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"DIGITAL PIGGING" AS A BASIS FOR IMPROVED PIPELINE STRUCTURAL INTEGRITY EVALUATIONS

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ABSTRACT

This paper describes the application of "digital pigging" procedures for converting field measurements of pipeline geometry (e.g., top of pipe survey profiles), results from geometry pig surveys, or analytically generated pipeline centerline profiles into corresponding profiles of pipeline curvature and bending strain. Application of digital pigging procedures to pipeline elevation and/or inclination profiles developed from accelerometer based geometry pigs provides a basis for performing the additional calculations required to develop bending strain profiles which may not be a part of the geometry survey deliverable but are required for pipeline structural integrity evaluations. This paper presents examples of digital pig runs over analytical pipe centerline profiles to illustrate the important effects of feature length, pig length and curvature gage length. Comparisons of the results from digital pig runs over actual geometry pig data profiles and digital pig runs over the corresponding known analytical profiles will illustrate how basic pattern recognition concepts can be used as a basis for improved synthesis of real pig data signatures. This paper also presents examples of digital pigging calculations performed on geometry pig survey data that show how low-pass filtering can be used to reduce the effects of noise in the survey data as well as the influence of curvature gage length on the computed curvature/bending strain profiles.

INTRODUCTION

The offshore section of BP Exploration Alaska, Inc.'s (BP's) Northstar oil pipeline is a strain-based design and part of the design involves periodic monitoring of the pipeline geometry for bending strain and comparison of the bending strain to limit strain criteria. The monitoring program started with a baseline Geopig [1] run in April 2000 shortly after construction and additional follow-up Geopig runs in December 2001, February 2002 and November 2002. In April 2003, another inertial survey was performed as part of a Vectra [2] pig run.

In October 2003 and again in November 2004, BP commissioned Weatherford Pipeline & Specialty Services to perform geometry surveys of the Northstar oil pipeline using the SAAM pig [3] which is an accelerometer based geometry pig. Three SAAM pig surveys were performed on October 16th, 17th and 19th, 2003 (Surveys 1, 2 and 4) and three SAAM pig surveys were performed on November 13th and 14th, 2004 (Surveys 8, 9 and 10). Because the Weatherford survey report deliverables did not include pipe bending strain profiles, BP engaged SSD, Inc. to perform bending strain calculations using the Weatherford elevation and inclination profile data. The SSD work deliverables included a FORTRAN program called *SSDigiPig* which can be used to perform calculations required to convert pipe elevation or inclination profiles into a profile of pipe curvature/bending strain.

DIGITAL PIGGING CONCEPT

The term "digital pigging" is used to describe numerical calculations performed on pipeline geometry profiles including top of pipe survey profiles, geometry pig survey results and analytically generated profiles e.g., buried pipeline deformation analysis results (see Reference [4]). Figure 1 provides a schematic illustration of a real geometry pig traversing a pipeline profile and a corresponding digital pig traversing a digital analytical pipeline profile. Digital pigging applications include numerical integration (e.g., Euler integration) of pipeline pitch and azimuth profiles to compute three-dimensional pipeline coordinate profiles and numerical differentiation of pipeline pitch and azimuth profiles to compute profiles of vertical and horizontal pipeline curvature [5]. In order to compute pipeline bending strain based on a pipe elevation profile, two passes (do loops) over the pipeline profile are required.

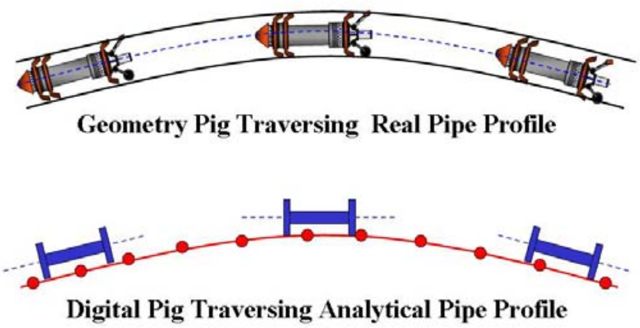

Figure 1. Overview of Digital Pig Concept

Figure 2 illustrates the calculations performed in a first pass loop over a pipe elevation (Y) profile to compute a profile of the pitch angle (θ) which is basically the slope inclination of the pig. Note that the pitch angle θ is directly related to the cup-to-cup length of the pig (L_{pig}). In cases where the location of either the front or back cup support of the pig is between elevation data points or pipe nodes, interpolation is required (e.g., using a beam element shape function). In situations where the pitch angle is directly available (e.g., based on a geometry pig run or based on inclinometer measurements), the first pass loop over the profile can be skipped.

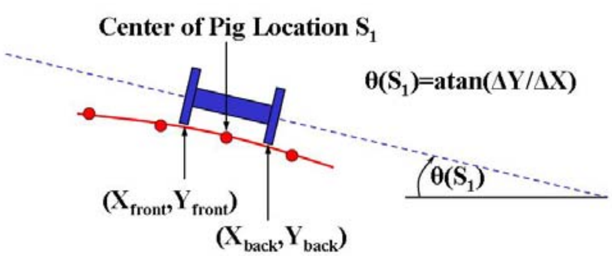

Figure 2. First Pass Calculations to Compute Profile of Pitch Angle θ(S) Based on Rise/Run Over Length of Digital Pig

Figure 3 illustrates the calculations performed in a second pass loop over a pipe pitch (θ) profile to compute a profile of the vertical curvature. The vertical curvature Ψ_V is the numerical derivative of the pitch profile and hence is a function of the curvature gage length (L_{gage}). The vertical curvature is directly proportional to vertical bending strain (i.e., $\varepsilon_b=\Psi_V \cdot D/2$, where D is the pipe diameter). The calculations can easily be extended to three-dimensional pipeline profiles to compute horizontal curvature base on the azimuth profile of the pig.

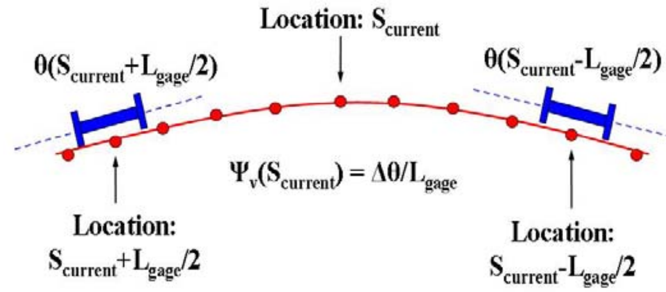

Figure 3. Second Pass Calculations to Compute Profile of Vertical Curvature $\Psi_v(S)$ Based on Pitch Change Over Gage Length

The calculations described above for computing profiles of vertical pipeline bending strain based on pipe elevation and inclination profiles have been implemented in a FORTRAN program called *SSDigiPig*. The program has been applied to pipeline profile data measured by SAAM pig surveys of the Northstar oil pipeline. The program also includes an option to filter the pitch and bending strain profiles based on finite impulse response (FIR) filtering techniques as described in Reference [6]. Overlay comparison of filtered and unfiltered profiles provides a useful basis for evaluating specific pipeline geometry features.

EVALUATION OF ANALYTICAL PROFILES

One of the work tasks undertaken as part of the Northstar pipeline work was to use the *SSDigiPig* program to study the "pig signatures" associated with known analytical geometry profiles. Evaluation of the bending strain profiles of known geometries based on different curvature gage lengths can lead to an improved understanding of the bending strain profile corresponding to other, general pipeline features. This section describes some example profiles, and presents the corresponding "pig signature" plots.

Example 1: Miter Bend. The geometry of the analytical "miter" bend consists of a 50-foot run section of 10-inch pipe with a pitch (slope) of $+1^o$, followed by a 2^o overbend with bend radius of 5D (53.75 inches or 4.479 feet), followed by another 50-foot run section with a pitch (slope) of -1^o. Note that a 5D bend radius corresponds to a curvature of 0.2233 ft^{-1} and an *apparent* "exact" (theoretical) bending strain of 10%. A plot of the along-the-pipe distance coordinate (S) vs. the pipe elevation coordinate (Y) for this "miter geometry" is shown in Figure 4(a) while Figure 4(b) presents the corresponding pitch profile. The *SSDigiPig* program was used to perform bending strain calculations over this geometry using gage lengths (L_{gage}, i.e., the length of pipe over which cuvature is measured) of 2 feet, 6 feet, and 12 feet. Plots of the resulting bending strain profiles are shown in Figure 4(c) together with the "exact" bending strain profile. The main observations from these plots are that the maximum computed bending strain for a given gage length is equal to the product of the pipe radius (r) and the curvature computed as $\Delta\theta/L_{gage}$.

