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3RD PARTY REVIEW OF GEOMETRY PIG INERTIAL SURVEY DATA AT THE COLVILLE RIVER HDD

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ABSTRACT

This paper describes a 3rd party review of geometry pig inertial surveys of the ConocoPhillips Alaska, Inc.-operated Alpine 14-inch diameter oil and 12-inch diameter water pipelines at the horizontal directionally drilled (HDD) Colville River crossing. The geometry of these pipelines is periodically surveyed to monitor for potential thaw-induced differential settlement between thaw-stable and thaw-susceptible soils along the HDD profile under the river. Preliminary reviews of the elevation profiles from multiple surveys showed significant run-to-run variations within the HDD. However, considering the long distances between the reference elevation tie points, the observed elevation differences appeared to be within the position accuracy of the inertial survey specifications. As a follow up to the initial review, a more detailed 3rd party review of the data was performed. This paper describes how the elevation, pitch and bending strain data from four different inertial surveys performed for each pipeline over a five year period was processed to look for monotonic trends and/or locations of significant pipe deformation. It was determined that the bending strains for both pipelines were small compared to the allowable strains and that the most critical locations for both pipelines occurred in the vicinity of the end of the below grade casing and the adjacent aboveground pipe support. At each end of the HDD, the pig data signatures indicate the presence of a sagbend curvature lobe at/near the end of the casing and an overbend curvature lobe at/near the adjacent pipe support which is clearly indicative of relative movement between the below grade section of the pipe and the pipe support. The response at the pipe support was confirmed by visual inspection of the pipe where minor buckling damage to the external sheet metal insulation jacket at the ends of the saddle was observed. The results from this review were used to develop a recommended forward-looking geometry monitoring schedule.

INTRODUCTION

ConocoPhillips Alaska, Inc. (CPAI) operates the Alpine oil and seawater pipelines on the North Slope of Alaska on the coastal plain of the Arctic Ocean. These 34-mile-long pipelines connect the Alpine and Kuparuk oil fields. The pipelines are entirely aboveground and supported on pipe supports except where they cross the Colville River. The river crossing was horizontal directionally drilled and cased, with each pipe centralized in its own casing. The pipe passes 85 feet below the surface of the river.

BJ Pipeline Inspection Services (BJ) has performed four smart pig geometry surveys each for the 14-inch diameter oil and 12-inch diameter water pipelines since just before startup in Year 2000. The first two surveys (in June 2000 and September 2001) were performed using BJ's Geopig [1] while the second two surveys (in June 2003 and June 2005) were performed using BJ's Vectra pig [2]. These smart pigs provide a characterization of the overall pipeline geometry using measurements from a strap-down inertial navigation system (INS) and a set of odometer wheels. The main location of concern related to pipeline geometry changes is at the Colville River crossing where both pipelines cross under the river in a below grade HDD configuration. Because the pipelines pass through permafrost, the elevated temperatures of the pipelines may, over time, lead to differential thaw-induced soil settlement between thaw stable and thaw susceptible sections of soil along the HDD profile under the river. The concern is that differential settlement may lead to excessive deformations (i.e., strains) in the pipelines. The strain-based design of the HDD section of the pipelines included deformation analysis for a range of differential settlement scenarios and also provided strain criteria to limit the deformations to acceptable levels. The idea behind ongoing periodic monitoring of the pipelines' geometry across the HDD section is to identify locations where the pipelines may be experiencing significant movement or developing significant levels of pipe deformation/strain.

Preliminary review of the inertial survey data from the Alpine pipelines showed that the elevation profiles from the different surveys exhibit significant run-to-run variations within the HDD section. However, considering the long distances between reference elevation tie points, the observed elevation differences appear to be within the position accuracy of the inertial survey specifications. In September 2006, as a follow up to the initial review of the geometry pig data, CPAI requested that SSD, Inc. (SSD) perform a formal 3rd party review of Geopig and Vectra pig geometry data for the Alpine pipelines at the Colville River HDD crossing and make recommendations regarding the forward-looking monitoring interval. The SSD review focused on changes in the pipeline pitch and bending strain profiles which, unlike the pipeline elevation profile, do not rely on integration between tie point coordinates and hence provide more reliable indicators of differential pipeline movement.

