

NPS 8 GEOPIG: INERTIAL MEASUREMENT AND MECHANICAL CALIPER TECHNOLOGY

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ABSTRACT

The Geopig inspection tool provides pipeline operators with three-dimensional geographic and geometric information of their pipeline system. This paper reviews two of the primary technologies onboard the NPS 8 Geopig that are used to provide such information: the inertial measurement unit (IMU), which provides structural and geographical characteristics of the pipeline, and the mechanical caliper arms, which capture the internal diameter of the pipeline.

Recognizing the benefits of the tool and the data it can provide, Wascana Energy Inc. executed an inspection of a natural gas pipeline in Northern Alberta. The pipeline, which had buckled and sheared at a specific location, was inspected with the Geopig to further identify any other possible buckles, wrinkles or dents prior to re-commissioning. This paper reviews the inspection project undertaken, the data compiled by the Geopig, and the steps taken in the development of a predictive finite element model of the pipeline.

BACKGROUND

Geopig Inspection Capabilities

The Geopig has traversed through many onshore and offshore oil and gas pipelines worldwide, inspecting their respective fitness for service levels from a pipe deformation perspective. Its' uniqueness as compared to standard caliper inspection tools is that it provides pipeline operators with a highly accurate, three-dimensional geographic and geometric representation of the pipeline. Both internal cross-sectional details and centerline axial data are obtained in a single inspection run. This allows operators to identify, characterize and locate pipeline dents, buckles, wrinkles, ovalities and bending strain to very high degrees of accuracy. The dynamics associated with such features (e.g. slope instability, subsidence, frost heave, upheaval buckling, river crossings, free spanning, overburden and pressure and

temperature changes) can also be assessed, predicted and/or analyzed by incorporating the data from the Geopig into a finite element model of the pipeline. Such modeling can effectively simulate responses to changes in the loading conditions (i.e. stress/strain) associated with the system.

The (x,y,z) coordinates gathered by the Geopig also provide the end-user with a plan and profile view of the pipeline (i.e. as-builts), which can be used to accurately locate defects in the desired (x,y,z) coordinate plane. This type of true pipeline routing and feature location information, when assembled in digital format, can be downloaded directly into any Geographical Information System (GIS).

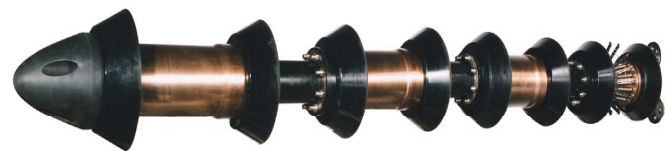
NPS 8 GEOPIG

General Tool Features

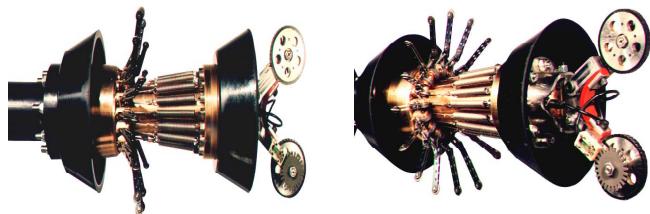
Development of the NPS 8 tool required the incorporation of some of the latest electronic and mechanical advances as to ensure its' operational effectiveness in small diameter pipelines. The miniaturization of a commercially available inertial measurement unit and the utilization of mechanical caliper arms (i.e. as opposed to ultrasonic sensors) represent the two major modifications incorporated into the infrastructure of the tool. Both of these technologies are separately discussed in more detail in later sections of this paper.