Example 2: Cold Bend. The geometry of the analytical cold bend consists of a 50-foot run section of 10-inch pipe with a pitch (slope) of +1°, followed by a 2° overbend with a bend radius of 18D radius (193.5 inches or 16.125 feet), followed by another 50-foot run section with a pitch (slope) of -1°. An 18D bend radius corresponds to a curvature of 0.0620 ft^{-1} and an *apparent* "exact" (theoretical) bending strain of 2.78%. A plot of the along-the-pipe distance coordinate (S) vs. the pipe elevation coordinate (Y) for this geometry is shown in Figure 5(a) while Figure 5(b) presents the corresponding pitch profile. The *SSDigiPig* program was used to perform bending strain calculations over this geometry using gage lengths (L_{gage}) of 2 feet, 6 feet, and 12 feet. Plots of the resulting bending strain profiles are shown in Figure 5(c) together with the "exact" bending strain profile. Again, the main observations from these plots are that the maximum computed bending strain for a given gage length is equal to the product of the pipe radius (r) and the curvature computed as $\Delta\theta/L_{gage}$.

BENDING STRAIN CALCULATION AT KNOWN RISER

Although as-built pipeline bends (i.e., elbows, induction bends or cold bends) do not necessarily represent deformations that are of concern for pipeline geometry monitoring, the signatures developed based on data recorded by geometry pigs as they traverse such bends can provide useful information toward understanding other real pipe deformations. This section illustrates this issue.

Figure 6(a) shows the X-Y coordinate profiles for the riser section of the Northstar oil pipeline at the shore crossing location. Figure 6(b) shows the corresponding bending strain vs. pipe distance profiles at this location. Note that the gage length selected for curvature calculation was 12 feet (a typical value for curvature screening). The riser bends are induction bends with a radius of 5D (53.75 inches or 4.479 feet). This bend radius corresponds to a curvature of 0.2233 ft^{-1} and an equivalent "exact" (theoretical) bending strain of 10%. The main observation from these plots is that the maximum computed bending strain at the sag and over bends is approximately ±6% which is about 60% of the "exact" value.

In order to illustrate the bending strain "signature" these induction bends would be expected to exhibit based on digital pigging curvature calculations, an evaluation of an analytical riser section was also undertaken. The geometry of the analytical riser was selected to be similar to the shore crossing riser. The geometry consists of a horizontal run section followed by a 90° sagbend with a 5D radius, followed by a vertical run section, then a 90° overbend with a 5D radius, followed by another horizontal run section. A plot of the X-Y coordinate profile for this riser geometry is shown in Figure 7(a). The bending strain calculations were run over the S-Y coordinates of this riser using gage lengths of 2, 4, 6, 8 and 12 feet. Plots of the resulting bending strain profiles are shown in Figure 7(b) together with the "exact" bending strain profile. It is important to note that the maximum computed bending strain at the sag and over bends of this analytical riser geometry using a 12 foot gage length are approximately ±6% (about 60% of the exact value), which is consistent with values computed for the real shore crossing riser using the same gage length. This relatively significant under-prediction of the strain results from the use of a 12 foot gage length to monitor a short region of high curvature (the bends are approximately 7 feet long).

CALCULATIONS AT A SCREENED LOCATION

Several relatively high curvature locations along the Northstar oil pipeline were selected for more detailed review based on curvature/bending strain sceeening. Based on a review of the bending strain profiles, it was decided to screen the data to focus on locations where the maximum or minimum *unfiltered* bending stain equaled or exceeded ±0.12%, excluding any locations where the bending strain exceeded the screening value due to an obvious, spurious data "spike". For reference, a strain of 0.12% corresponds to an elastic stress of about 36 ksi (assuming E=30,000 ksi). Also, the Northstar pipeline limit strain criteria allow bending strains of 1.2% under operational conditions. Therefore, the screening bending strain value of 0.12% corresponds to $1/10^{th}$ of the 1.2% strain limit for operational conditions.

Figures 8(a), 8(b) and 8(c) present plots of the pipe elevation, filtered/unfiltered pitch and filtered/unfiltered bending strain profiles, respectively from Survey 8 for a pipe distance of 250 feet centered on Screened Location 13. The bending strain was calculated using a gage length of 12 feet. The frequency content of the pitch and curvature data was evaluated in the frequency domain using a Fourier Amplitude Spectrum (FAS). The frequency axis of the FAS spans from 0 Hz up to the Nyquist frequency of 11.42 Hz (half of the sampling frequency of 22.84 Hz). The frequency axis can be converted to a wave length axis by dividing the average pig velocity (about 10.3 feet/sec) by the frequency value. Based on experience and engineering judgement, the pitch and strain profiles were low-pass filtered to remove high frequency/short wave-length features which are a manifestation of pig motion/vibration in the acceleration data. The selected filter was a 150-term, low-pass finite impulse response (FIR) filter with a cut-off frequency of 1.5 Hz (corresponding to a cut-off full sine wave length of about 6.67 feet or a bending lobe length of 3.33 feet). The filter was applied to the data in the forward and backward direction in order to provide zero phase distortion. Figures 8(b) and 8(c) which overlay the unfiltered and filtered pitch and strain profiles show that the filtered profiles still capture all of the significant "lobes" while exhibiting a significant reduction in the overall "fuzziness" of the profiles.

For the same screened location, Figures 9(a), 9(b) and 9(c) present overlay plots of the pipe elevation, filtered pitch and filtered bending strain profiles, respectively from Surveys 8, 9 and 10. Figure 9(d) presents an overlay comparison of the average bending strain profiles from the October 2003 and November 2004 surveys. The overall observations from Figure 9 are that the degree of difference between the Survey 8, 9 and 10 profiles (e.g., the vertical difference between the individual profile curves) is most significant for the elevation profiles (which are based on numerical integration of the pitch profiles) and least significant for the bending strain profiles (which are based on numerical differentiation of the pitch profiles). This indicates that the reliability of run-to-run or year-to-year comparisons can be increased by comparing pitch profiles in favor of or in addition to elevation profiles and by comparing bending strain profiles in favor of or in addition to pitch profiles.

CONCLUSIONS

The main observations from this work are as follows:

- For short angle change features such as the analytical 2° miter bend and the analytical 2° cold overbend, the maximum curvature that can be measured for a given gage length is equal to $\Delta\theta/L_{gage}$. The length of the curvature/bending strain signature increases with increasing gage length.
- For the vertical riser example with a 90° sagbend and overbend, the maximum bending strains computed at the bends using gage lengths of 2 and 6 feet are approximately equal to the "exact" (theoretical) value. The maximum bending strain computed at the sagbend and overbend using a gage length of 12 feet is approximately 58% of the "exact" value.
- The maximum bending strains computed in the bends of the real shore crossing riser and those computed for the bends of the analytical riser are quite consistent. This indicates the bending strain/curvature signature from the real riser is consistent with what would be expected from a 5D induction bend, even though the bending strains/curvatures are less than the "exact" (theoretical) values.
- The maximum bending strains computed at the sag and over bends of the analytical riser using gage lengths of 2 and 4 feet are approximately equal to the "exact" value. The maximum bending strains computed at the sag and over bends using gage lengths of 6, 8 and 12 feet are approximately 90%, 80%, and 60% of the "exact" value, respectively.
- The bending strain/curvature signatures from the analytical riser for each gage length have a "lobed" shape with a narrower peak and wider base than the "blocked" shape of the "exact" bending strain/curvature profile. The lobe width is wider for longer gage lengths. For all gage lengths, the bending strain values at the distance coordinates corresponding to the beginning and end of each bend are equal to approximately 50% of the maximum "exact" bending strain.
- The approach of running a "digital pig" over analytically generated pipe elevation profiles and computing curvature/bending strain using a range of gage lengths provides a useful basis for understanding the curvature/bending strain profiles that can be expected for various real pipeline features such as accidentally mitered welds, cold bends, risers, etc. These comparisons indicate that it is not necessary to compute the exact curvature of a given geometry provided that the bending strain signature corresponding to a given gage length can be recognized.
- Comparison of figures which overlay the unfiltered and filtered pitch and strain profiles show that the filtered profiles still capture all of the significant "lobes" while exhibiting a significant reduction in the overall "fuzziness" of the profiles. Careful selection of the filter parameters is required to insure that meaningful pipeline features are not removed by filtering.
- As shown in Figure 8, the observed degree of difference between the Survey 8, 9 and 10 profiles (e.g., the vertical difference between the individual profile curves) is most significant for the elevation profiles (which are based on numerical integration of the pitch profiles) and least significant for the bending strain profiles (which are based on numerical differentiation of the pitch profiles). This indicates that the reliability of run-to-run or year-to-year comparisons can be increased by comparing pitch profiles in favor of or in addition to elevation profiles and by comparing bending strain profiles in favor of or in addition to pitch profiles.
- A total of 3 pig runs per year were performed for the Year 2003 and Year 2004 SAAM pig surveys. Comparisons showed considerable run-to-run variability of the SAAM pig data for a given year. Therefore, year-to-year comparisons were made based on average bending strain profiles computed from a given year's runs in order to minimize/smooth out the effects of run-to-run variations. An improved characterization of the pipeline geometry could be obtained by averaging the profiles from more than 3 runs for a given annual set (i.e., the average profile from 6 runs would provide an improved characterization of the geometry than the average profile from 3 runs). Examination of individual profiles prior to averaging might provide a basis for removing a section of a given run which exhibited significant deviations from the other runs in the set (e.g., removing an "outlier") prior to averaging. Therefore, it was recommended that BP undertake more than 3 (e.g., 4 to 6) runs for future SAAM pig rsurveys in order to provide a better characterization of the pipeline geometry.