DISCUSSION OF KEY GEOMETRY MEASURES

Prior to discussing the data processing results, it may be helpful to discuss the key geometry measures:

(1) *Pitch Angle.* The pitch (θ) is the vertical inclination angle of the axis of the pig canister containing the strap-down INS. Positive and negative values indicate "nose up" and "nose down" inclinations, respectively. A fundamental assumption used to develop pipeline geometry based on Geopig or Vectra pig inertial data is that the path of the pig canister containing the INS is closely aligned with the pipe centerline as it travels through the pipeline. An example of when the axis of the pig is not aligned with the axis of the pipe is when the axis of the pig temporarily skews with respect to the pipe axis. Overlays of the pitch data and computation of run-to-run pitch differences over short distance windows across the HDD section showed fairly consistent shaped profiles of pitch from run-to-run except that the pitch signals for different runs sometimes exhibit an almost uniform vertical difference (i.e., a different θ intercept). The uniform pitch differences are in the range from 0.2° to 0.4°.

(2) *Bending Strain.* Bending strain (ε) is equal to the product of the pipe radius (r) and the pipe curvature (Ψ) where the pipe curvature is the inverse of the radius (R) of the path of the pipe centerline:

$$\varepsilon = \Psi \cdot r = \frac{r}{R}$$

The vertical curvature Ψ_V is taken as the numerical slope of the pitch vs. pipe distance plots:

$$\Psi_V = \frac{\Delta\theta}{\Delta S} = \frac{\Delta\theta}{L_{gage}}$$

where the pitch change $\Delta\theta$ is measured over a set pipe distance change ΔS (which is usually referred to as a curvature gage length L_{gage}). It follows that the "steepest" sloped sections of the pitch profile correspond to peaks or troughs in the vertical curvature and bending strain profiles. Positive and negative values of vertical curvature or vertical bending strain, ε_V, correspond to sagbends and overbends, respectively. The computed curvature can be sensitive to the curvature gage length [3,4]. Because the pitch profile contains low amplitude "noise" (i.e., due to vibrations of the pig, minor imperfections in the pipe wall, etc.), the numerical derivative of the pitch profile (i.e., the vertical curvature) can amplify the noise in the curvature signal to the point where, for very short gage lengths, the amplitude of the noise can dominate the curvature signal. A reasonable "signal-to-noise" ratio can be obtained by either utilizing a low-pass filter or by using a gage length that does not result in significant noise amplification. The horizontal curvature Ψ_H (and bending strain, ε_H) is computed in a similar fashion based on the horizontal projection of the azimuth (or yaw) change $\Delta\gamma$ over a set distance change ΔS. The resultant/total curvature Ψ_T (and bending strain, ε_T) is computed as the square-root-of-the-sum-of-the-squares of the corresponding vertical and horizontal values:

$$\Psi_T = \sqrt{\Psi_V^2 + \Psi_H^2} \quad \text{and} \quad \varepsilon_T = \sqrt{\varepsilon_V^2 + \varepsilon_H^2}$$

The specifications for the Geopig and Vectra pig indicate a bending strain accuracy of ±0.02% strain (which corresponds to a stress of about ±6 ksi). However, BJ indicates the stated ±0.02% accuracy is conservative and that they can usually obtain strain measurements with accuracy *better* than ± 0.005%. A theoretical analyis of the explicit strain error involves the gyroscope resolution and bias, the tool velocity, the odometer accuracy, the gage length as well as a characterization of the deviation of the tool trajectory from the pipe centerline. For the purposes of this work, the BJ specified accuracy was accepted.

(3) *Elevation.* The computed elevation profile (height vs. pipe distance) is based on numerical integration of the pitch data (θ) and the odometer data (S) and represents one component of the three-dimensional position profile of the pipeline (the other two components are the northing and easting). The fundamental numerical assumption is that the local pitch angle θ at a location of interest can be used to compute the incremental elevation change ΔH over the incremental pipe distance change ΔS:

$$\Delta H = \sin\theta \cdot \Delta S$$

Integration of the elevation profile can be performed numerically in different ways (e.g., using a combination of forward and backward Euler integration) subject to the end constraints that the profile must pass through the elevation coordinate tie-points (which can be accomplished by a rigid body rotation of the profile between tie-points). Similar calculations are performed using the azimuth (or yaw) angle (γ) profiles with the odometer data (S) to obtain profiles of northing and easting. Due to inertial survey error, the accuracy of the integrated three-dimensional position profiles is specified as 1:2000 of the distance between tie points. The maximum position error that can be expected from each survey at the Colville River crossing is ±1 foot and therefore, a maximum difference between any two surveys could be as much as 2 feet.