The NPS 8 Geopig, as shown in Fig. 1, is a multi-body inertial inspection tool, which can also be configured to inspect NPS 10 pipelines. It weighs approximately 91 kg (200 lbs) and spans roughly 2.4 m (8.4 feet) when assembled under a four-canister configuration. The composition of the canisters is beryllium copper, which is a corrosion resistant alloy that enables inspections to be performed in the harshest of oxidizing environments (i.e. seawater, sour gas). The front can houses the tools' lithium batteries. Run times of approximately 70 hours per battery pack are achieved. Depending on the length of the

pipeline and/or the inspection velocity anticipated, an additional canister can be mounted at the front to accommodate more batteries. The inertial measurement unit, solid-state data storage, and mechanical caliper system complete with odometers, electromagnetic tracker and control electronics consecutively occupy the remaining canisters. They are all pressure tested to 20,685 kPa (3,000 psi) prior to operation and are connected via flexible, polyurethane universal joints. These flexible couplers allow the tool to navigate 3D bends (minimum) in an NPS 8, 25.4 mm (1.0 inch) wall thickness, pipeline configuration. Navigation of 1.5D bends (minimum) under an NPS 10 configuration may also be achievable when specific modifications are made to the universal joints.



Full View of NPS 8 Geopig



Side Views of Rear Canister, Mechanical Calipers and Odometers

Figure 1 NPS 8 Geopig

The drive cups are composed of standard, polyurethane material and are modified accordingly when corrosive environments are anticipated.

Data storage capacity is rated at 248 Mbytes, representative of approximately 60 hours of inspection time. Flash card (i.e. microchip) technology is utilized. Denser memory cards can also be inserted if the requirement for more memory is anticipated.

Operating Specifications and Defect Detection Accuracies

General pipeline operating conditions required to execute a Geopig inspection project are summarized in Table 1. These operating specifications can vary as a result of differing pipeline parameters encountered with each inspection project.

The accuracies the Geopig inspection tool can provide with respect to defect detection and characterization are summarized in Table 2.

Table 1 General Pipeline Operating Specifications

Mission Length	70 hours
Operating Speed	5 m/s (16 ft/s)
Minimum Passable Bend Radius	3D
Maximum Operating Pressure	15,170 kPa (2,200 psi)
Operating Temperature	0 – 60 °C (32 – 140 °F)

Table 2 Specified Defect Detection

Detection Parameter	Accuracy
Survey Accuracy	1:2,000 (x,y,z)
Dent & Feature Size & Depth	+/- 1.0 mm (+/- 0.04 inches)
Dent & Feature Orientation	+/- 11.25 deg. arc
Ovality	+/- 1.0 mm (+/- 0.04 inches)
Curvature Detection	+/- 0.02% Strain
Weld to Weld Distance	+/- 1.0 cm (0.4 inches)

Inertial Measurement Technology

Overview. Post-construction forces can act on a pipeline via the interaction between the earth and the pipeline, causing non-anticipated bending to occur. These forces can be in the form of unstable slopes acting laterally or along the pipe, scouring that causes spanning of the pipeline, thermal changes that cause upheaval buckling, frost that causes cycling and fatigue, or overburden that can stress the pipe.

A Geopig run and analysis will identify the areas where there is bending in the pipeline through the marriage of: pipeline positional data provided by the inertial measurement unit, odometer data, and actual Universal Transverse Mercator (U.T.M.) geographic coordinates of Geopig identifiable pipeline features (i.e. valves, tees, bends). When a Geopig run is conducted immediately after construction, the initial construction bending (inactive forces) can be separated from the earth movement bending (active forces). It is the active forces that are usually of concern as they are continuing to act on the pipeline and may result in yielding and ultimate failure.

Inertial Measurement Systems. The positional vector data collected by the Geopig during an inspection run represents a critical information set needed to accurately calculate pipeline curvature and bending strain. Development of a small diameter Geopig thus relied heavily on the miniaturization of commercially available inertial measurement systems for incorporation into the inspection tools' infrastructure.

The NPS 8 Geopig uses a miniature, strap down, fiber optic gyroscope (FOG) based inertial measurement unit (IMU) to acquire position and dynamics information within the pipeline environment.

Inertial navigation systems utilize data from accelerometers and inertial angular velocity sensors (gyroscopes) to determine a physical body's position and velocity relative to some reference coordinate frame. IMU's do not become inertial navigation systems (INS) until the data that they generate has been processed to provide positional

information. Plotting position versus chainage will give the plan and profile of the pipeline but will not provide information about the pipeline environment, such as vehicle dynamics. The NPS 8 Geopig records all IMU data, and that data is post-processed after the run to provide positional, attitude and dynamics information.