ACKNOWLEDGEMENTS

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[6] "*Programs for Digital Signal Processing*", IEEE Press, New York, 1979, Algorithm 5.2.

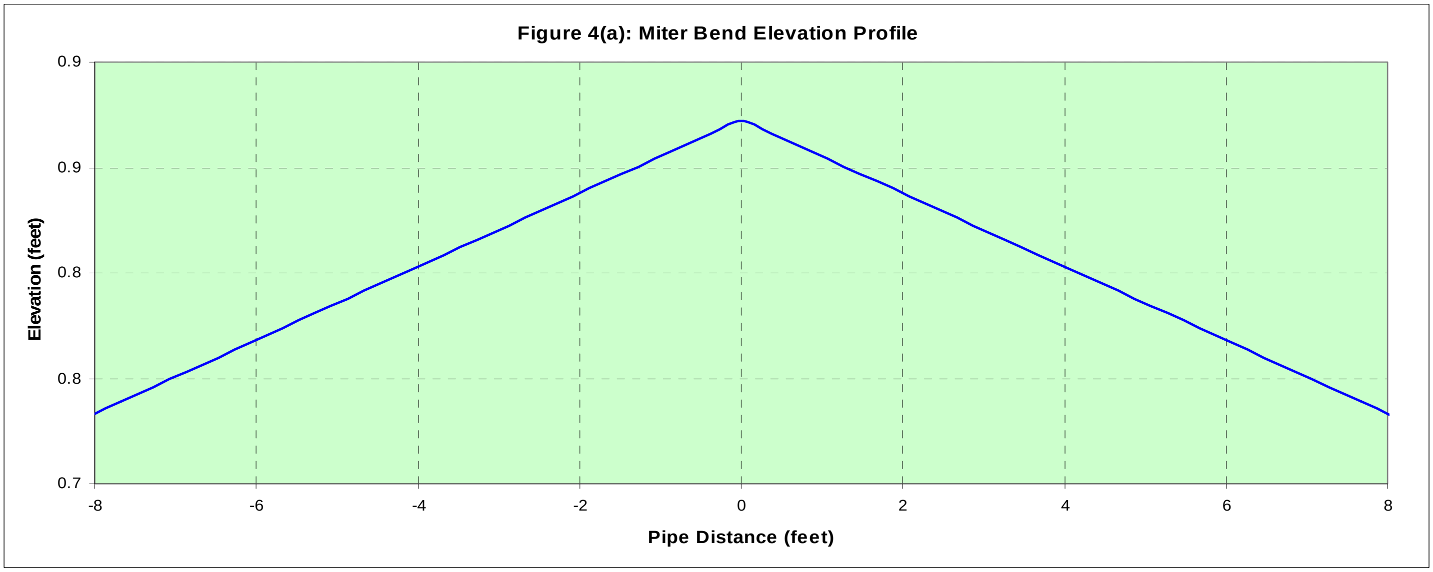


Figure 4(a): Miter Bend Elevation Profile
Elevation (feet)
0.9
0.9
0.8
0.8
0.7
-8
-6
-4
-2
0
2
4
6
8
Pipe Distance (feet)

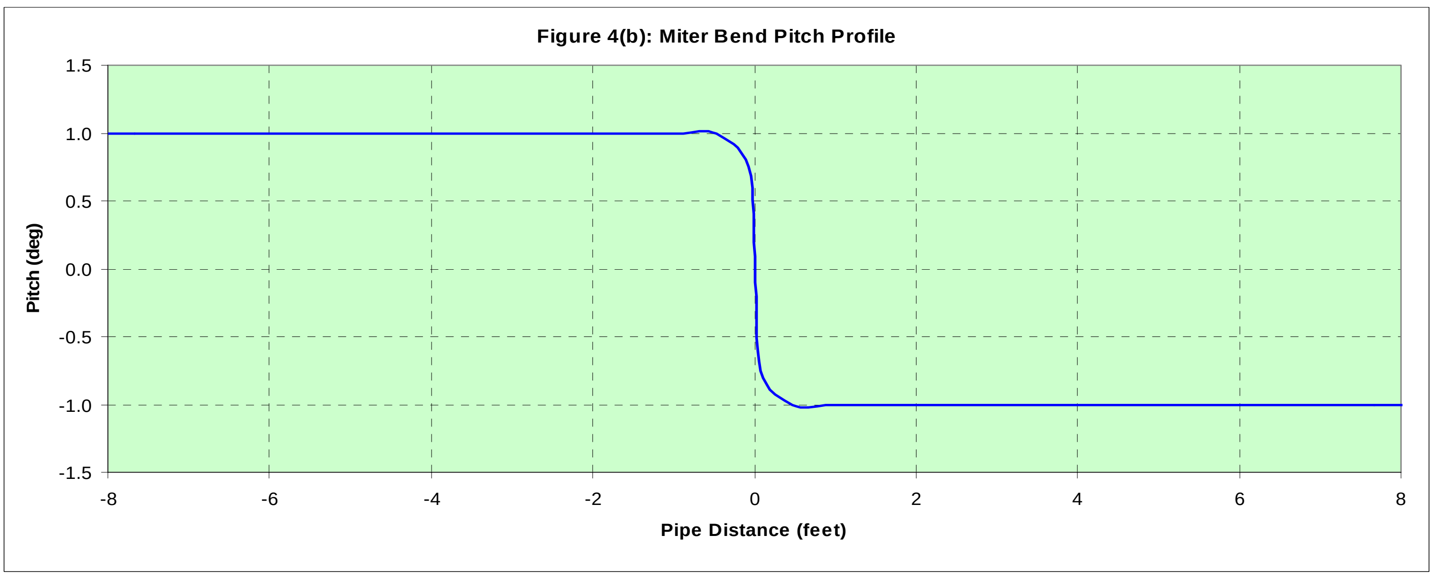


Figure 4(b): Miter Bend Pitch Profile
Pitch (deg)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-8
-6
-4
-2
0
2
4
6
8
Pipe Distance (feet)