Overall, the geometric quantity which is given the most weight for this review is the profile of vertical bending strain. Because this quantity is the numerical derivative of the pitch vs. pipe distance profile, it is not sensitive to small uniform differences in the inclination of the pig in different runs. Although the bending strain is sensitive to the sudden jumps in the pitch profile that can occur at girth welds, the corresponding curvature/bending strain "spikes" *are not* associated with true pipe strain but rather with a small angular misalignment of the two pipe joints on either side of the weld (typical misalignments for the oil and water pipelines in the HDD section range from 0.2° to 0.4°). The curvature/bending strain spikes at girth welds are normally addressed by using a curvature gage length that is long enough to diminish the amplitude of the spike but still short enough to capture true changes in the pipeline geometry. A gage length of 10 feet was used for curvature screening consistent with the gage length selected by BJ for analysis of these lines since it smoothed out spikes in the data (e.g., at girth welds) without missing real curvature changes. Another reason that bending strain is given the most weight for this review is that the HDD portion of the pipelines are strain-based designs whose thaw settlement performance was evaluated using pipe deformation analyses to compare predicted pipe strain demands to specified allowable strain limits. The specified allowable strain limits are 0.71% compression and 0.42% tension for the 12-inch water line and 0.89% compression and 0.45% tension for the 14-inch oil line. The *governing* strain limit for the bending strain evaluation is taken as the lesser of the tension or compression values (i.e., 0.42% for the water line and 0.45% for the oil line). Note that these are conservative strain limits.

Although the pitch profile is the closest geometry measure to the raw measurement made by the Geopig (i.e., it does not depend on numerical differentiation or numerical integration), it was given somewhat of a secondary weighting for this review. Although overlay plots of the pitch data from different runs over short distance windows across the HDD section show fairly consistent shaped pitch profiles, they sometimes exhibit an almost uniform vertical difference (i.e., a different θ intercept) on the order of about 0.2° to 0.4°. For this reason, direct comparison of the pitch profiles may give misleading results in terms of run-to-run pitch changes.

For the purposes of this review, elevation profiles were given essentially zero weight and were considered only for reference. The reason for this is that due to the long distance between tie-points at the HDD crossing, the positional accuracy of the inertial survey data within the HDD exceeds the level of pipe movement that might be expected.

The data described above were obtained over 7000-foot-long chainage ranges encompassing the HDD section of each pipeline. For the oil line, the chainage range of interest was from 47,000 feet to 54,000 feet while for the water line, the chainage range of interest was 129,000 feet to 136,000 feet. Note that the discrepancy in these chainage ranges is because the pig travels through the pipe in the flow direction (i.e., from Alpine to Kuparuk for the oil line and from Kuparuk to Alpine for the water line). In the plots presented herein, the horizontal axis is presented in terms of pipe distance from chainage 47,000 feet and 129,000 feet, for the oil and water lines, respectively. Throughout this paper, pipe distance is referred to with respect to these reference chainage locations.

PRESENTATION OF GEOMETRY DATA BLOCKS

The data was processed using the MATLAB program [5]. The most useful measures of the pipeline geometry for this review were (a) the resultant bending strain, (b) the vertical bending strain and (c) the pitch angle. Due to the long length of the HDD, the data was broken into 250-foot-long pipe distance "blocks" for detailed examination. For each "block" of data, several sets of plots/views were developed. The "block view" plots are described as follows:

Detailed Color Contour Plots:

Plot (a): This is a color contour surface plot showing the profile of the *resultant* bending strain over the pipe distance block of interest and spanning the nominal 5 year period between the 1st and 4th inertial surveys.

Plot (b): This is a color contour surface plot showing the profile of the *vertical* bending strain over the pipe distance block of interest and spanning the nominal 5 year period between the 1st and 4th inertial surveys.

Plot (c): This is a color contour surface plot showing the profile of the pitch angle over the pipe distance block of interest and spanning the nominal 5 year period between the 1st and 4th inertial surveys.

Along-the-Pipe ProfilePlots:

Plot (a): This is a profile plot showing the profile of the *resultant* bending strain over the pipe distance block of interest with a different line color assigned to the year of each inertial survey (2000, 2001, 2003 and 2005).