The inertial system on-board the NPS 8 Geopig can be classified as analytic. Analytic inertial measurement systems do not instrument a reference frame but use gyroscopic and accelerometer outputs to calculate the relative orientation between the system's initial and present state. This type of system is called a strap-down inertial system. Strap-down IMU's have a triad of mutually orthogonal angular rate sensors as well as a triad of mutually orthogonal accelerometers rigidly mounted to the body to be instrumented.

Fiber Optic Gyroscope Technology. Fiber optic gyroscope (FOG) technology is a reasonably new angular rate sensor development. A beam of coherent light from a laser diode is split and is sent in both directions around a fiber optic spool. The light is detected in a photo sensor and the amplitude of detected light is a function of the phase difference between the two incident beams. Angular rotation of the sensor about the bobbins central axis will change the phase shift seen at the sensor. The light beam has to be modulated to determine the sign of the angular rate. In short, optical interferometry. The sensitivity of the sensor is a function of the fiber length, spool radius and phase detector accuracy. There are several other parameters that need to be monitored and accounted for to ensure accurate sensor operation. The sensor requires reasonably low power, has no moving parts to wear, and can measure a wide range of angular rates. Another benefit of using FOG technology is there are only gravity-sensitive drifts to account for in the error budget. Gravity-sensitive drifts in rotating gyroscopes are largely due to small mass imbalances in the rotor of the gyroscope and their orientation to any acceleration. Basically, a FOG's drift does not change as the attitude of the sensor changes in an accelerated field.

Mechanical Caliper Arm Technology

The NPS 8 Geopig has a total of 16 mechanical fingers that measure the interior pipe geometry by contacting the inner surface of the pipe. Each finger has a rotational magnetic sensor utilizing a Hall Effect transducer to convert finger (or caliper) movement to the equivalent deviations of the pipe wall from the circular shape. The signal from each of the rotational sensors is converted to an analog voltage proportional to the deflection of the fingers. The data is then processed and stored by the on-board circuitry for post run retrieval and analysis. Hall Effect transducers were selected as they characteristically produce high-resolution measurements with noise immune signals and require very little power to run.

The fingers are fabricated from high strength steel material and are epoxy coated for corrosion resistance. As with the sensor, miniaturization of the caliper parts was necessary to accommodate several calipers on the NPS 8 tool. It was also realized that the mechanical fingers needed to be robust and flexible to survive the vibration and dynamic impact from a high-speed pig run. The remote chance of the tool moving backwards in the line was also considered by allowing the mechanical fingers to articulate should the arm hit an

obstacle. A set of small springs snaps the arm extension back into position once the tool starts moving forward. Contact with the pipe wall is maintained at all times by the large extension spring under high pre-load. Dynamic tests on the fingers, as well as results from recent live runs, have shown that the spring pre-load is sufficient to maintain contact with the pipe surface with no skipping or arm bounce problems.

The tip of the mechanical finger has a small wheel that is in contact with the inner pipe wall. It is made from a hardened tool steel material and tempered for optimum wear and impact toughness. The rolling wheel allows the fingers to maintain physical contact with the pipe wall with minimum friction and leaves no abrasion marks on the pipe surface. The wheel and bearing assembly on the NPS 8 tool has undergone long duration, unlubricated testing with conditions of up to 5 m/sec (16.4 ft/sec) for 350 km (217 miles) with minimum wear on the bearings and no appreciable wear on the wheel.

INSPECTION PROJECT OVERVIEW

The Pipeline

A sour gas pipeline was installed for the purpose of transporting sour natural gas and associated liquids from the wellhead to a central processing facility. The line consists of approximately 27 km (17 miles) of 219.1 mm OD (8.625 inches) x 5.6 mm WT (0.22 inches), Gr. 359, Cat. 2 steel line pipe, complete with 25.0 mm (0.98 inches) of Shaw 'Insul-8' insulation. The line was designed to operate at a maximum pressure of 9,310 kPa (1,350 psi) and a maximum temperature of 80°C (176 °F).