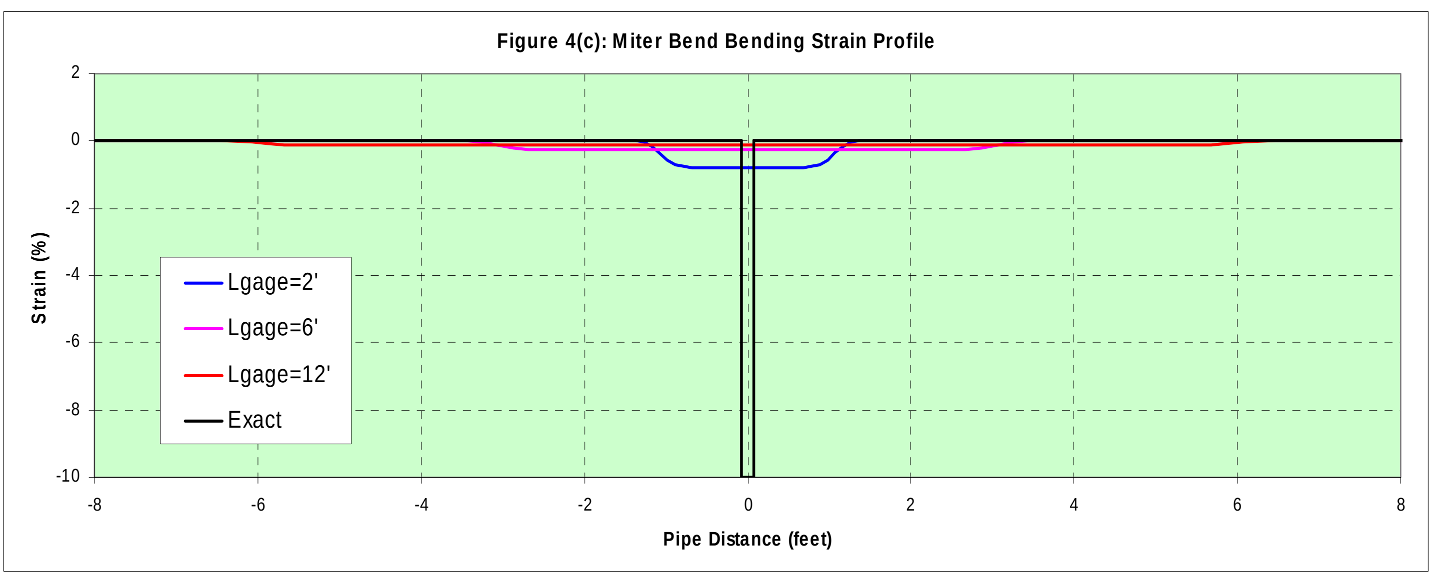


Figure 4(c): Miter Bend Bending Strain Profile
Strain (%)
2
0
-2
-4
-6
-8
-10
Lgage=2'
Lgage=6'
Lgage=12'
Exact
-8
-6
-4
-2
0
2
4
6
8
Pipe Distance (feet)

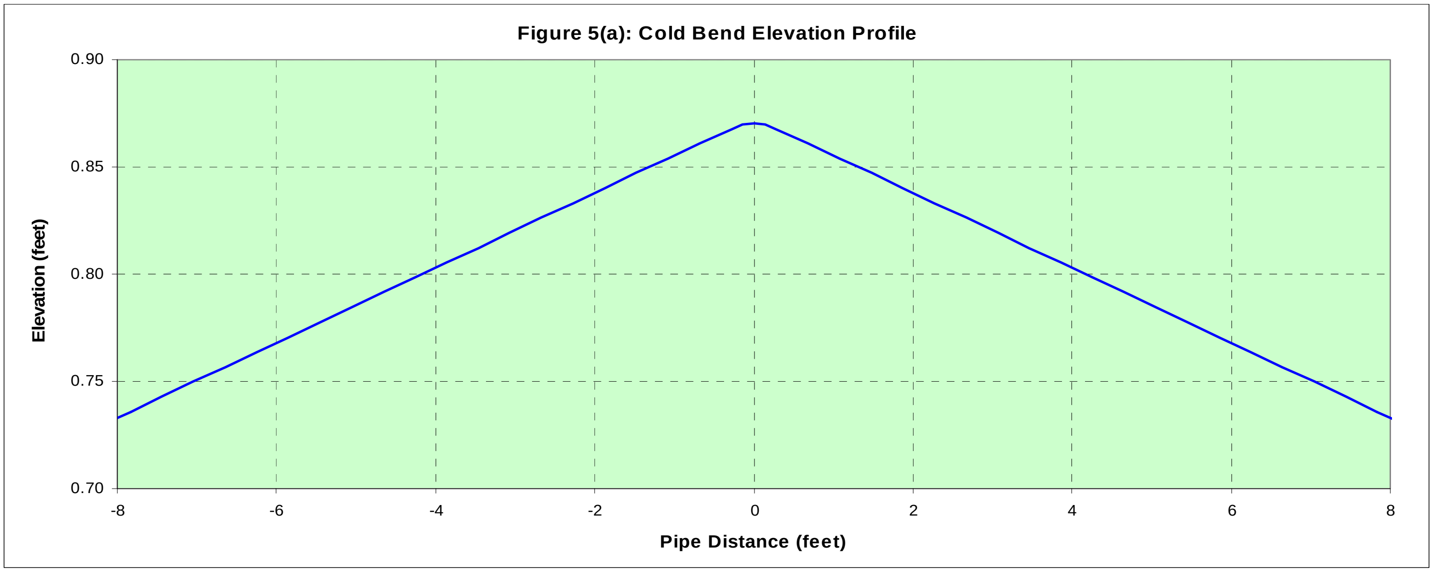


Figure 5(a): Cold Bend Elevation Profile
Elevation (feet)
Pipe Distance (feet)

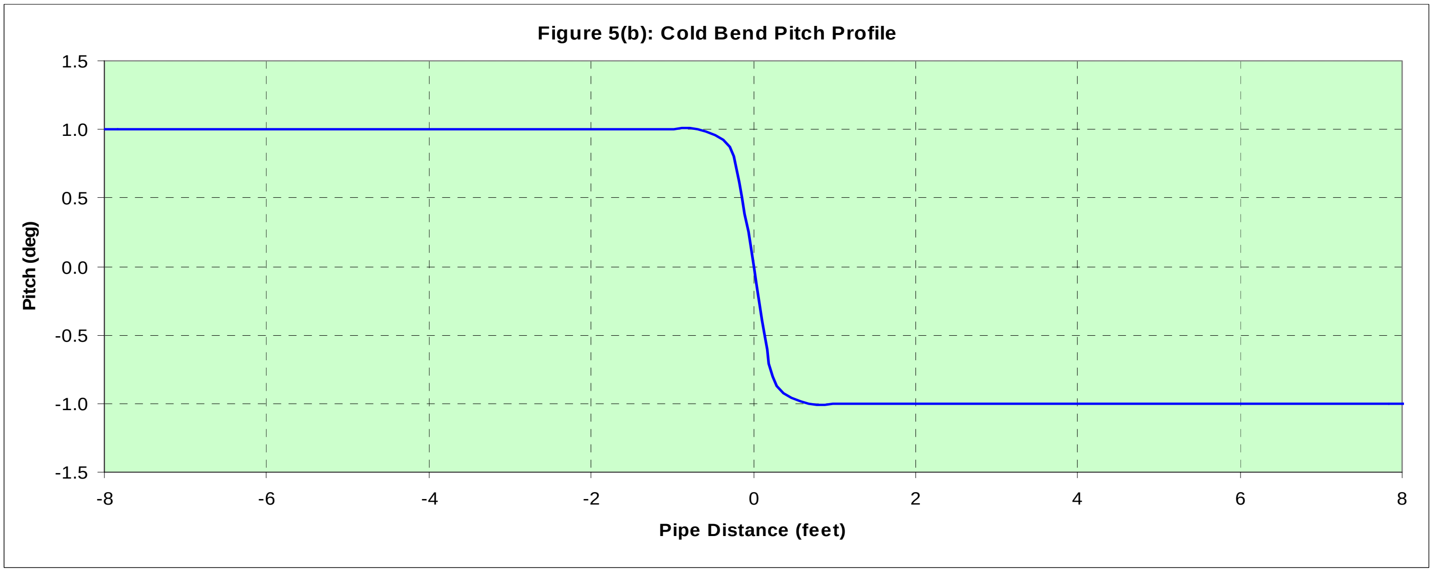


Figure 5(b): Cold Bend Pitch Profile
Pitch (deg)
Pipe Distance (feet)

