Geometry Monitoring of the Trans-Alaska Pipeline

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Abstract

An important aspect of the ongoing operation of the buried sections of the Trans-Alaska Pipeline System (TAPS) is the curvature imposed on the pipeline by differential settlement of the surrounding soil as a result of thawing of ice-rich subsurface soils. High pipe curvature is a source of concern since it can potentially lead to wrinkling of the pipe wall and/or tensile fracture of the pipe at girth welds. Alyeska Pipeline Service Company has monitored pipeline settlement using different techniques since start up of the line in 1977.

This paper provides a brief historical overview of how the techniques used to monitor pipe settlement have evolved over the life of TAPS. The paper also provides a discussion of the how the pipe geometry is currently monitored using the BJ Pipeline Inspection Services (BJ) Geopig "smart" pig. The discussion includes a brief description of the Geopig measurements which are numerically processed to obtain the three-dimensional pipeline displacement and curvature (bending strain) profiles. Several illustrations of this technology are presented. The paper concludes with a summary of how Alyeska's state-of-the art pipeline geometry monitoring program is used to help make decisions related to maintaining the structural integrity of TAPS.

Introduction

It was recognized during the TAPS design that a hot oil pipeline to transport North Slope crude oil to Valdez would have to cross permanently frozen ground. In areas of known thaw unstable ground, the pipe was elevated to keep this ground from thawing. In areas were the pipe was buried, it was recognized that all the thaw unstable ground may not be identified, and differential settlement could potentially occur. Differential settlement of the soil in which a pipeline is buried can impose significant curvatures and strains on the pipe. If left unchecked, excessive pipe curvature and strain can eventually lead to damage of the pipe, for example due to localized wrinkling of the pipe wall and/or tensile fracture of the pipe at girth welds.

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Based on this concern, a monitoring program was required by the Stipulations to the Grant of Right of Way. Alyeska Pipeline Service Company (Alyeska) has monitored potential settlement areas of TAPS using different techniques since start up. This paper provides an overview of how the techniques used to monitor pipe settlement have evolved over the life of TAPS. The pipeline geometry is currently monitored using the BJ Geopig "smart" pig. The Geopig measurements provide a remarkably accurate means of computing the precise geometry of the pipeline including locations with high curvature, ovality or denting of the pipe wall, and locations of girth welds and other features.

History Of Alyeska's Pipeline Geometry Monitoring Program

Since start-up of TAPS in June of 1977, a variety of techniques have been used to monitor pipe settlement. Initially, the pipeline was monitored using an inline inspection device called the "Super Pig" (Anderson, 1979). The data from this pig was difficult to interpret and in 1979, it became stuck at a check valve and was destroyed during recovery.

In 1980, Alyeska began development of a technique to estimate pipeline curvature based on the use of polynomial curve fits of the pipe profile based on measurements at a series of discrete monitoring points (Simmons, 1988). The idea was to measure top-of-pipe elevations at discrete points across a settlement zone and compare these measurements with the as-built top-of-pipe elevations. The discrete measurement points consist of aluminum "monitoring rods" that are permanently cad-welded to the top of the buried pipe. The tops of the monitoring rods are exposed at the ground surface to facilitate measurement of elevation changes using conventional surveying techniques. A series of monitoring rods across a settlement zone provided a basis for estimating the pipe profile through the settlement zone and allowed for observations on the rate of settlement. Alyeska has over 2300 of these monitoring rods in place throughout 612 km (380 miles) of buried line. The curvature estimation method uses a divided difference approach to establish an interpolating polynomial for the pipe elevation profile. The resulting profile polynomial is then differentiated twice to obtain estimates of curvature. The accuracy of this procedure is influenced by the degree of the polynomial, the spacing of the monitoring rods and the accuracy of the pipe elevation measurements. Based on experience, it was determined that a 5th degree polynomial used with a monitoring rod spacing of between 3 and 15 meters (10 and 50 feet) and an elevation accuracy of ±0.6 cm (±0.02 feet) resulted in acceptable estimates of the pipeline curvature.

In 1981 Alyeska began using a Deformation Pig developed by Tubescope, formerly Vetco Pipeline Service Company (Tubescope, 1981). This "caliper pig" proved very accurate in measuring and locating dents, ovalities and pipeline wrinkles. The main disadvantage of the Deformation Pig is that it would not provide an indication that the pipe was settling and bending until the pipe wall had experienced plastic deformation on the compression side and formed a wrinkle. Alyeska has also used an electronic device to monitor the elevation of below ground pipe. This device, which was dubbed the TSI for Technical Service Instrument (TSI, 1981) used a radio signal induced in the pipe and a directional antenna used by a field crew to measure the depth of the mainline pipe below the ground surface. Unfortunately, the TSI is only accurate to within 0.3 m (1 foot) in flat ground. This survey method, while useful for locating the pipe was not adequate to measure progressively increasing bending deformations.