The pipeline was installed during severe winter conditions from December 1996, to February 1997, through varied terrain including intermittent muskeg. In early April 1997, a leak was detected in the pipeline at a road crossing located approximately 600 m (1,969 feet) from the wellhead.



Figure 2 Photographs of Failed Pipe

Lab analysis of the failed pipe (see Fig. 2) indicated that the failure was a result of compressive buckling due to thermal expansion.

It was imperative to fully understand the failure mechanism to eliminate the possibility of future incidents on this or other similar

installations. A detailed inspection was required to evaluate the condition of the entire pipeline. Since the mode of failure was not corrosion, conventional “smart pigs” would be ineffective in identifying any unusual movement or distortion in the pipeline due to thermal expansion. The Geopig offered the ability to accurately map the pipeline as well as identify any buckles, wrinkles and/or dents along with their associated geometries prior to re-commissioning. Further, Geopig data would allow calculation of actual stress and strain at any location along the pipeline. By establishing appropriate stress and strain thresholds, specific locations requiring repair could be identified.

Geopig Inspection Results

Curvature and Bending Strain Theory. The curvature of a line in a three dimensional space is defined as the change of direction (in radians) over the distance. The distance traveled is measured by the odometers, whilst the direction of the pipe centerline is computed from the inertial measurement system in terms of azimuth and pitch. As described by Czyz et al (1996), the pitch $P(s)$ describes the pipeline tilt with respect to the horizontal plane at chainage s , while the azimuth $A(s)$ specifies the angle between the pipe direction and north. The horizontal component of the curvature is proportional to the change of the azimuth, and the vertical component is proportional to the change of pitch. The following formulae are used for computation of total pipeline curvature (κ) and its vertical (κ_v) and horizontal (κ_h) components, based on the changes ΔP and ΔA of pitch and azimuth over a distance Δs along the pipe centerline (Czyz and Adams, 1994):

$$\kappa = \sqrt{\kappa_v^2 + \kappa_h^2}, \quad \kappa_v = \frac{\Delta P}{\Delta s}, \quad \kappa_h = -\frac{\Delta A}{\Delta s} \cos(P) \quad (1)$$

The relationship between curvature and bending strain (i.e. total curvature and its’ vertical and horizontal components) is as follows (Czyz et al, 1996):

$$\varepsilon = \frac{D}{2} \kappa, \quad \varepsilon_v = \frac{D}{2} \kappa_v, \quad \varepsilon_h = \frac{D}{2} \kappa_h, \quad (2)$$

where D is the pipe outside diameter. The curvature radius is the inverse of the curvature.

Geographic Survey. Geographic coordinates (U.T.M.) of the pipeline are determined by establishing Global Positioning System (GPS) control points along the pipeline every 5 km (3 miles) and then “tying” the inertial measurement data to these points during data processing. By transforming the pig’s trajectory into the tie points, accurate “real world” northings, eastings, and heights (N,E,h) can be obtained for any point along the pipe.

A technique known as differential GPS is used to establish the tie points and subsequently locate any features or defects found by the inspection tool. Location accuracy is controlled by the separation of control points. Co-ordinates and elevations of the launch and receive

traps plus intermediate pipeline locations (i.e. valves, bends, tees, heavy wall sections) are used for the control network.

Geopig Results and Actual Findings. The two-section pipeline was inspected in the spring of 1997. The data from the first 15 km (9.3 miles) section has been summarized within this section of the paper.

Results were analyzed using two separate, interactive computer software programs: Geodisplay and Geodent. Geodisplay’s primary function is to summarize processed information related to the geographic and bending/strain data (i.e. plan, profile, horizontal and vertical curvature, curvature radius, slack chainages, etc.). Geodent displays processed information related to the geometric integrity of the pipeline (i.e. buckles, wrinkles, dents, etc.).