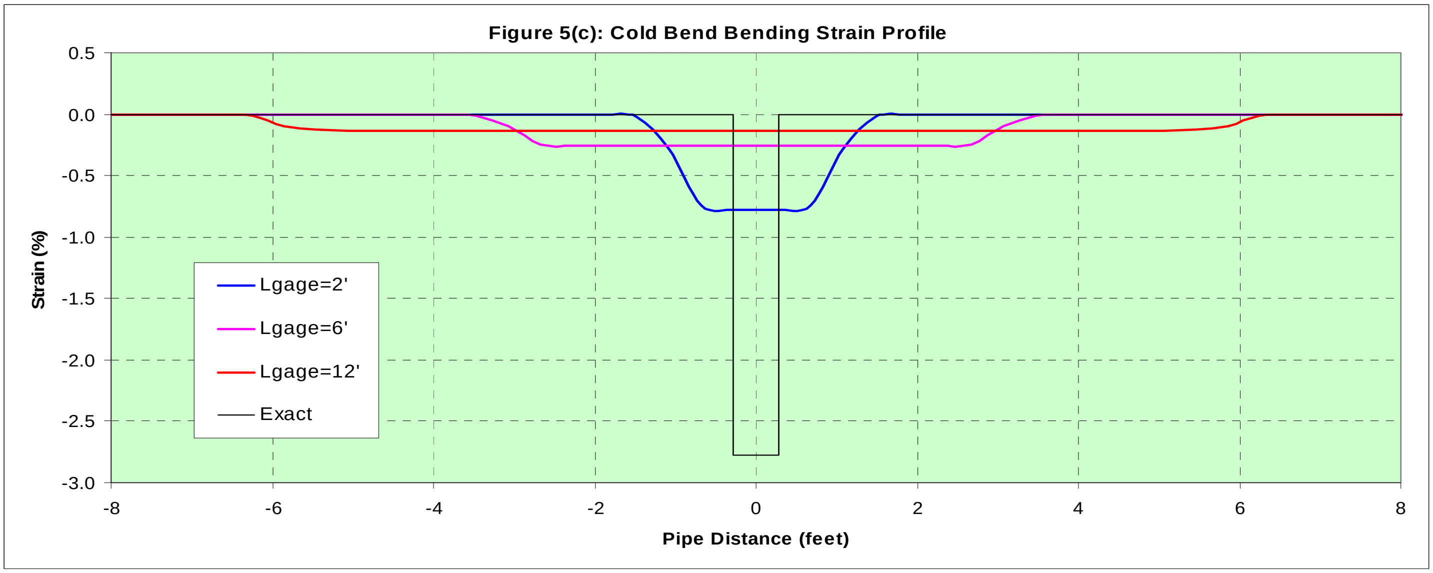


Figure 5(c): Cold Bend Bending Strain Profile
Strain (%)
Pipe Distance (feet)
Lgage=2'
Lgage=6'
Lgage=12'
Exact

Figure 6(a) Elevation Profiles at Riser

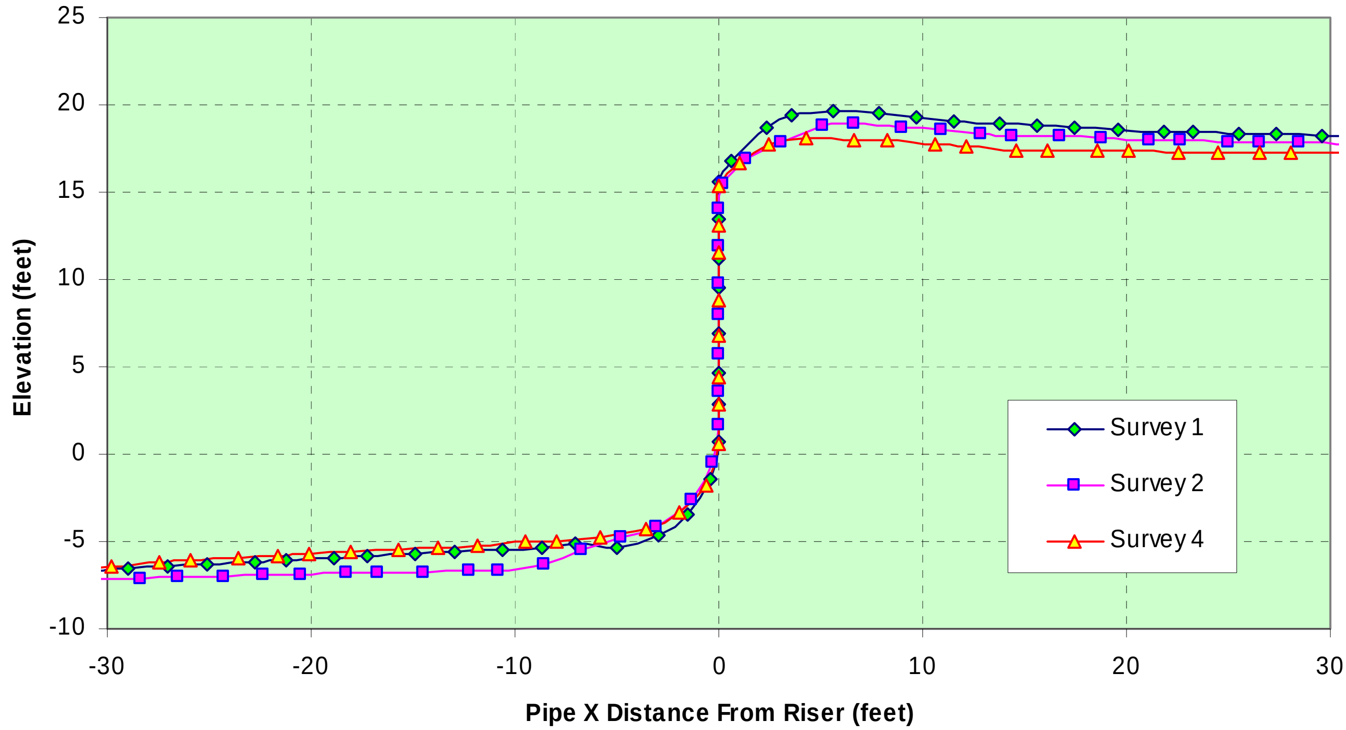
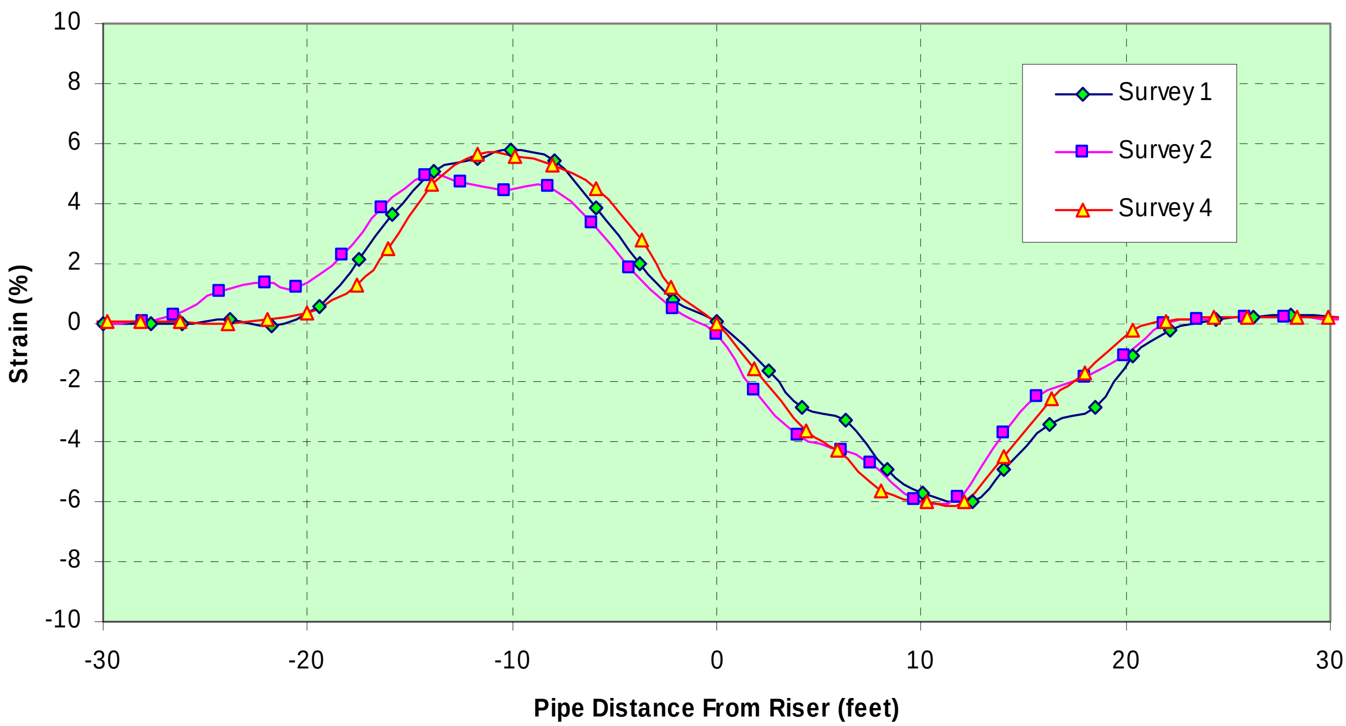


Figure 6(b) Bending Strain Profiles at Riser, Lgage=12'



