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Monitoring Pipeline Movement for the Prevention of Pipeline Failures Using an Inertial Geometry Inspection Pig

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Abstract

In 1994, Snam SpA, the owner and operator of a large network of transmission and distribution pipelines in Italy, tested the GEOPIG, an Inertial Geometry Inspection Pig capable of measuring very small changes in pipeline bending strain with the conclusion that the tool could be integrated into the existing, though proven, programme of strain gauge monitoring. In 1996 a baseline geometry survey was performed on an additional 6 sections of main transmission lines to further evaluate the capabilities and benefits of inertial geometry data for assessing pipeline movement with a view to incorporate this technique as a key monitoring tool for the entire network.

This paper discusses the pipeline movement identified over the following 3 year period by the inspection tool, the infield verification of areas of concern and the early identification of wrinkles induced by pipeline instability using onboard high resolution callipers. In addition, the benefits of this technology with respect to the overall integrity monitoring system are discussed.

Introduction

When it comes to intelligent pigging, if asked, most people would think of corrosion inspection. However, throughout the world, a significant proportion of pipelines failures are due to geometry related defects caused by pipeline movement, upheaval and induced bending strain.

SNAM SpA. operates a 29,000 km pipeline transmission and distribution system in Italy. Due to the mountainous geography, many of these pipelines cross areas where the risk of movement or subsidence is high.

As a result, the entire Italian network is monitored. All areas of geological risk are identified and classified, and any pipeline laid in a possible risk zone is pinpointed and surveyed. All these areas are periodically inspected and the most active ones are monitored using vibrating wire strain gauges on the pipe, and inclinometers and piezometers on the ground.

Generally 3 to 4 piezometers and inclinometers are used for a pipeline section 100 m to 150 m long, and 4 to 5 pipe sections are instrumented by means of 3 longitudinal strain gauges placed around the pipe circumference at 120° one to another. The instruments are read at intervals, more frequently during the rainy months.

Having identified that over 1,800 geotechnically unstable areas exist, Snam has, for more than 20 years, successfully monitored over 320 critical areas using this combination of pipeline strain gauges, inclinometers and piezometers. In all of them the rate of ground movement falls into the categories of "very slow - extremely slow" of the Varnes classification. These movements can obviously escape visual examination even by specialised staff, and can be discovered only by using strain gauges and inclinometers.

Therefore, any pipeline lying in a potentially unstable area is geologically surveyed in order to determine morphological evolutions. Periodic inspection is carried out thereafter. The monitoring system, combined with direct observation from landslides has enabled Snam to control the ongoing effects of ground movement due to soil instability and the resulting stresses induced on the pipelines. On areas where pipeline movement is identified, if soil consolidation, draining and remedial support works do not have adequate effect, then if strain gauge data exceeds a threshold value, intervention may be deemed necessary. In such an event the pipe can be exposed and relieved or in extreme cases can be cut to remove the build up of mechanical stress. (See Fig. 1.)

In 1994, Snam approached BJ Pipeline Inspection Services based in Calgary, Canada to evaluate the potential of Inertial Geometry Surveying to compliment the existing monitoring system. After initial examination, it became evident that the Inertial Surveying provided an opportunity to assess bending strain and internal bore changes e.g. ovalisation and wrinkling, due to ground movement for the entire pipeline length in a single inspection run. This was a key benefit as the existing method using strain gauges and piezometers required early identification and localised monitoring at areas of concern. This technique requires intensive surveying, planning and monitoring work to ensure that all risk areas are being observed.

The overall specification claimed by BJ with regard to run to run strain and caliper accuracy was promising to Snam and it was decided that a performance test should be carried out. The primary objective of the test was to verify BJ’s ability to obtain the declared performances and to check the accuracy and repeatability of the collected data. A second objective was to evaluate fitness and usefulness of the inertial geometry data for the particular aim of monitoring unstable areas. In more detail Snam wanted to evaluate the Inertial Geometry tool in order to:

- support the geotechnical periodical surveys
- support expert selection of terrain, areas and pipe sections to be instrumented
- complete the information collected by means of the vibrating wire strain gauges
- support and validate the mathematical models now available and to give improved indications to develop the new ones
- detect risky areas that escaped the geological surveys.