Figure 3 is a Geodisplay output summarizing some of the more important geographic-related parameters of the entire pipeline. The plot is divided into five panels, each displaying a different piece of information. The top panel displays an aerial view of the pipeline (i.e. plan). The distance between the large crosshairs is 1,000 m (3,280 feet) and 500 m (1,640 feet) between the smaller ones. The numbers along the pipeline indicate pipeline slack chainage, as measured by the Geopig. The next panel displays the profile view of the pipeline with a vertical scale of 100 m (328 feet). Elevations between 581 – 681 m (1,906 – 2,234 feet) were encountered along the pipeline route, inclusive of two water crossings. The next two panels display horizontal and vertical pipeline strain percentages, respectively. The final panel displays the curvature radius of each bend in terms of pipe diameters. Most of the bends in the pipeline have a bend radius of about 30 pipe diameters.

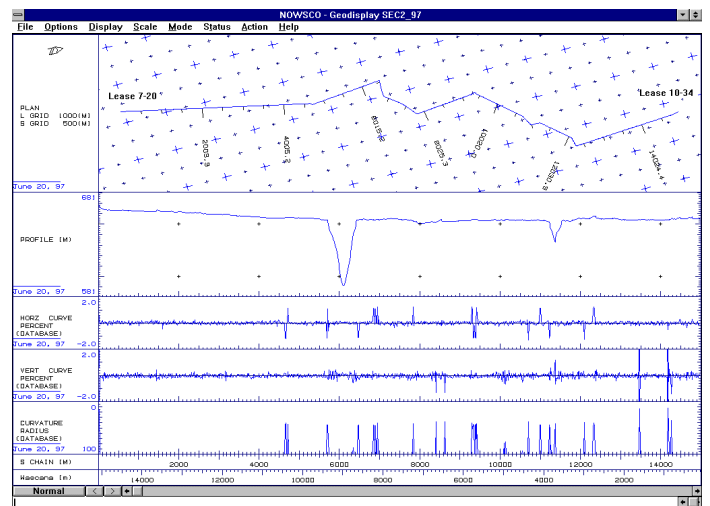


Figure 3 Geodisplay Output of Entire Pipeline Section

Figure 4 shows much of the same information as Fig. 3, however the plot is expanded around the area of a discovered buckle/wrinkle (i.e. at chainage 14,181 m (46,526 feet)). The profile view shows a

vertical displacement of approximately 0.7 m (2.3 feet) over a distance of about 10 m (33 feet). A horizontal strain of 0.5% and a vertical strain of 3.2% is associated with the discovered anomaly. Displayed directly beneath the vertical curvature panel is a track of information displaying the location of welds and the joint lengths. The identified buckle is located 2 m (6.6 feet) upstream from the nearest weld. Further down, another panels displays the internal diameter of the pipeline as measured by the Geopig mechanical calipers. It shows that the diameter increases by about 1.0 cm (0.39 inches) at the location of the identified buckle.

Figures 5 and 6 are Geodent displays of the identified buckle at chainage 14,181 m (46,526 feet). The top panel in Fig. 5 shows a contour map of the feature, with different colors representing the depth at different points (i.e. as per the color gradient to the left of the display). The pipe is displayed as if it had been cut along the top (i.e. 12:00 position) and then folded open so that the bottom of the pipe (i.e. 6:00 position) is in the middle of the track. The top of the pipe is thus along the top and bottom edges of the plot. From this, it was determined that the deepest point of the buckle was located at the bottom of the pipe (i.e. 6:00 position) and had a depth of about 1.0 cm (0.39 inches). The bottom panel displays a three dimensional view of the feature and its' respective shape when "opened" at the 12:00 position.

at the bottom of the pipeline. Field measurements confirmed the values predicted by the Geopig with respect to the geographic location of the anomaly, the amount of upheaval, the existence of the buckle and its' size and location on the pipeline.