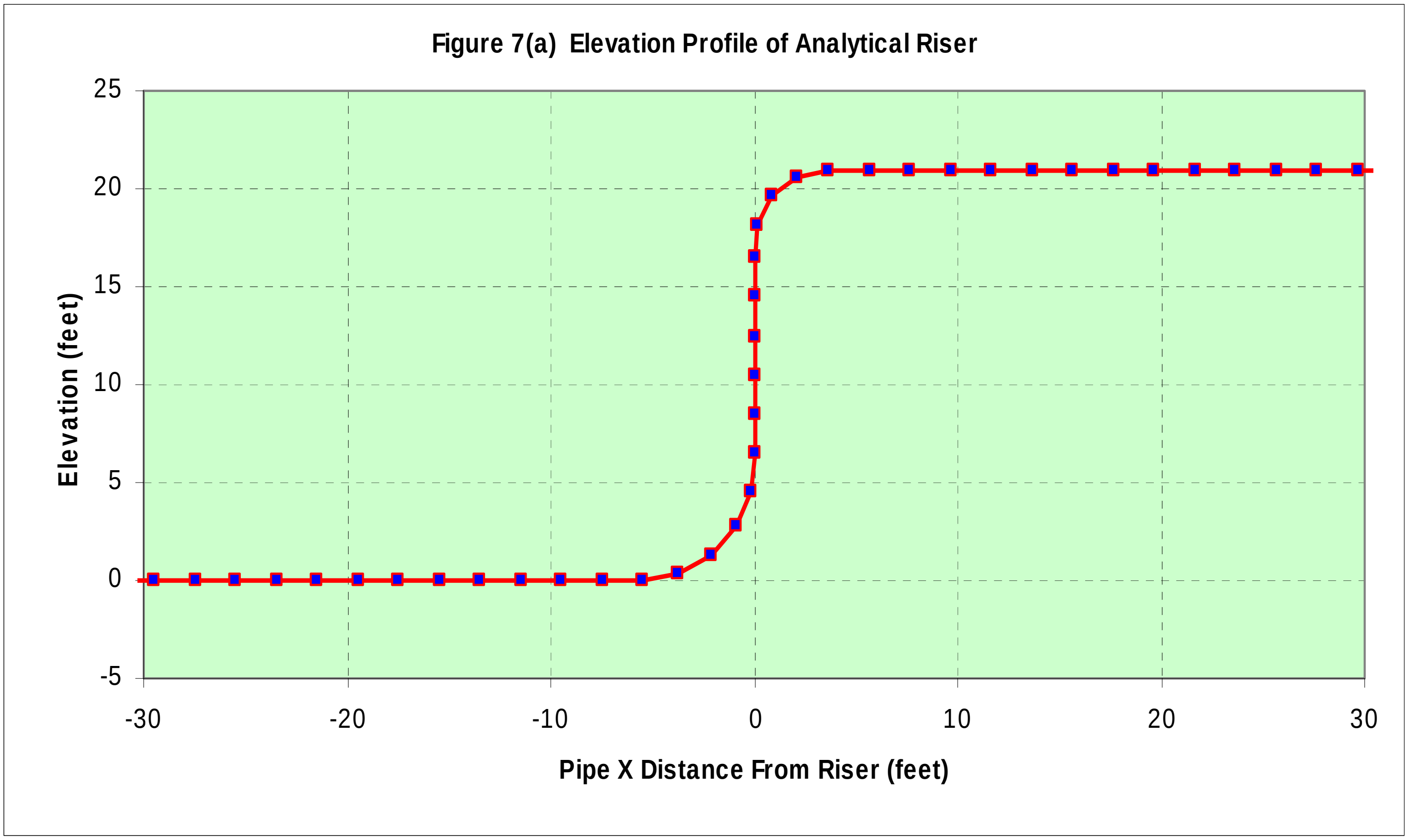


Figure 7(a) Elevation Profile of Analytical Riser
Elevation (feet)
25
20
15
10
5
0
-5
-30
-20
-10
0
10
20
30
Pipe X Distance From Riser (feet)

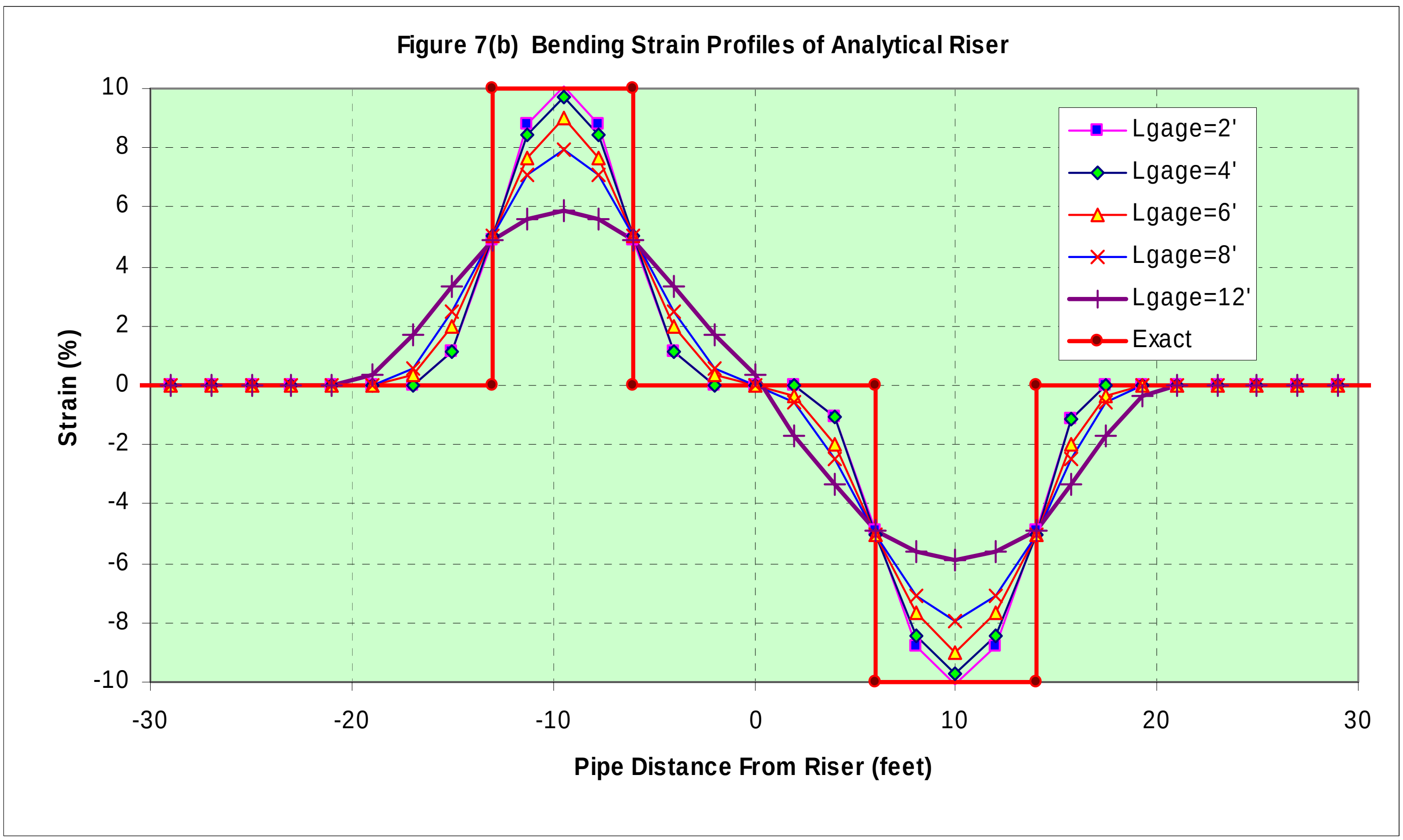


Figure 7(b) Bending Strain Profiles of Analytical Riser
Strain (%)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-30
-20
-10
0
10
20
30
Pipe Distance From Riser (feet)
Lgage=2'
Lgage=4'
Lgage=6'
Lgage=8'
Lgage=12'
Exact