Plot (b): This is a profile plot showing the profile of the *vertical* bending strain over the pipe distance block of interest with a different line color assigned to the year of each inertial survey.

Plot (c): This is a profile plot showing the profile of the pitch angle over the pipe distance block of interest with a different line color assigned to the year of each inertial survey.

SYNTHESIS OF GEOMETRY DATA

Based on discussions with BJ, the Year 2000 "baseline" Geopig surveys across the HDD section of both the oil pipeline and the water pipeline were troubled by unfavorable tool dynamics. Basically, as the pig ran through certain sections of the pipe, the axis of the pig canister containing the strap-down INS was skewed such that it was not parallel to the pipe axis. This "pig-to-pipe attitude" problem complicated subsequent post-processing adjustments of the inertial data (e.g., corrections to account for pig roll, etc). BJ reprocessed the Year 2000 data at the HDD section multiple times attempting to make it as useful as possible. Despite these efforts, the problems with the Year 2000 survey data are readily apparent in the pitch, curvature and elevation profiles across the HDD section. This is especially true for the oil line, but there are some sections of the water line where the Year 2000 data is reasonably consistent with survey data from other years. Given the above, although the Year 2000 data was included in our data processing it was largely discounted for the review.

This review has focused on the geometry of the pipelines between the compound 5D bends at each end of the HDD section (i.e., between ≈1,345 and ≈5,820 feet from chainage 47,000 feet for the oil line and between ≈1,240 and ≈5,725 feet from chainage 129,000 feet for the water line). Strain changes in the aboveground compound bends at the ends of the HDD are not considered herein since they can be caused by different operating conditions and/or by typical run-to-run differences in the pig path as it travels through bends.

Based on an overall review of the geometry profiles in 250-foot-long blocks across the HDD section, it was concluded that the bending strains for both pipelines within the HDD section were small compared to the allowable strain levels.

Even though the pipe strain levels are basically benign, a short list of “locations of interest” which exhibit either a *relatively* high vertical bending strain (e.g., $|\varepsilon_V| > 0.05\%$) and/or a monotonically increasing bending strain amplitude or some other feature of interest was developed for each pipeline.

Figures 1 and 2 present plots of the primary location of interest for the oil pipeline while Figures 3 and 4 present plots of the the primary location of interest for the water pipeline. The format of these figures corresponds to the view block plots described above.

Oil Pipeline

The two main locations of interest for the oil pipeline are both located in the aboveground section at the transitions (e.g., at/near the end of the casing and the adjacent vertical support member (VSM)). Figures 1 and 2 correspond to the primary location of interest in the oil line at ≈1,380 feet (from 47,000 feet) on the west side of the HDD. Due to problems with the Year 2000 survey data in this section, it has been excluded from these plots for clarity. This governing location is approximately 35 feet away from the compound bend and coincides with the last VSM before the casing. Although this location does not indicate that the strain is monotonically increasing, the Year 2003 bending strain (approximately 0.12% strain, with an overbend sense) is the largest value in either of the two pipelines. The governing allowable strain value for the oil pipeline is 0.45% and hence the maximum strain “demand” at this location (0.12%) is about 27% of the allowable strain. This level of strain corresponds to an elastic stress of about 36 ksi. The data indicates that the pipe is being pulled down onto the VSM causing the observed overbend curvature at ≈1,380 feet while the adjacent sagbend curvature lobe at ≈1,395 feet coincides with the end of the casing. This curvature pattern is consistent with differential settlement between the below grade pipe in the vicinity of the HDD entry point and the relatively fixed VSM. Figure 5 presents photographs of the oil pipeline at this VSM. The visible opening of the sheet metal jacket around the insulation at the downhill end of the saddle and the localized buckling of the sheet metal jacket near both ends of the saddle confirms the presence of a significant bearing reaction and a pipe overbend at this VSM. A field observed gap between the bottom of the casing pipe and the soil at the HDD entry point of the oil line suggests that the soil around the pipe has settled. Hence, the most likely cause of this deformation pattern is downward settlement of the below grade pipe at/near the HDD entry point. CPAI indicated that the insulation damage was first observed in November 2004. At ≈1,380 feet, the ranking of overbend strains from different surveys was as follows: 2000 < 2001 < 2005 < 2003. This means that the overbend strains increased from 2000 to 2001 to 2003 then in 2005 dropped back down to below the 2003 level. An explanation for the reduction in strain between Years 2003 and 2005 is that the insulation damage somehow allowed the pipe to “straighten out” to some extent (i.e., the insulation damage acted as a “fuse” for the bending). This explanation is consistent with the strain history: maximum strain in 2003, followed by jacket damage (and “fusing”) in 2004, followed by slightly reduced strain in 2005. The maximum observed rate of strain increase at this location was 0.00697% per year between the Year 2001 and 2003 surveys As a simple illustration to put this strain rate and the current strain level into perspective, projection of this rate forward from 2003 (i.e., neglecting the reduction in strain between 2003 and 2005) indicates that it would take about 47 years for the pipe to reach the strain limit at this location.