Each of these monitoring methods had deficiencies and it became increasingly clear that a more advanced method was required. The declassification of cruise missile technology by the U.S. Government in the late 1980s allowed for the development of an internal inspection device based on a sophisticated Inertial Navigation System (INS) called the Geopig. In 1992, the first run of the Geopig through TAPS was successfully completed. The Geopig data provided not only the pipe elevation and vertical curvature profiles but also the horizontal profile and horizontal curvature of the pipe as well as accurate locations of girth welds, pipe ovality and field (sag, over, side and compound) bends. The development of the Geopig tool advanced Alyeska's pipeline geometry monitoring program to the cutting edge of this technology.

Description of the Geopig and Geopig Data

The 1219 mm (48-inch) diameter Geopig tool is illustrated in Figure 1. The pig is supported on four flexible urethane support cups; a pair near the front and a pair near the back of the pig body. The distance between the centers of the front and back cups is about 1.67 meters (5.5 feet). The Geopig is equipped with a counterweight in order to maintain a constant roll angle in the pipe. Due to its self weight, the pig is in more intimate contact with the 6:00 position than with the 12:00 position of the pipe cross section. This is evident from the substantial amount of cup wear (up to 0.25 cm or 0.1 inches) on the bottom (6:00) side of the cups. The "steady-state" elevation of the pig body at the front supports is lower than the elevation of the pig body of the back supports, indicating that the pig travels through the pipeline in a slightly "nose heavy" position. The pig travels through the line at the same speed as the oil flow, which for recent TAPS flow rates is about 2.5 m/sec (100 inches/sec).

The Geopig collects data from the following independent types of instruments; gyroscopes, accelerometers, calipers, and odometers. The pitch, roll, and yaw rotations of the pig are recorded using three gyroscopes at a sampling frequency of 50 Hz. The three-dimensional accelerations of the pig are recorded using three accelerometers at a sampling frequency of 50 Hz. Four odometers measure the position of the pig at a sampling frequency of 4 Hz. In its original configuration, the Geopig had a total of 96 sonar transducers (80 on the front sonar ring, and 16 on the back sonar ring) which measured the shape of the cross section of the pipe at a sampling frequency of 32 Hz. Recently, the Geopig sonar calipers have been replaced with one ring of 64 contact caliper "fingers" around the circumference. There is also a separate analog girth weld detector system. More details regarding the Geopig data and its accuracy can be found in (Czyz, 2000).

The most important data for use in curvature screening is the gyroscope and odometer data. The resolution of the gyroscope data is 2 arc sec (10 μrad). The odometer data is interpolated to the same spacing as the gyroscope data, which at the 50 Hz sampling rate, results in data spacing of approximately 5 cm (2 inches). Note that the BJ GeoDisplay software (BJ, 2001) scales and rotates the odometer data in order to provide a match with GPS position control points located every 5 to 10 kilometers along the TAPS alignment. This procedure results in an odometer accuracy of 1 in 2000 (i.e., $\Delta L/L=1/2000$).

The second most important data from the Geopig is the caliper data, which can be useful in investigating the effects of dents and/or asymmetric ovality in conjunction with the gyroscope and odometer data. The calipers can measure the inside radius of the pipe to within an accuracy of ±1.27 mm (±0.05 inches). The calipers are sampled at a frequency of 128 Hz. BJ indicates that the caliper data is able to successfully locate incipient wrinkles with amplitudes less than or equal to 6.4 mm (0.25 inches) over lengths ranging from 30 to 71 cm (12 to 28 inches). The caliper data is the key to an accurate centerline correction that can be applied when the path of the pig is significantly different from the path of the pipe centerline (such as when it travels over an asymmetrical ovality or a dent). In this situation, the dent/ovality feature can erroneously manifest itself in the gyroscope data as a pipe curvature feature. Centerline correction is discussed in a later section of this paper.

Geopig Data Processing Applications

A detailed discussion of the numerical methods used to process the Geopig data to obtain pipe curvature and three-dimensional coordinates is beyond the scope of this paper. Some of the procedures are discussed in other references (Czyz, 2000). In essence, the gyroscope and odometer data is numerically differentiated to obtain the curvature of the pig path and numerically integrated to obtain three-dimensional coordinates of the pig path. This section provides some illustrations of results from Geopig data processing.