In order to achieve this secondary objective, the availability of inertial data collected on a geotechnically well known pipeline was considered of great importance. Therefore a 26 line was chosen for this purpose.

Inertial Geometry Tool Description

The Geopig is designed to meet a large variety of requirements using a modular design approach integrating a variable number of different sensors. The tool can be customised and adapted to fluid or gas lines with minor modifications. A typical layout drawing of one of the inspection tools in Snam's pipelines is included in Fig. 2.

The major systems of the Geopig consist of the inertial navigation system and the mechanical calipers. Other sensors and devices complement the tool, such as the odometers, pig-tracking transmitter, solid-state memory system and power supply. The Geopig is generally suspended in the pipeline by urethane pig cups at the front and rear of the carrier, however in this case due to the known dynamics experienced on previous runs, support wheels were also adopted. The aim of wheel/cup combination being to maintain the inspection tool's movement close to the centreline of the pipe.

Strapdown Inertial Navigation System

A Strapdown Inertial Measurement Unit (IMU) is the heart of the equipment and delivers position and attitude of the pig along its trajectory within the pipe. The IMU produces three-dimensional measurements of inertial acceleration and angular rate directly from orthogonal triads of accelerometers and gyroscopes. The Geopig uses an inertial navigation system containing three fibre optic gyroscopes and three single-axis accelerometers. The strapdown accelerometers and gyros deliver the measurements for computing pipeline curvature, orientation of the curvature, and the positioning capability for location of the curvature or other detected features. The accuracy of these is listed below:

Bending strain accuracy	+/- 0.02%
Run to Run Accuracy	+/- 0.01%
Bend angle accuracy	+/- 0.1 °

Calipers

A ring of mechanical fingers scans the wall of the pipe in order to measure the internal pipe shape and diameter. They are also used to detect the location of girth welds in the pipeline. There are 32 fingers spaced at constant angles around the ring on the pig. This corresponds to a spacing of 6cm between caliper traces on the pipe wall. The data from the caliper arms is sampled at 128 Hz. A typical pig velocity in this line of 0.4 m/s results in a distance of about 3mm between samples for each caliper arm. The specifications for the caliper data is as follows:

Dent /ovality sizing accuracy	+/- 2.5mm
Feature detection level	2.5mm

Inertial Data Processing

The Geopig inertial survey provides pipeline plan, profile and bending strain. This allows to locate the pipeline in the desired UTM mapping projection, and to detect pipeline movement between runs. Pipeline position is provided in terms of Northing, Easting and height as a function of the chainage.

Pipeline Position

Inertial data is translated, rotated and scaled to the "tie points" with known co-ordinates. Those points are typically selected at traps, valves, welds, bends, wall thickness transitions, or any other pipeline features that can be detected directly or indirectly by the Geopig sensors. The co-ordinates of those points are usually obtained from the GPS survey. This procedure provides correction for long term drifts that can introduce an absolute position error in the inertial survey over time. By transforming the Geopig trajectory into the tie points, the Northing, Easting, and height can be obtained for any point along the pipe.

The specified accuracy of the inertial survey is 1:2,000 of the distance from the tie points, therefore for the following sample distances between the tie points the following absolute accuracy is obtained:

Distance Between Tie Points [m]	**Absolute Accuracy [m]**
5,000	1.25
3,000	0.75
1,000	0.25
100	0.025

For example, if the data from two Geopig run have been tied to the points that are 3 km apart, then the allowable error in-between the ties points can reach 0.75 m, which corresponds to up to 1.5 m difference between two runs.

Pipeline Movement

Inertial data can be used to monitor pipeline movement between two runs. The overlaid strain data from two runs are compared in order to identify the areas of strain differences associated with pipeline movement. For easy comparison and accurate measurement of the movement the chainage from the subsequent runs is aligned with the chainage from the baseline survey my means of matching girth weld positions.