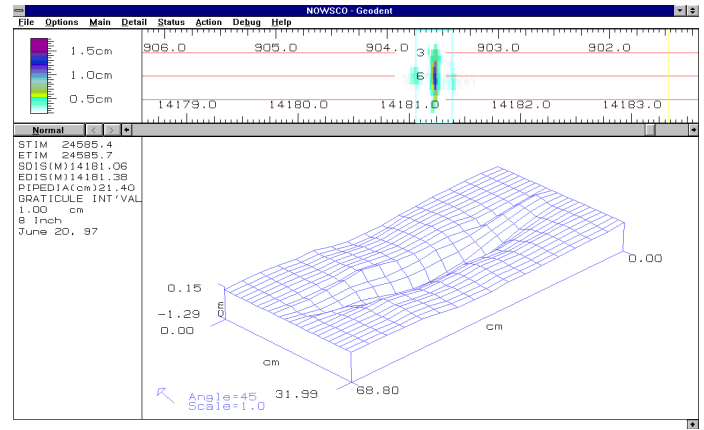


Figure 5 3-D View of Buckle/Wrinkle

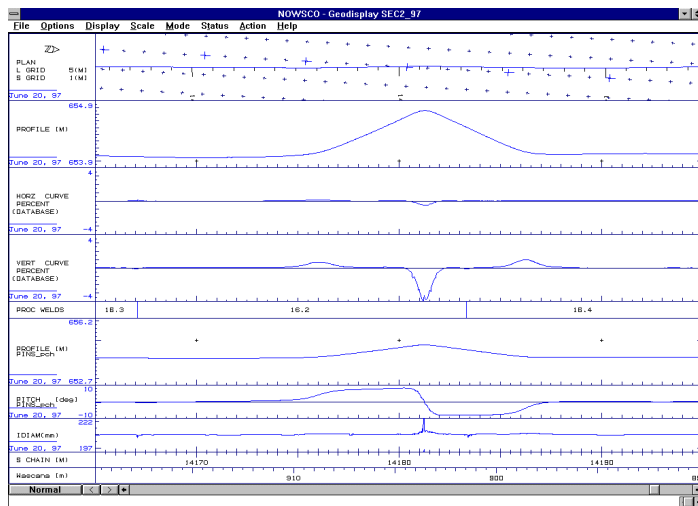


Figure 4 Buckle/Wrinkle at Chainage 14,181 m

The bottom panel in Fig. 6 shows a cross-sectional view of the pipe at the location of the buckle, using an exaggerated scale. The concentric circles represent 5 cm (2 inches) intervals. This plot re-confirms that the pipe diameter has increased by about 1 cm (0.39 inches) at the location of the buckle.

Figures 7 and 8 are photographs of the pipeline excavation site. Figure 7 shows the upheaval of the pipeline (i.e. with the insulation removed) at the location predicted by the Geopig. The square on the photograph identifies the area where the buckle/wrinkle was found. Figure 8 is an expanded view of the buckle/wrinkle, which was located

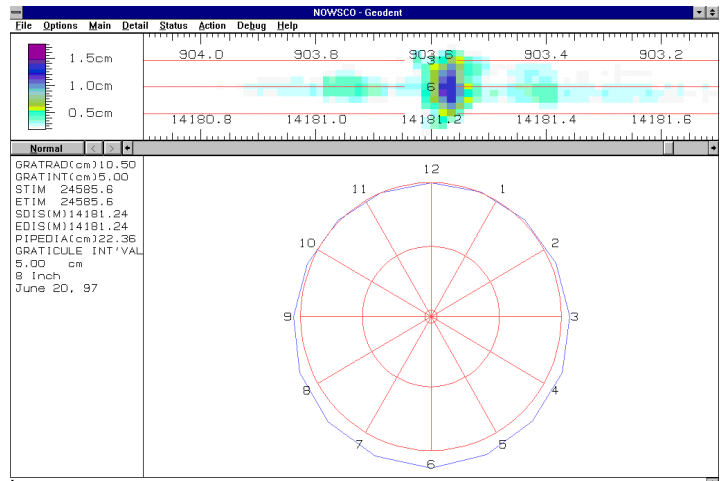


Figure 6 Cross-Section at Crest of Buckle/Wrinkle

Pipeline Stress and Geotechnical Modeling Overview

Ultimately, a finite element model would be developed to predict the pipeline's behavior for various operating conditions. Several critical variables were required for input into this model. Firstly, a geotechnical investigation was required to characterize the soil-pipe interaction (i.e. namely, soil modulus (spring constant)) and, to a lesser extent, sidewall friction.