Illustration of Noise in Geopig Gyroscope Data

Figure 2 presents an illustration of the pitch data from the 1994 Geopig run across the Salcha River. Figure 2(a) presents the relative pitch angle vs. odometer data and Figure 2(b) presents the corresponding power spectral density spectrum of the pitch data. The location of the high curvature zones are coincident with the steep sections of the pitch profile. In order to focus on the frequency range where most of the energy is concentrated, the spectral plots are shown only over a zoomed frequency range from 0 to 10 Hz. As previously noted, for a given frequency, the equivalent wavelength is estimated by dividing the average pig speed by the frequency. The pitch spectrum plots indicates the presence of a component of “pitch energy” centered at a frequency of about 8 Hz which corresponds to a feature length of about 34 cm (13.5 inches). Subsequent investigation of the noise, including examination of similar noise features in pipe joints from three different pipe manufacturers indicates that the noise features are actually different for different pipe manufacturers. The most likely cause of the noise is that the pig is responding in a pitching motion as it traverses small, periodic diameter changes (expander marks) in the pipe joints that result from the (UOE) pipe manufacturing process. None of the available evidence indicates that the noise is in any way related to real pipe curvature demand. In order to illustrate the influence of this noise on the computed curvature, the Salcha River pitch data was processed to compute curvature using a range of gage lengths. Figure 3 presents vertical bending strain profiles computed from the pitch and odometer data across the Salcha River using different gage lengths (from about 3 meters to 0.3 meters). These plots show that high-frequency oscillations are present in the computed curvature and that the amplitude of the noise increases with decreasing gage lengths (especially for gage lengths shorter than the length of the pig). Again, the dominant wavelength of this “noise” is about 34 cm (13.5 inches). It is apparent that the “noise” component has a significant effect on the computed bending strain (i.e., curvature).

Effect of Filtering

Figure 4 presents the same information as shown in Figure 3 except in this case the data has been low pass filtered using a filter cut-off frequency of 1.5 Hz. This cut-off frequency was selected to match the length of the Geopig and because it will remove both the low amplitude noise in the signal near 4 Hz and the more significant noise near 8 Hz. The effect of the filtering is very pronounced since it virtually eliminates the bothersome noise and provides a much clearer picture of the pipe curvature.

Discussion of Gage Length

There are two lengths involved in the curvature calculation, namely the pig length and the gage length. The pig length is approximately 1.67 m (5.5 feet), and is fixed. The gage length can be varied, and has a minimum value of approximately 10 cm (4 inches). The pitch (or azimuth) of the pig is the difference in elevation over the pig length, divided by the pig length. It is important to note that this is not the exact pitch at the center of the pig, but an average value over the pig length. The calculated curvature is the difference in this average pitch divided by the gage length. No matter how short the gage length, the pitch will always be an average value, and hence the exact maximum curvature can never be calculated (except in the rare case where the curvature is uniform over a substantial length). The calculated curvature will, however, be progressively more accurate as the gage length is reduced. The Geopig has remarkable accuracy, with a pitch resolution of 2 arc seconds, or 0.00001 radians. For a 10 cm (0.33 foot) gage length, an error of 0.00001 radians in pitch corresponds to an error of 0.00001 radians / 10 cm = 0.000001 cm^{-1} = 0.00003 ft^{-1}. This is only about 1.5% of the wrinkling curvature capacity of TAPS pipe (the curvature capacity varies from roughly 0.00005 cm^{-1} to roughly 0.00008 cm^{-1}, depending on the pressure, wall thickness and other parameters). Hence, the pig is sufficiently accurate to allow a gage length of 10 cm (4 inches) to be used for detailed curvature comparisons (based on a pig speed of 2.54 m/sec (100 inches/sec) and a sampling rate of 50 Hz). However, in order to use this short of a gage length, low-pass filtering of the data is typically required.

Centerline Correction Processing

At one of the Salcha River crossing high curvature locations, the pipeline curvature is of overbend type (i.e., with the longitudinal compression strain located at the bottom of the pipe). The caliper data from the Geopig shows that there is what can be characterized as an asymmetrical ovality of the pipe at this location. This ovality extends over a length of roughly 6 to 7.6 m (20 to 25 feet) and has a maximum depth at the bottom of the pipe of about 2.54 cm (1 inch). As the Geopig traverses this location, it must ride up and over this ovality, thus causing the pitch angle recorded by the pig to deviate from that of the centerline. As a result, the calculated curvature has two components, one associated with the overbend curvature and one associated with the ovality. At the point of maximum curvature, the two components have the same sign, and hence the calculated curvature is significantly larger than the overbend curvature alone. Because the gyroscope measures the pitch (slope) of the pig, rather than that of the pipe, the pitch measurements must be corrected to obtain the pitch of the pipe. This "pig-to-pipe attitude correction" or centerline correction can be performed using the caliper data. A very simple approach is described below.