Water Pipeline

There are two main locations of interest for the water pipeline both located in the aboveground section at the transitions (e.g., at/near the end of the casing and the adjacent VSM). Figures 3 and 4 correspond to the primary location of interest in the water pipeline at a pipe distance between about 1,260 and 1,310 feet (from 129,000 feet). The feature at ≈1,275 feet is an overbend which coincides with the last VSM before the casing and the feature at location ≈1,300 feet is a sagbend which coincides with the beginning of the casing. The feature at ≈1,300 feet has the largest bending strain in the entire HDD portion of the water pipeline. Both of these locations clearly indicate that the magnitude of the strain is monotonically increasing (e.g., at ≈1,300 feet the vertical bending strain progressively increased from about 0.060% in Year 2000 to about 0.085% in Year 2005). The governing allowable strain value for the water pipeline is 0.42% and hence the maximum strain “demand” at this location (0.085%) is about 20% of the allowable strain. This level of strain corresponds to an elastic stress of about 25 ksi. Since this location exhibited the clearest trend of monotonically increasing vertical bending strain, it provides a useful reference for projecting the strains forward in time. The maximum observed rate of strain increase at this location was 0.0075% per year between the Year 2001 and 2003 surveys. As a simple illustration to put this strain rate and the current strain level into perspective, projection of this rate forward from 2005 indicates that it would take about 45 years to reach the strain limit at this location.