Bending Strain

There are two main components of the strain tensor in a pipe wall: the longitudinal strain (in the direction of the pipe axis) and the hoop strain (in the circumferential direction). The longitudinal strain is further separated into the axial component (i.e. membrane strain that is constant in a pipe cross-section) and the bending component that changes linearly along the pipe cross-section (Fig. 3a)

The bending component of the longitudinal strain at any location in the pipe cross-section can be computed based on the bending strain at two points, e.g. at the top of the pipe (6 o'clock position) and on a right side (3 o'clock position). The bending strain at the bottom of the pipe is called the vertical strain ε_v, because it is induced by bending in the vertical plane (the bending strain at the top of the pipe has the same absolute value, but the opposite sign, i.e. - ε_v). For a similar reason the bending strain on the right side of the pipe is called the horizontal bending strain ε_H (the bending strain on the left side is equal to - ε_H). The maximum bending strain ε in the entire pipe-cross-section is equal to: [Ref. 1]

$$\varepsilon = \sqrt{\varepsilon_v^2 + \varepsilon_h^2}\ . \qquad (1)$$

Both the vertical and horizontal bending strains are computed from the Geopig survey using the measurements of the pipe centreline curvature (see figure 3b). The curvature of a line in a 3-D space is defined as the change of direction (in radians) over the distance. The distance is measured by the odometers, and the direction of the pipe centreline is computed from the inertial system in terms of azimuth and pitch. 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 the 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 formulas are used for computation of the pipeline total 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 centreline:

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

The relationship between curvature and bending strain is as follows:

$$\varepsilon = \frac{D}{2}\kappa \qquad \varepsilon_v = \frac{D}{2}\kappa_v \qquad \varepsilon_h = \frac{D}{2}\kappa_h \qquad (3)$$

where D is the pipe outside diameter.

The curvature radius is the inverse of the curvature. The BJ software reports strain in percents and the radius of curvature in pipe diameters. Strain is a unit less value, which can be expressed in percents by multiplying it by 100%, e.g. 0.2% corresponds to 0.002 strain.

Characteristics of Strain Induced by Environmental Forces

The Geopig measures the total bending strain of a pipeline at the time of inspection, which includes both strain induced during the construction, and the strain caused by the operating conditions and geo-technical forces affecting the pipeline during operation (e.g. slope instability, soil settlement, erosion at river crossings, etc.).

When analysing the bending strain induced by pipe interaction with soil the high residual plastic strain present in the field bends should be disregarded. The main features distinguishing the bending strain caused by geological forces from the field bends are briefly discussed below. The bending strain in the field bends is usually in the range from 0.5 to 2 % strain, is confined to one pipe joint and is characterised by an abrupt change of strain at the beginning and the end of a bend. The bending strain induced by the soil movement is usually of smaller amplitude, spans more than one pipe joint and undergoes gradual change over longer transition sections.

Horizontal strain is indicative of slope instability, although it might have also been induced during the construction as a result of out-of-straightness of the trench, e.g. a rope bend. The vertical strain is usually the result of pipeline conforming to the as-built unevenness of the trench or the ground profile, upheaval buckling or geo-technical phenomena other than slope instability, e.g. soil erosion or settlement.

Phase 1 - The Test

The test was performed in October 1994 and is described in detail in Reference 2. In summary, two inertial surveys were performed on the Rimini - Sansepolcro pipeline which would demonstrate both the accuracy and the repeatability of the survey method. The first survey was deemed a baseline survey, the purpose of which was to determine the initial strain condition of the pipeline. After a baseline had been acquired, Snam introduced an unknown imperfection, imitating ground movement, into the pipeline at an unknown position. The pipeline was displaced horizontally with 4 jacks as shown in Fig. 4. At the test site, 16 vibrating wire strain gauges were installed to accurately determine the induced strain. (see Fig 5.)

Following the second inertial survey run, a comparison of the strain and displacement introduced was made with the field verified data. A comparison of the data is shown in Figs. 6a and 6b.

Based on the close agreement of the survey results Snam were able to conclude that periodical inertial surveys can:

- Monitor geotechnically unstable areas;
- Measure accurately bending strain and movement between runs.

When compared to the existing strain gauge technique:

- Inertial surveying can monitor the entire line whereas strain gauges cannot;

Inertial surveying can work in support of strain gauges but not eliminate them since axial strain must also be monitored. The Geopig is capable of achieving an accuracy of 1-2cm per pipe joint, which is large in comparison to the axial strains anticipated. Additionally a single inertial survey offers the following significant benefits:

- Detection of pipewall deformations e.g. wrinkles
- Reveal areas of risk or movement unidentified from geological surveys
- Provide geographic co-ordinates of the pipeline for easy identification of features or areas of concern;
- Provide and accurate pipeline tally.