Figure 5 shows contours of the pipe ovality along the bottom half of the pipe at this location. The figure also shows a dashed line associated with the 6:00 o'clock position of the pipe. The maximum height of the idealized ovality is just under 2.54 cm (1 inch) and it extends over a length of about 6 m (20 feet), i.e., from circular to maximum asymmetrical ovaling and back to circular over about 6 m. It is assumed that an ovality of 1 unit on one side of the pipe corresponds to a change in the location of the effective pipe axis of 0.5 units (i.e., a maximum axis shift equal to one half of the depth for a one-sided ovality). The assumed centerline profile is shown in Figure 6(a). By running a "mathematical pig" with a pig length of 1.67 m (5.5 feet) over this profile, it is possible to develop a corresponding profile of pig pitch angle based on the elevations of the front and back pig support cups. The resulting pitch profile is shown in Figure 6(b). Based on this pitch profile, the vertical bending strains computed using different gage lengths are shown in Figure 6(c). The curvature (or bending strain) of the pipe centerline can now be estimated by subtracting the curvature due to the ovality from the total vertical curvature. Application of a centerline correction resulted in a 40% to 50% reduction in the curvature demand at this location.

It is also possible to remove the effect of the unsymmetrical ovality using low pass filtering, provided that the length of the ovality feature is less than the length of the true curvature feature. Note that in order to be consistent, removal of dent/ovality features from the curvature demand requires that the effect of the curvature and ovality features on the curvature capacity are properly considered.

Conclusions

Since the Geopig first successfully traversed TAPS in 1992, the Geopig data has been looked at in a variety of new and different ways and a keen understanding of how to best use the data from this remarkably sensitive and accurate tool has been developed. This paper has provided an overview of various techniques used to process the data from the Geopig. Alyeska uses these techniques for routine screening as well as detailed evaluation of data from a Geopig run. Advanced processing techniques can be used to examine high curvature areas, to make run-to-run profile comparisons or to perform centerline corrections at locations where high curvature is coincident with un-symmetric ovalities or dents. Ultimately, decisions regarding the pipeline structural integrity are based on a demand-capacity comparison. The computed curvature demand is compared to estimates of the curvature capacity which depend on the internal pressure, the wall thickness, the proximity to pipe girth welds and other factors. Special care and engineering judgment must be exercised to ensure that the calculated results are consistent and meaningful, especially in relation to filtering of the data and selection of the gage length for calculating curvature demand for use in screening the data vs. the gage length for performing detailed demand-capacity comparisons.

Acknowledgements

The work described in this paper is based largely on projects undertaken by SSD, Inc. for Alyeska Pipeline Service Company. Alyeska's support for this work and permission to publish this paper is most gratefully acknowledged. The authors would also like to thank Dr. Jaroslaw A. Czyz and Mr. Joel Falk of BJ Pipeline Inspection Services for their efforts in support of these projects.

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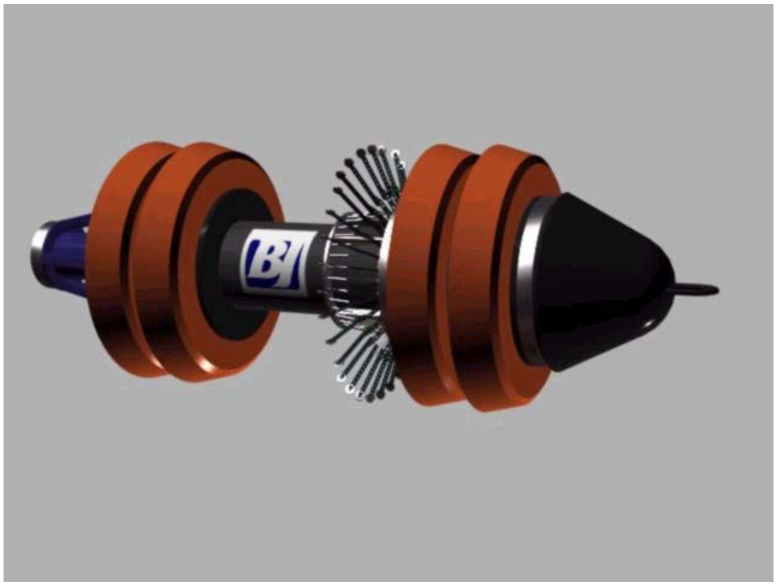

Figure 1 Illustration of 48-inch Diameter Geopig
(Image Courtesy of BJ Pipeline Inspection Services)