Figure 1(a): Oil Line: Resultant Bending Strain Contour History

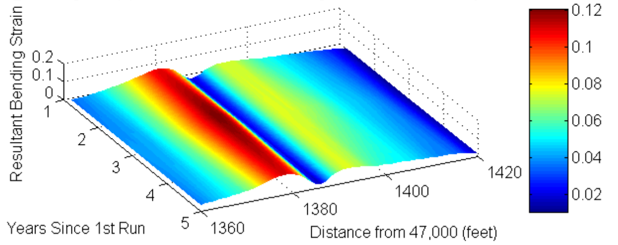

Figure 1(b): Oil Line: Vertical Bending Strain Contour History

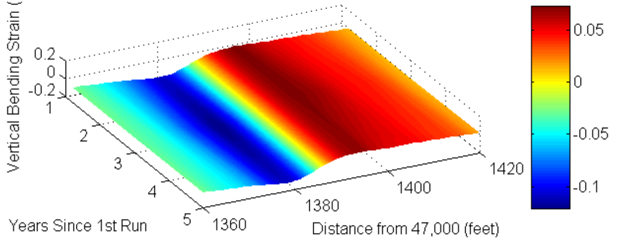

Figure 1(c): Oil Line: Pitch Contour History

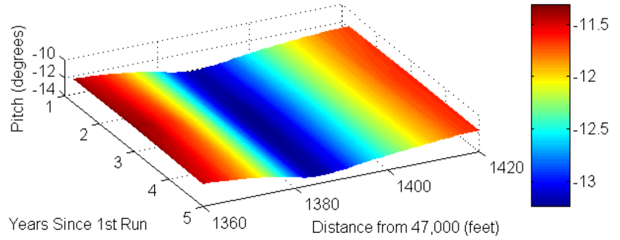

Figure 2(a): Oil Line Resultant Bending Strain Comparison

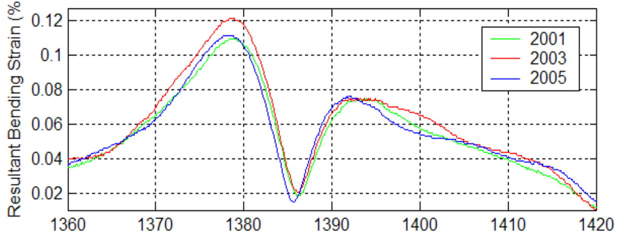

Figure 2(b): Oil Line Vertical Bending Strain Comparison

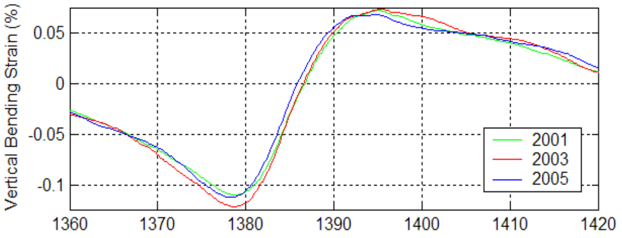

Figure 2(c): Oil Line Pitch Comparison

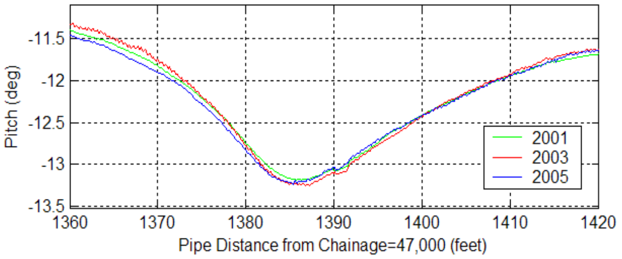

Figure 3(a): Water Line: Resultant Bending Strain Contour History

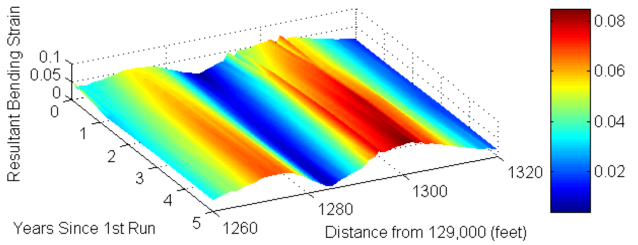

Figure 3(b): Water Line: Vertical Bending Strain Contour History

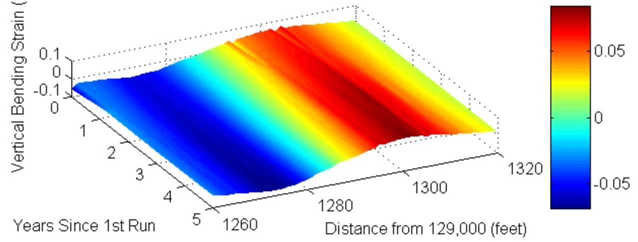

Figure 3(c): Water Line: Pitch Contour History

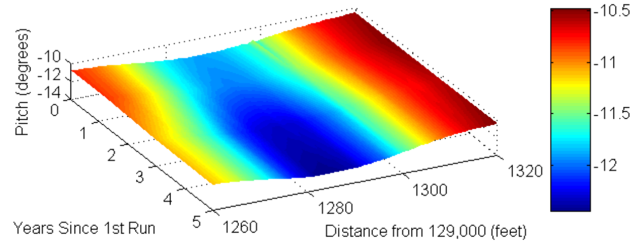

Figure 4(a): Water Line Resultant Bending Strain Comparison

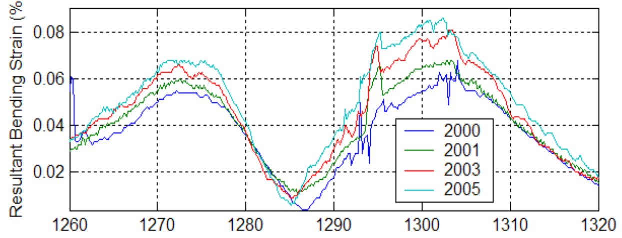

Figure 4(b): Water Line Vertical Bending Strain Comparison

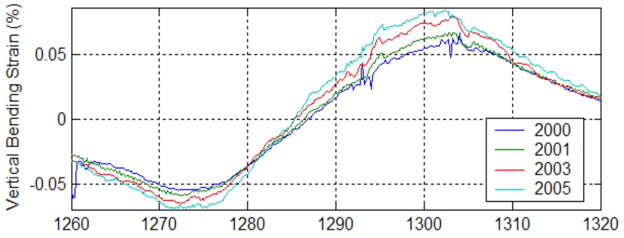

Figure 4(c): Water Line Pitch Comparison

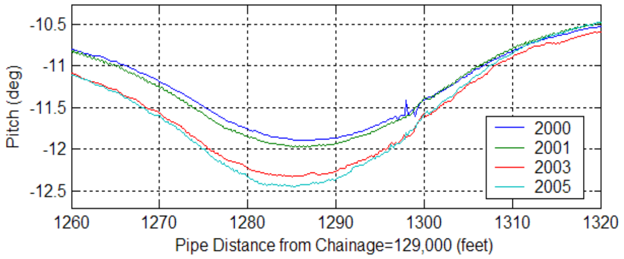

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Figure 5: Photographs of Insulation/Jacket Damage on Oil Pipeline at First VSM Adjacent to HDD