Various in situ tests were conducted to determine these characteristics. Field models were assembled where a portion of pipe was buried and then hydraulically jacked against a variety of backfill

types, measuring the applied load and displacements. The resulting load-displacement curves for backfill provided a bi-linear soil modulus with a spring constant and an ultimate value beyond a given strain. Pull out tests were also conducted to assess the longitudinal friction. Lastly, the entire pipeline was manually probed at 10 m (33 feet) intervals to classify the type and depth of soil encountered. These results were then entered into the finite element model to characterize the soil-pipe interaction.

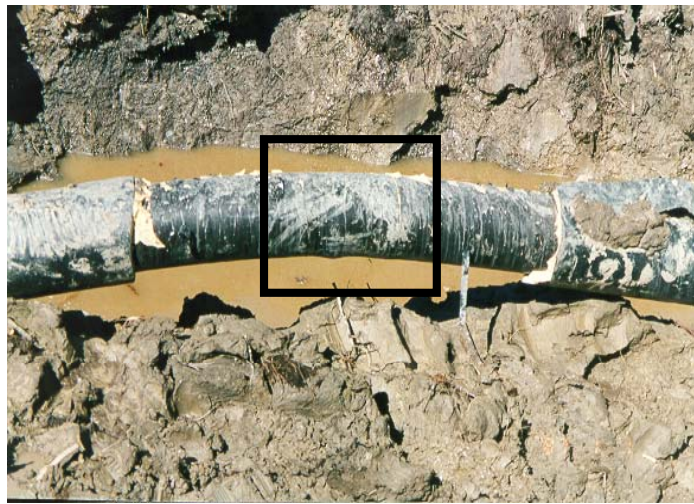


Figure 7 Upheaval and Buckle/Wrinkle at Excavation Site



Figure 8 Excavated Buckle/Wrinkle

Another significant variable required for the model was the operating temperature profile. The line temperature is dependent on the makeup of the fluid in the pipe and on the flow rate. The

equivalent properties of a single fluid in the pipe were calculated for a range of mixes of the individual fluids (i.e. water, condensate and gas). A blended average of heat capacity was used for each mix and flowrate in the line simulations.

The geometric data compiled by the Geopig was used to calibrate the model. The predicted shape of the pipeline from the model, at given locations, was compared against the actual results from the Geopig. Discrepancies were accounted for by adjusting the soil-springs within the model until the actual pipeline displacement was duplicated. Once satisfied with the model, it was used to predict pipeline behavior when subjected to a wide range of operating conditions with varied flowrates, temperatures and fluid compositions. Repairs and remedial action were recommended based on this model and ultimately resulted in fewer repairs than had been originally anticipated. Several 'upheaval sites' did not pose an unusual risk for a specific set of operating conditions. Further, the model was used to provide a threshold for increased thermal load beyond which additional field repairs would be required.

CONCLUSIONS

The use of the Geopig provided two especially valuable pieces of information. Firstly, and most importantly, it identified abnormalities in the pipeline that would have otherwise been undetected, two of which may potentially have resulted in line failures. This triggered a more detailed investigation into the condition of the pipeline and may have prevented prematurely re-commissioning the pipeline. Secondly, the data from the Geopig was a critical component in developing the pipeline model. This model was eventually used to defer some costly repairs indefinitely and delayed others until necessitated by future changes in operating conditions. The model also proved to be invaluable in evaluating the effectiveness of proposed repairs to the pipeline. This is an extremely cost effective approach especially when dealing with expensive remote access pipelines.

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