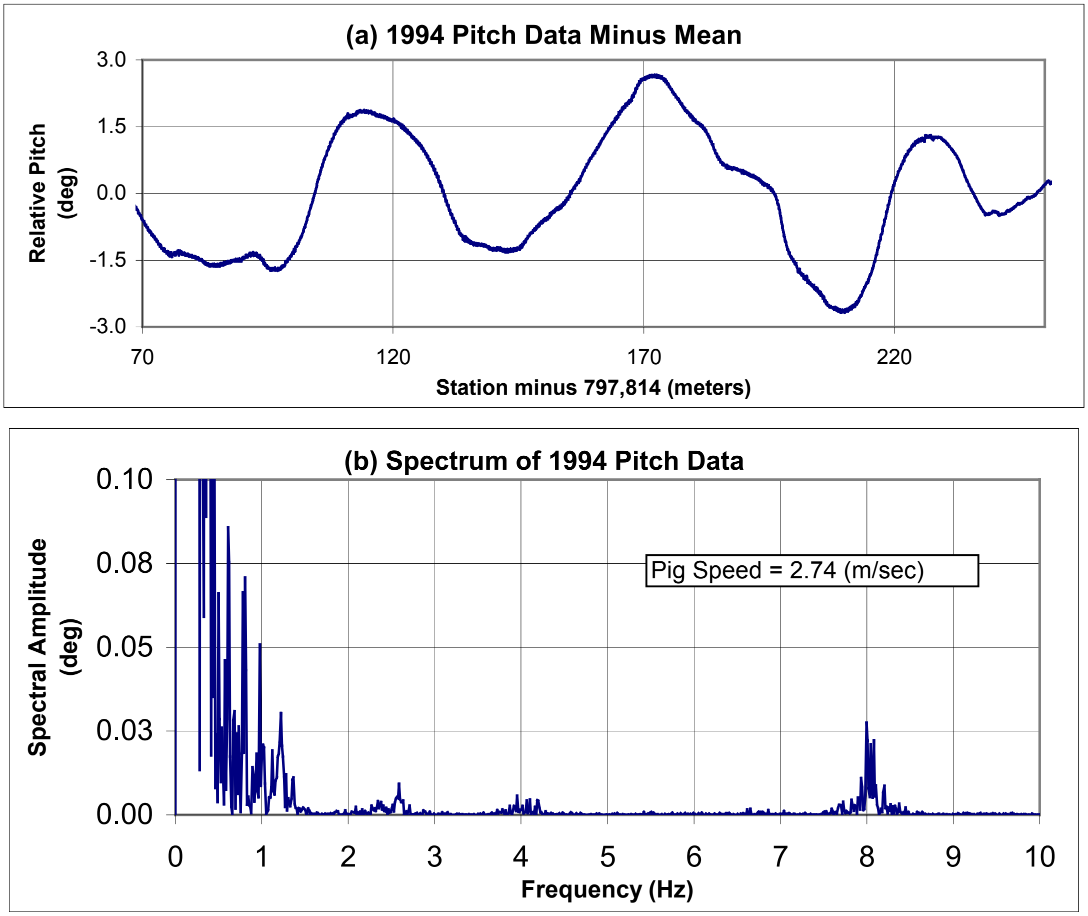

Figure 2 Illustration of Pitch Data from Salcha River Crossing

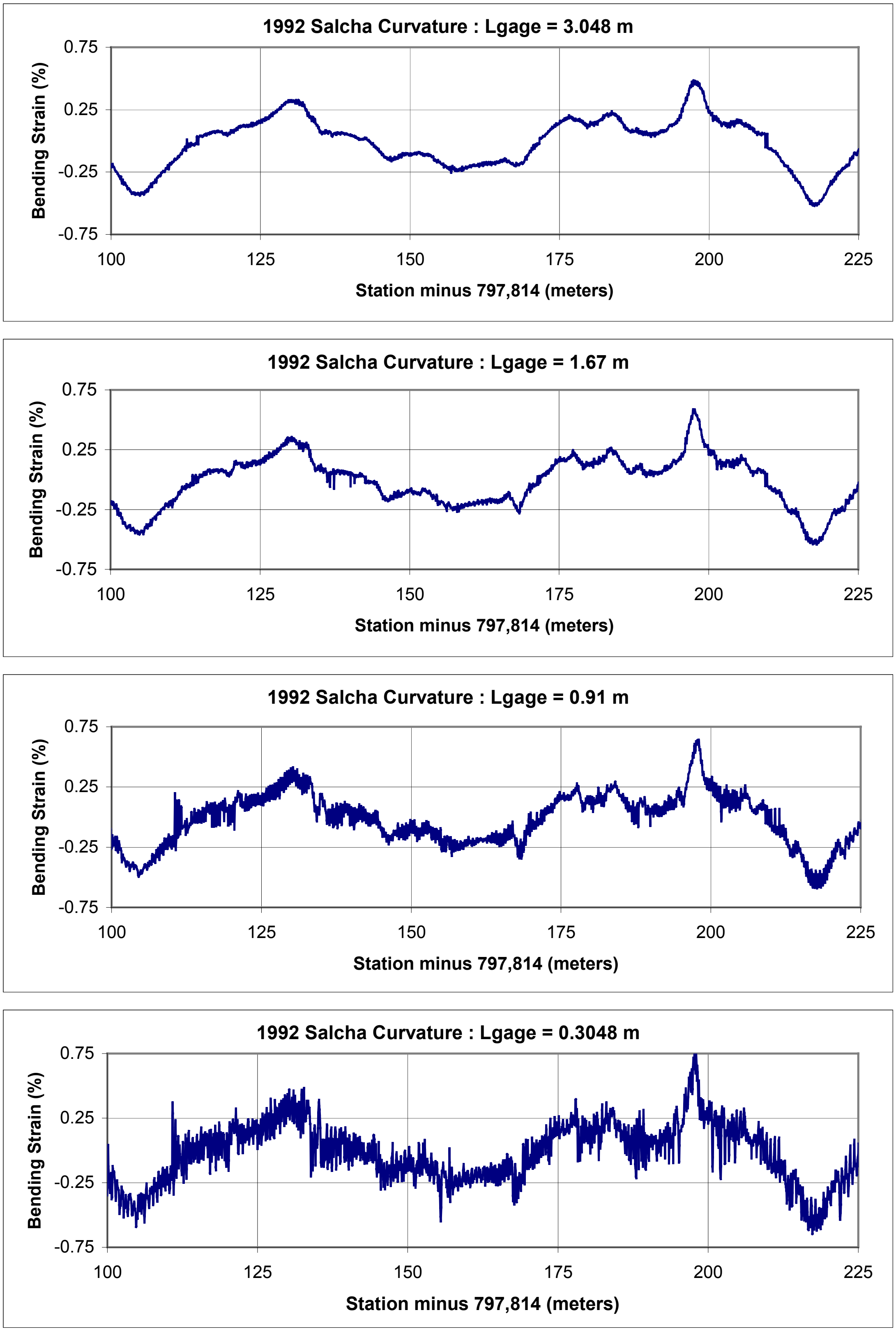