Snam, having reviewed the test results, were satisfied that Inertial surveying offered a complementary method to the existing strain gauge monitoring technique and so proceeded to the next phase of the project. Additional pipelines known to experience movement would be surveyed and then monitored over a number of years to provide a further evaluation of the inspection tool's capabilities to detect strain differences due to "real" pipeline movement.

Phase 2 - Baseline Survey of 26” and 30” Transmission Pipelines

In 1996 Snam surveyed two further main gas transmission lines in order to provide a baseline survey.

The first was 26” pipeline approximately 123 km in length. The line was surveyed in two sections. In general terms no significant dents or wrinkles were identified and 489 areas of strain were identified that exceeded Snam’s required reporting threshold. Of these reported features only one was considered noteworthy.

The second line was a 30” pipeline of approximately 75km length. Again no significant dents or wrinkles were identified and 239 reportable strain incidents were identified. In this case, none were reported to be of concern.

Snam’s geological survey department determined that re-survey of the pipelines with the inspection tool would not be possible until 1999 in the case of the 30” and year 2000 for the 26” line. This decision was based upon estimated rate of ground movement compared to the inertial geometry tool’s minimal detectable strain change.

Phase 3 - Re-Survey of 26” and 30” Transmission Pipelines

The 30” pipeline was re-surveyed in November 1999. The aim of this survey being to identify any wrinkles or dents that had appeared or grown during the survey interval and to perform a strain difference assessment on the two sets of survey data which would indicate ground movement. The software used to analyse the inertial data collected has been developed such that the recorded strain from two sets of data are “differenced” and plotted directly. This allows for easy detection of very small pipeline movements in a reliable and efficient manner.

The findings of the two 30” survey runs are discussed in terms of the caliper or internal geometry changes and the strain changes noticed due to line movement.

Internal Geometry

The second run of the inertial tool identified two wrinkles that were not seen during the 1996 survey. Both wrinkles were excavated for further examination. The first wrinkle being quite severe was cut out as a precautionary measure. Figure 7 shows an image of this as determined by the inspection tool. Fig 8 shows the corresponding horizontal strain occurring at the location of the wrinkle.

Table 1 below presents a comparison between the dimensions of this wrinkle as detected by the Inertial Geometry Tool and as measured in field.

	Inspection Survey Data	Field Measured (after cut-out)
Height of the wrinkle	25 mm	36 mm
Base	150 mm	230 mm
Relative distance from the upstream girth weld	980 mm	----
Clock position-apex of the wrinkle	9:00	9:00

Table 1 Geometry Data for Wrinkle at Chainage 13642m.

It can be seen that there is a discrepancy in the wrinkle geometry determined during verification and as measured during the inspection. This discrepancy is believed to have arisen prior to manual measurement and as a result of relief when the pipeline was excavated, cut and removed.

	Inspection Survey Data	Field Measured
Height of the wrinkle	6 mm	4 mm
Base	50 mm	46.5 mm
Relative distance from the upstream girth weld	910 mm	910 mm
Clock position-apex of the wrinkle	8:00	8:00

Table 2 Geometry Data for "Incipient" Wrinkle at Chainage 13642m.

The second wrinkle, as described in Table 2, was very small and was deemed to be a deformation or defect induced during construction. In this case there was good agreement between the caliper data and field measured results. This defect was not considered a risk to the integrity of the pipeline. This defect was not significant in terms of it's size as it lay well below the required reporting threshold and was highlighted and identified as a result of the differential strains measured between the two inspections.

Strain Changes/ Pipeline Movement

As a result of the comparison of two successive inspections of the 30" transmission line, in 1996 and 1999, the Inspection Tool has indicated more than 50 areas where the strain differences developed over the distance of at least one pipe joint with the peak value exceeding 0.01%. Strain differences were identified in both the horizontal and the vertical plane. An example of a typical movement area is presented in Fig. 10

Each area of movement highlighted was assessed by Snam and considered real. However, due to necessary excavation work and intervention at most locations performed in the period between the surveys in most cases movement was not and could not be attributed to geological instability alone. Local relief or movement on the pipeline caused by pipeline intervention has made the cause of the strain differences along the pipeline identified in both the inertial data and strain gauge data difficult to relate directly to a real geologically unstable area.