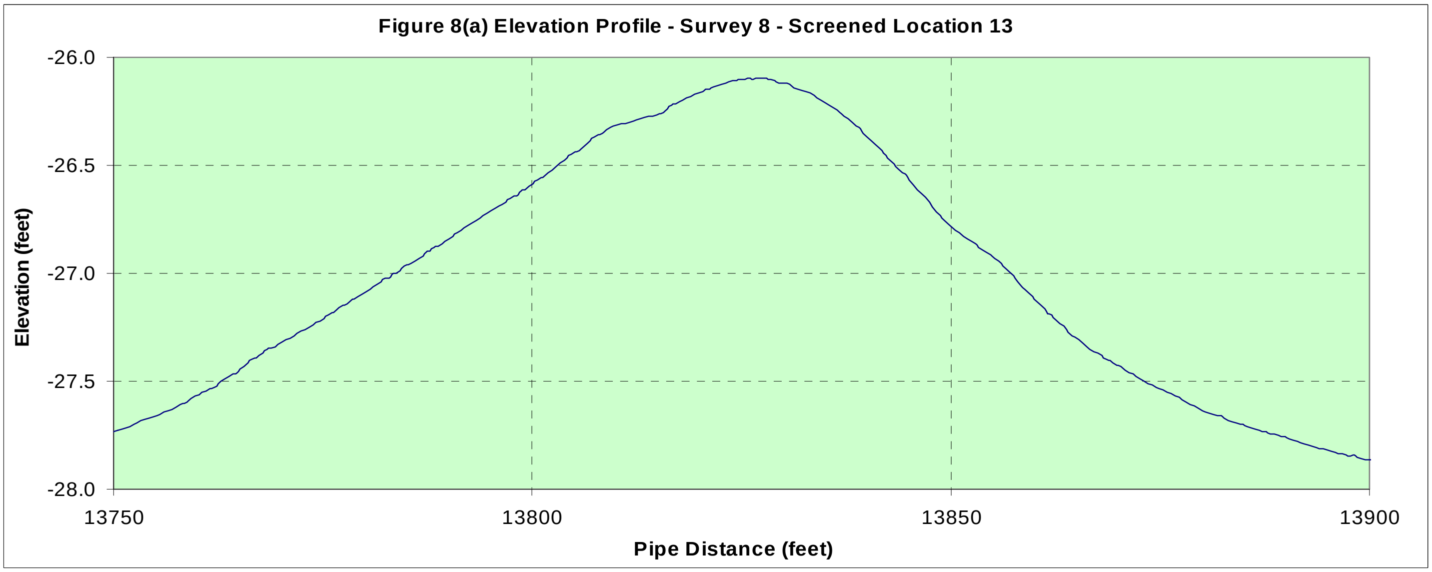


Figure 8(a) Elevation Profile - Survey 8 - Screened Location 13
-26.0
-26.5
-27.0
-27.5
-28.0
Elevation (feet)
13750
13800
13850
13900
Pipe Distance (feet)

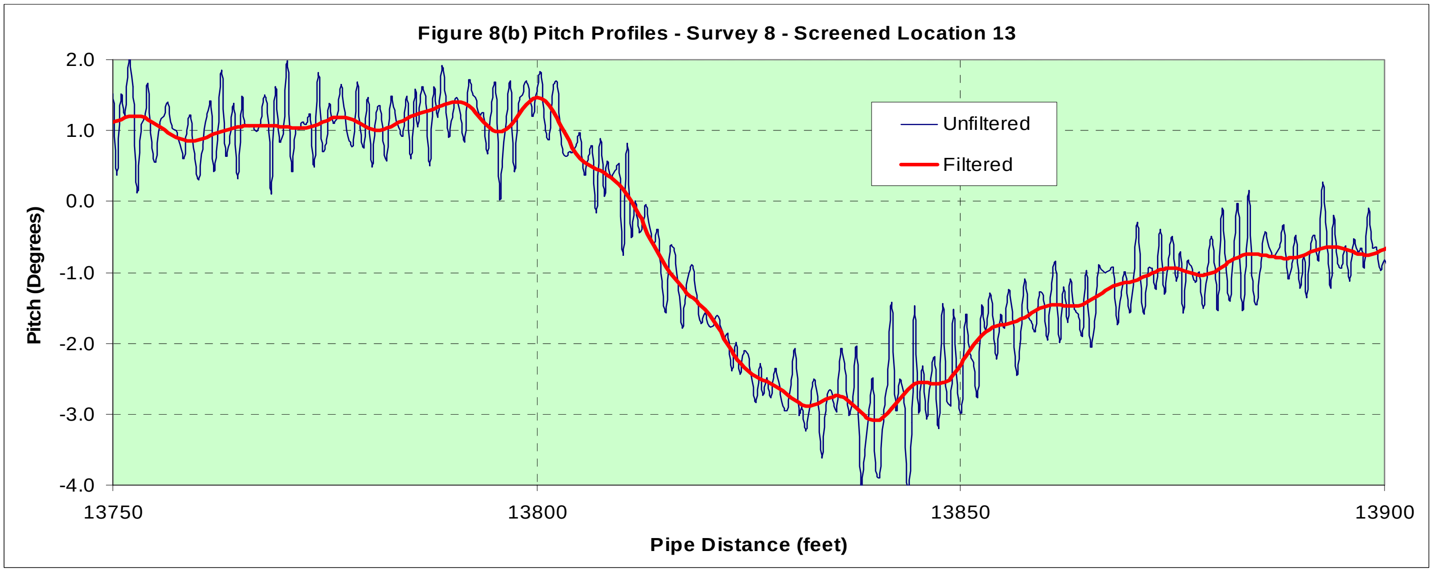


Figure 8(b) Pitch Profiles - Survey 8 - Screened Location 13
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
Pitch (Degrees)
Unfiltered
Filtered
13750
13800
13850
13900
Pipe Distance (feet)

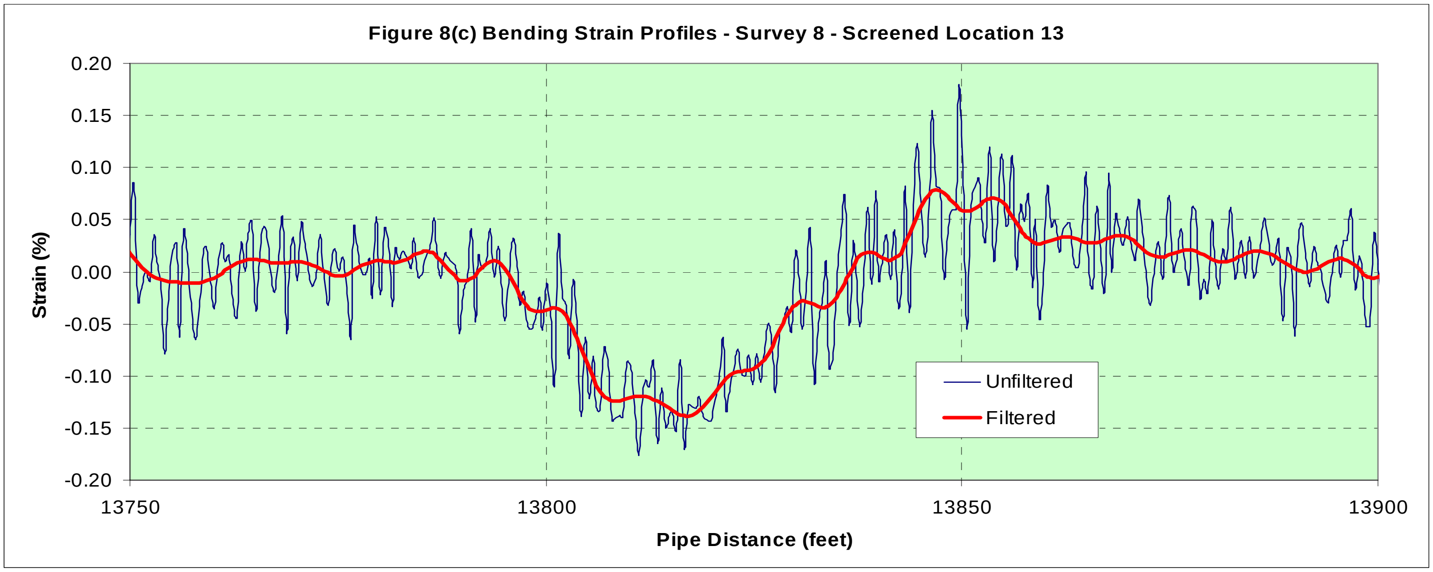


Figure 8(c) Bending Strain Profiles - Survey 8 - Screened Location 13
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
-0.15
-0.20
Strain (%)
Unfiltered
Filtered
13750
13800
13850
13900
Pipe Distance (feet)

