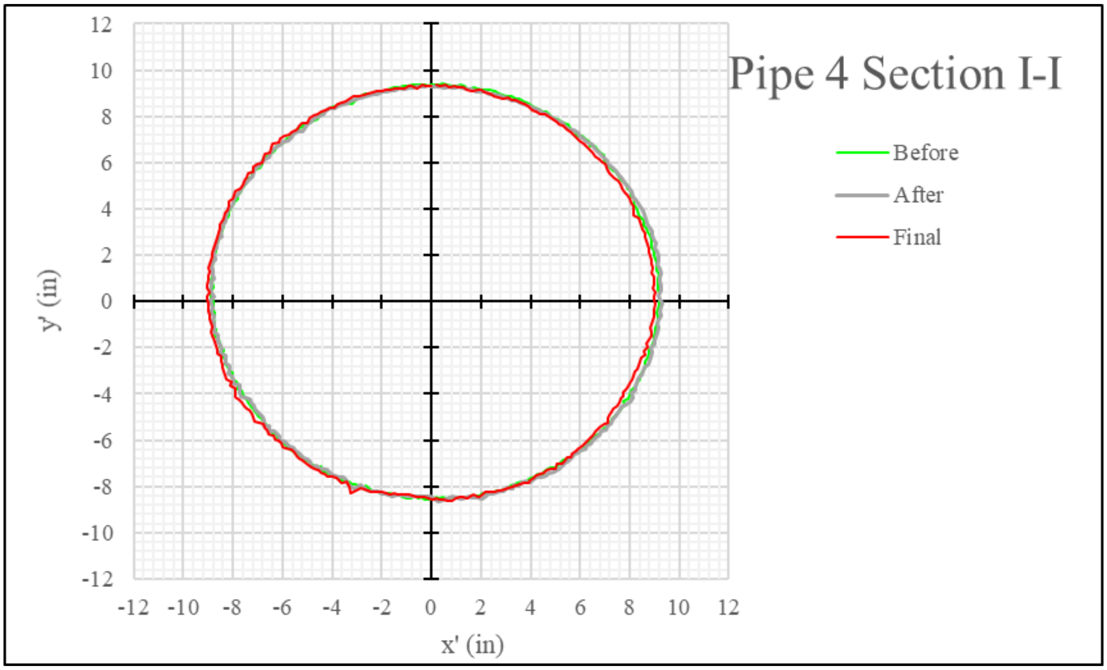

Pipe 4 Section F-F
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12

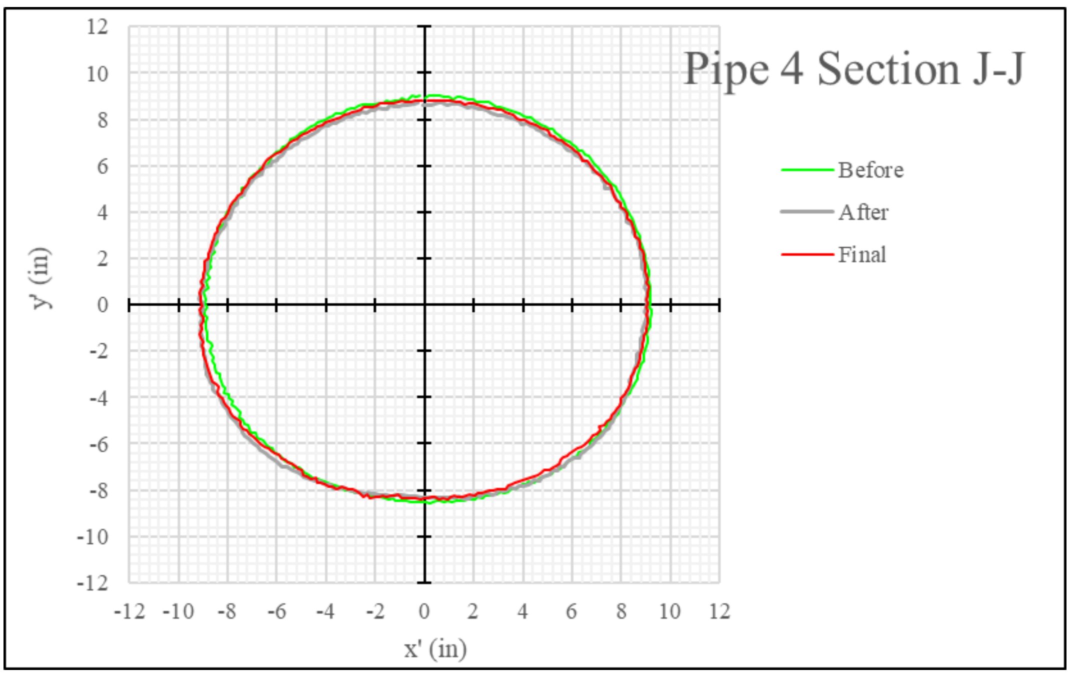


Pipe 4 Section G-G
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12



Pipe 4 Section H-H
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12


Pipe 4 Section I-I
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12


Pipe 4 Section J-J
Before
After
Final
y' (in)
x' (in)
12
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-12 -10 -8 -6 -4 -2 0 2 4 6 8 10 12

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