Figure 3 Illustration of Unfiltered Curvature Data from Salcha River Crossing

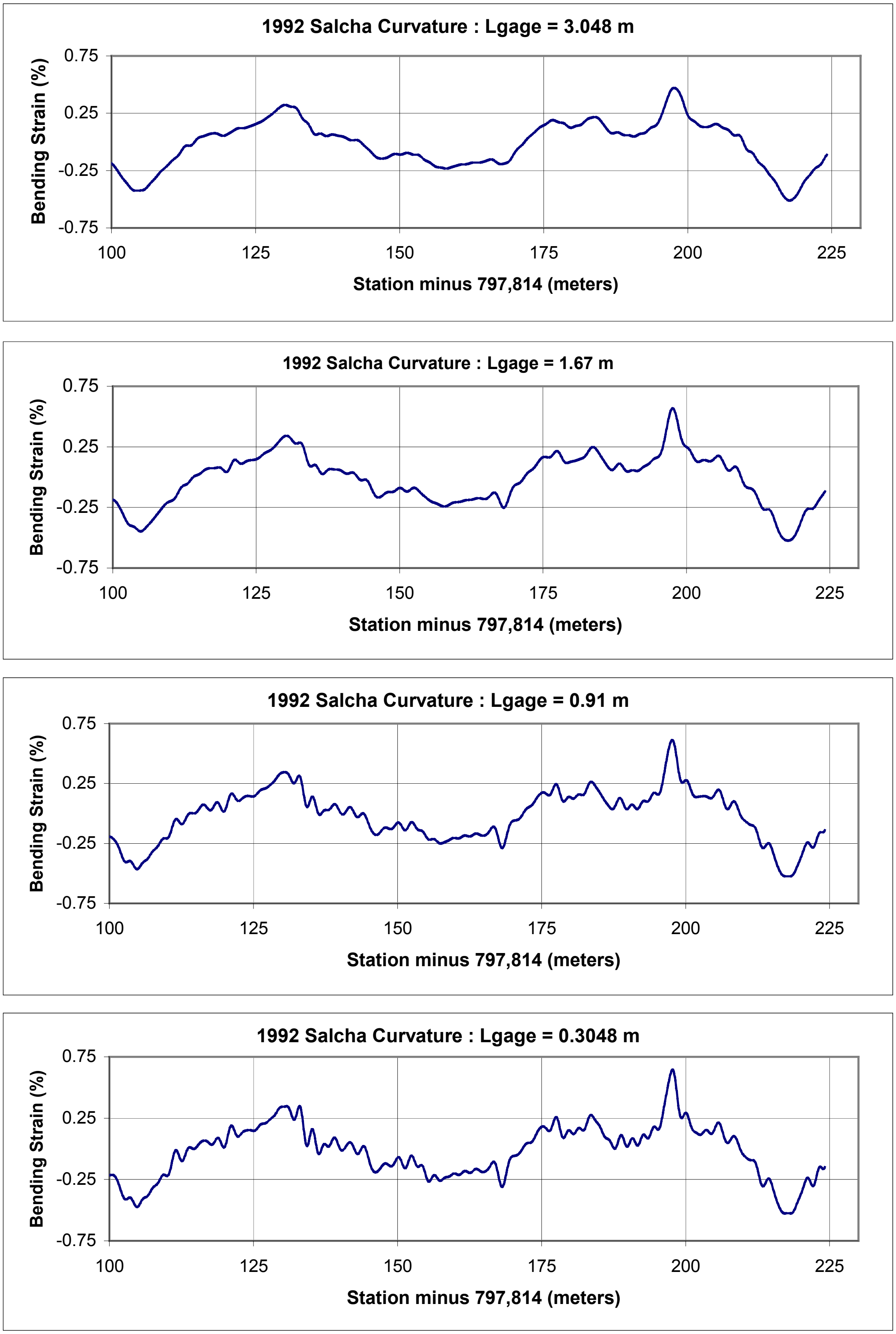