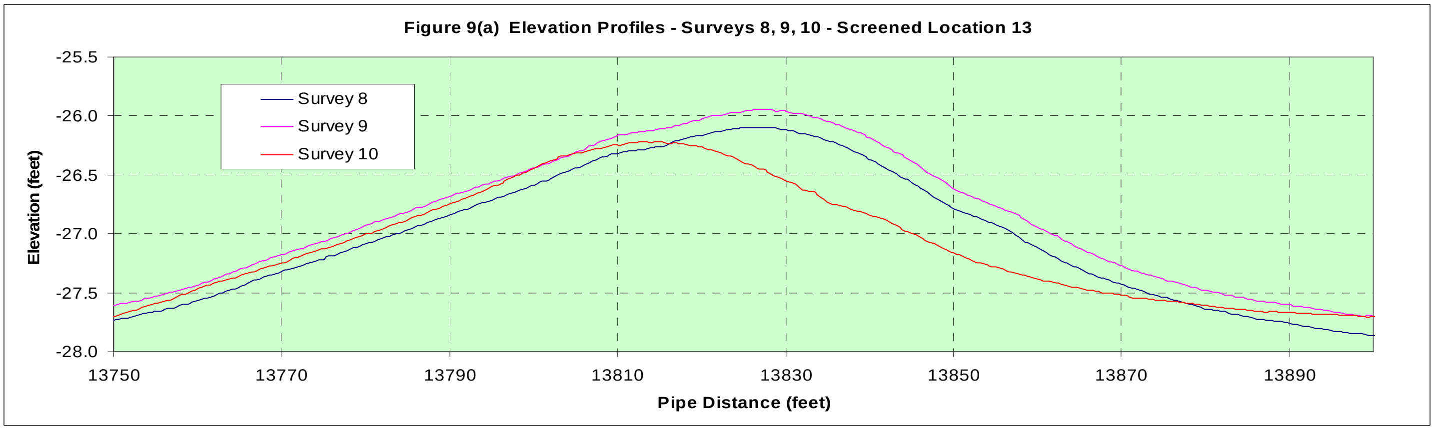


Figure 9(a) Elevation Profiles - Surveys 8, 9, 10 - Screened Location 13
Survey 8
Survey 9
Survey 10
Elevation (feet)
-25.5
-26.0
-26.5
-27.0
-27.5
-28.0
13750
13770
13790
13810
13830
13850
13870
13890
Pipe Distance (feet)

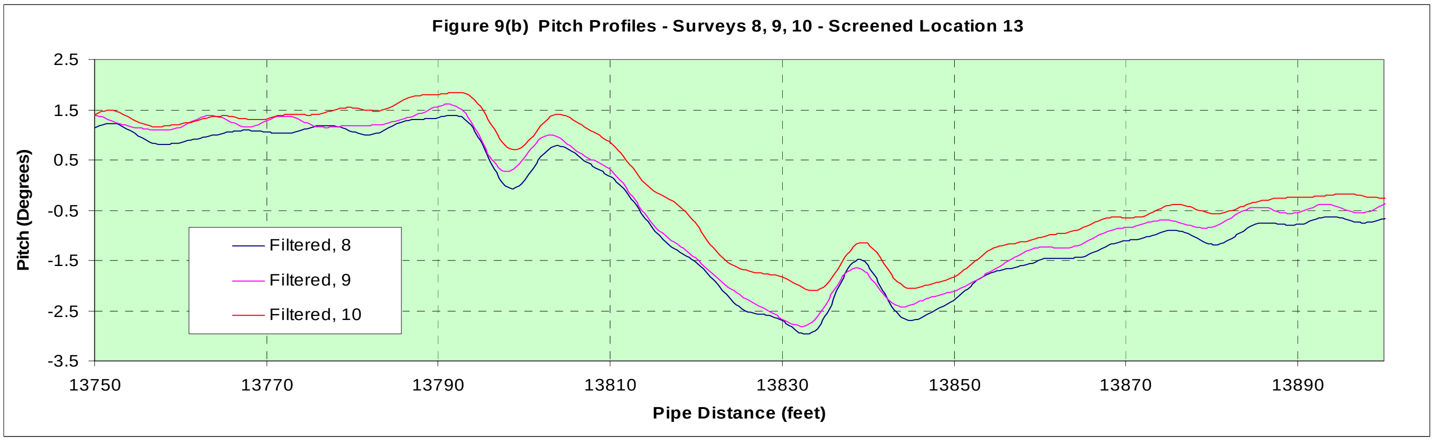


Figure 9(b) Pitch Profiles - Surveys 8, 9, 10 - Screened Location 13
Filtered, 8
Filtered, 9
Filtered, 10
Pitch (Degrees)
2.5
1.5
0.5
-0.5
-1.5
-2.5
-3.5
13750
13770
13790
13810
13830
13850
13870
13890
Pipe Distance (feet)

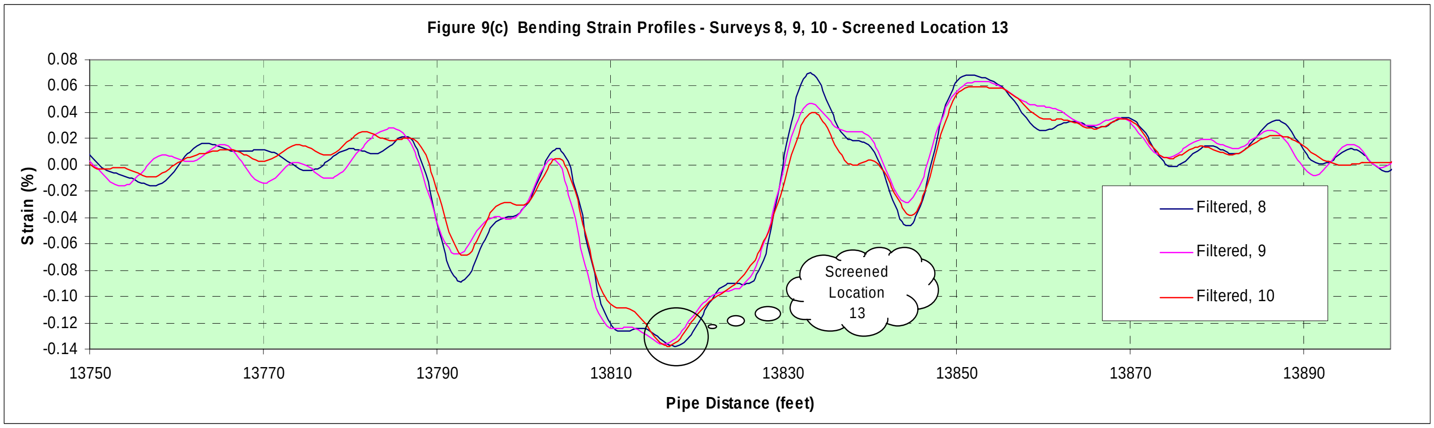


Figure 9(c) Bending Strain Profiles - Surveys 8, 9, 10 - Screened Location 13
Filtered, 8
Filtered, 9
Filtered, 10
Screened
Location
13
Strain (%)
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
13750
13770
13790
13810
13830
13850
13870
13890
Pipe Distance (feet)

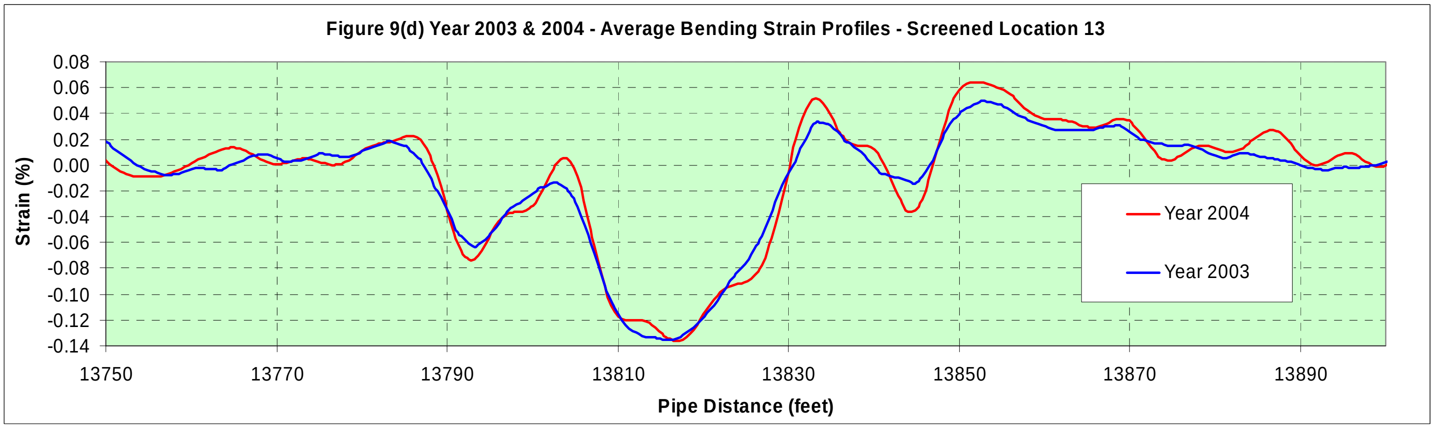


Figure 9(d) Year 2003 & 2004 - Average Bending Strain Profiles - Screened Location 13
Year 2004
Year 2003
Strain (%)
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
13750
13770
13790
13810
13830
13850
13870
13890
Pipe Distance (feet)