SUMMARY AND OBSERVATIONS

In summary, CPAI has performed four smart pig geometry surveys between 2000 and 2005 to monitor strain changes in oil and water pipelines at the Colville River HDD. These smart pig surveys provide a characterization of the overall pipeline geometry using measurements from a strap-down INS and a set of odometer wheels. The concern for the pipelines at the HDD is that differential thaw settlement could eventually lead to excessive bending strain in the pipelines.

This analysis has shown the following:

(1) The most interesting finding is that the governing strain locations for both pipelines occur in the aboveground transition sections in the vicinity of the end of the casing and the adjacent VSM. At each end of the HDD, the pig data signatures indicate the presence of a sagbend curvature lobe at/near the end of the casing and an overbend curvature lobe at/near the adjacent VSM. This deformation pattern is clearly indicative of relative movement between the below grade section of the pipe and the VSM. The most likely explanation is that the below grade section of pipe at/near the HDD entry point has settled. If the strains at these locations were to eventually increase to levels of concern, the high strain locations can be directly accessed and mitigated (e.g., by lowering the elevation of the VSMs).

(2) The highest bending strain, 0.12%, occurred in the oil pipeline, and was well below the design allowable strain value for that pipeline. Based on the maximum observed rate of strain change, it would take more than four decades at the calculated strain rate to exceed the design allowable strain.

(3) The highest bending strain was detected in the oil pipeline on the west side of the HDD in 2003. Damage to the sheet metal insulation jacketing was observed in the same location in 2004, which likely acted as a fuse to relieve strain build up at this location. As a result of this strain relaxation, the strain measured at this location in 2005 was less than in 2003.

(4) We recommended that close field observations be made at the end of casing and adjacent VSM locations to investigate whether there is any other evidence of either pipe-soil movement or VSM jacking (e.g., soil cracking, visible soil "skid marks" near the bottom of the VSMs, etc.). We also recommended that the pipes be closely observed at each VSM adjacent to the end of the casings for evidence of progressive tearing or buckling of the insulation jacket (e.g., as shown in Figure 5).

(5) We recommended that future geometry pig runs be processed and compared to the previous runs with special attention to the current "governing" bending strain locations in the vicinity of the ends of the casing and the adjacent VSMs in addition to detailed comparisons of the geometry data across the entire HDD. If the bending strains increase at the current governing bending strain locations, then it may eventually be necessary to mitigate the strains by lowering the VSM elevations.

FORWARD-LOOKING INERTIAL MONITORING

An important consideration in any strain-based pipeline design is the "*monitor and maintain*" component of the design philosophy. Periodic monitoring of the pipeline will identify locations that are of concern with respect to the pipe structural integrity. The monitoring interval is selected such that there will be enough time to plan and undertake intervention prior to the pipe experiencing a loss of structural integrity. For the sections of the Alpine oil and water pipelines within the Colville River HDD, the primary mode of intervention would likely be installation of a new bypass HDD pipeline since it would not be practicable to undertake an excavation and repair within the HDD section under the river. With this in mind, it is worth repeating that the *current* governing strain locations for both pipelines are in the aboveground sections of the HDD between the ends of the casing and the adjacent VSMs where a relatively straight-forward intervention could be performed (e.g., lower the elevation of the VSMs to reduce the support reactions and the pipe moments and to recover the elastic strains).

The maximum bending strain levels computed based on the geometry pig runs to date are much smaller than the allowable strains. Simple forward projection of the current strain levels through time indicates that it would take decades for the pipe strains to reach the allowable strain limits even if the maximum previously observed strain accumulation rates were doubled. Based on the observed levels of strain and strain accumulation, we believe that it would be reasonable to progressively increase the survey interval, provided that certain conditions related to data quality, maximum strain, and current rate of strain accumulation are met. Based on this thinking, we recommended that the inertial survey interval be increased to 3 years for the next two surveys (i.e., plan to perform inertial surveys for both pipelines in Year 2008 and 2011) and thereafter, the inertial survey interval be increased to a maximum ongoing value of 4 years (i.e., in Years 2015, 2019, 2023, etc.).