Figure 4 Illustration of Filtered Curvature Data from Salcha River Crossing

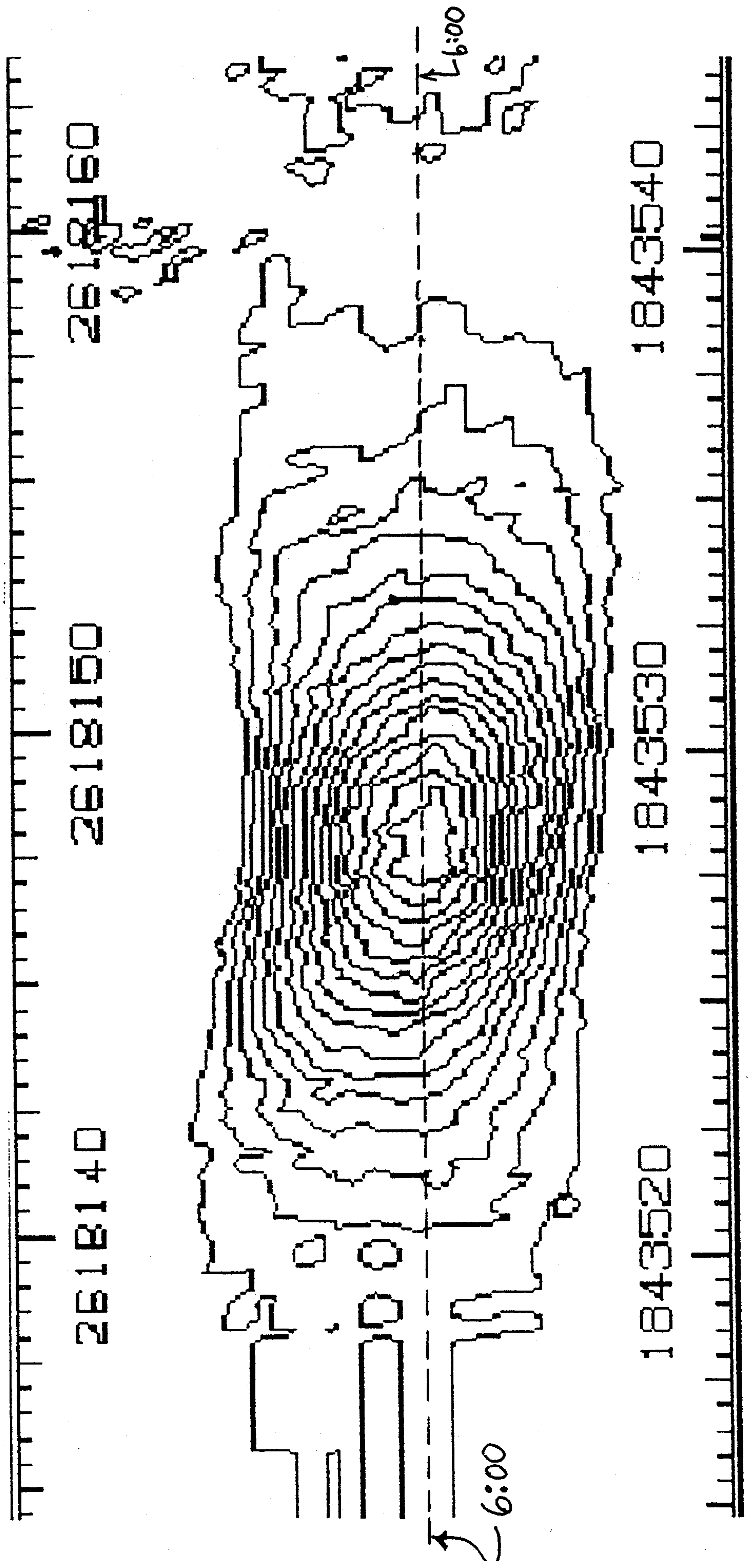

Figure 5 Contours of Ovality at Salcha River High Curvature Zone

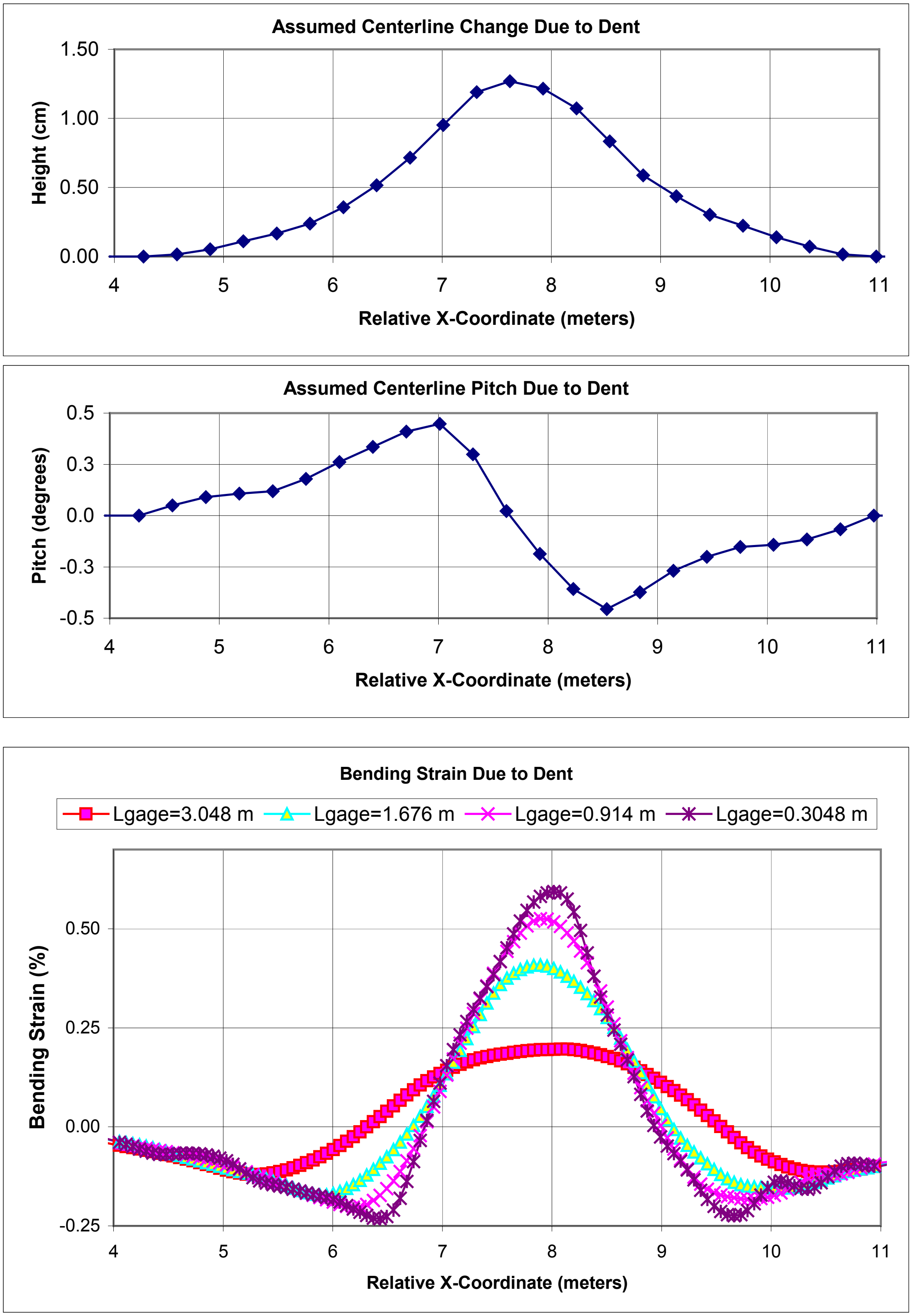

Figure 6 Illustration of Profile Due to Dent at Salcha River High Curvature Zone