This forward-looking monitoring strategy assumes that there are no data quality issues which would render the inertial survey data questionable or un-usable (e.g., like the Year 2000 surveys). If the inertial survey data from a given run is questionable, we recommend that the survey be repeated as soon as practicable.

In order to develop a strategy for determining appropriate forward-looking monitoring intervals, a simple framework that implements limits with respect to overall strain demand and the current rate of strain accumulation was proposed. A "take action" strain limit, which is taken as some fraction of the allowable strain limit, is established in order to provide a margin of strain and time to plan and undertake an intervention/repair. Although CPAI may wish to select an alternate value, we put forward a "take action" strain limit of 0.35% strain corresponding to roughly 80% of the allowable strains for the oil pipeline (0.45%) and the water pipeline (0.42%). The following steps summarize the recommended framework for evaluating future inertial survey intervals.

(1) Use the current inertial survey data to compute profiles of resultant/total bending strain across the HDD section. If the maximum total bending strain equals or exceeds the "take action" strain limit of 0.35%, perform a detailed review of the subject location to determine if the result represents a true trend in the data or is a spurious numerical result. If the result is valid, immediately proceed toward planning and executing an intervention for the affected line(s)/location(s).

(2) Based on the previous run and current run survey data, compute the along-the-pipe profile of the rate of total strain accumulation across the HDD section:

$$\dot{\varepsilon}_T = \frac{\Delta\varepsilon_T}{\Delta t}$$

where $\Delta\varepsilon_T$ is the difference between the total strain (in %) from the current and previous surveys at a given location and Δt is the elapsed time between surveys (years). Note that this rate corresponds to the current tangent slope of the strain vs. time plot at a given location. Based on a detailed review of the strain vs. time plots at the highest strain locations, the tangent slope provides a reasonable and defendable basis for linear forward projection over the monitoring time interval.

(3) Compute an estimate of the future total strain profile (ε_T^*) by projecting the strains forward in time by Δt years (i.e., to the end of the next monitoring time interval) based on the current values of total strain and the most recent rate of total strain accumulation:

$$\varepsilon_T^* = \varepsilon_T + \Delta t \cdot \dot{\varepsilon}_T$$

(4) If none of the projected strain values exceeds the "take action" strain limit of 0.35%, then proceed with the next scheduled inertial survey.

(5) If any of the projected strain values exceeds the "take action" strain limit of 0.35%, perform a detailed review of the subject location to determine if the result represents a true trend in the data or is a spurious numerical result. If the result is valid, then estimate the time that the strain value will reach 0.35% and schedule the next inertial survey based on the current year plus the next lowest integer year N computed as follows:

$$N = INT\left(\frac{(0.35\% - \varepsilon_T)}{\dot{\varepsilon}_T}\right)$$

If the above calculation is rounded down to N=0, then immediately proceed toward planning and executing an intervention for the affected line(s)/location(s).

The framework outlined above is based on a 3 year interval for the next 2 inertial surveys (i.e., in Year 2008 and 2011) followed by an ongoing 4 year inertial survey interval (i.e., in Years 2015, 2019, etc.). It is our understanding that CPAI may wish to shorten the recommended intervals to coincide with scheduled corrosion surveys (e.g., running a combined MFL/inertial pig). This is acceptable provided that the calculations for strain accumulation rate and forward projected strains are adjusted to reflect the selected interval.

It is important to point out that the framework outlined above should be applied with due caution and with engineering judgment. For example, this framework may "flag" slight misalignments at girth welds as locations of high bending strain, when in reality they are benign imperfections in the pipeline. Similarly, locations where the axis of the pig becomes temporarily skewed with respect to the pipe axis may also be flagged as locations of concern. Any locations which are flagged for intervention should be subjected to a detailed review to determine if the result represents a true trend in the data or is a spurious numerical result. The detailed review may include more detailed run-to-run comparisons (including pitch, yaw, etc.), evaluation with different curvature gage lengths, examination for girth weld effects, possible implementation of low-pass filtering for noise removal, etc.

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