In addition, another important finding from the first run to run comparison is the difficulty in identifying and discriminating small strains occurring on bends. This can be generally attributed to the different trajectory taken by the inspection tool as it negotiates a bend. Care must be taken in assessing such features as they may not be due to real ground movement.

Conclusions

After testing an Inertial Geometry Inspection tool in a number of transmission lines and having performed a detailed review, SNAM has verified the use and benefits of this technology.

In particular, after a single run Inertial Surveying can give the following useful indications:

- A precise measurement of geometric defects such as wrinkles, ovalities and dents.
- Pipeline curvature/strain due to bending
- Detailed tally and position data.

After having performed two runs this type of inspection technology can give the following further indications:

- A Monitoring method for assessing pipeline movement over the entire length of the pipeline resulting from ground movement or other intervention.
- The possibility to detect new unstable areas in lines that had previously gone unchecked or unmonitored
- Significance and growth of geometrical defects in relation to the strain changes occurring at the same location in the pipe

Future re-inspections of the 26" line scheduled for the end of this year, will be helpful to clarify the following two important outstanding issues:

- A better understanding of the run to run curvature accuracy in bends,
- Definition of criteria to establish the frequency of the re-inspections (possibly relying on the data from installed strain gauges).

Overall, Snam has determined that Inertial Geometry surveying is a useful method for monitoring pipelines in unstable areas but the technology in it's current form does not fully remove the need traditional techniques such as strain gauges, piezometers and inclinometers. Whilst it is clear, that intelligent pigging techniques provide a "picture" of the bending strain condition of the entire pipeline and are able to identify unmonitored areas of risk, the inability to measure axial strain remains an issue. For pipeline operators such as Snam, where axial strain is of considerable importance, Inertial surveying provides a complementary monitoring technique to existing and more traditional methods.

References

1. Czyz, J.A. and Adams, J.R., "Computation of pipeline bending strain based on Geopig measurements", Pipeline Pigging and Integrity Monitoring Conference, Houston, Feb. 1994.

2. Czyz J. A., Fraccaroli C., Sergeant A.P., "Measuring Pipeline Movement in Geotechnically Unstable Areas Using An Inertial Geometry Pipeline Inspection Pig", ASME 1-st International Pipeline Conference, Calgary, June 1996.

3. Czyz J. A., Falk J, " Use of the Geopig for Prevention of Pipeline Failures in Environmentally Sensitive Areas". The Pipeline Pigging Conference, Houston, Texas, February 2000.

4. Cox M., Garrigus A., Walker W., Wade R.L., 1995. "Pipeline monitoring and remedial action from inertial geometry surveys in buried pipelines". Pipeline and Inspection Technology Conference, Houston, Texas, February 1995.

Fig 1 Pipeline Excavation for Stress Relief

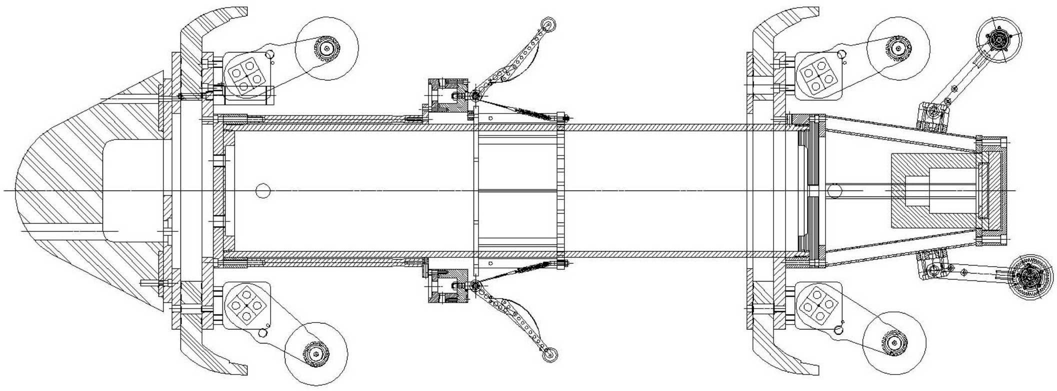


Fig 2 30"Inertial Geometry Tool

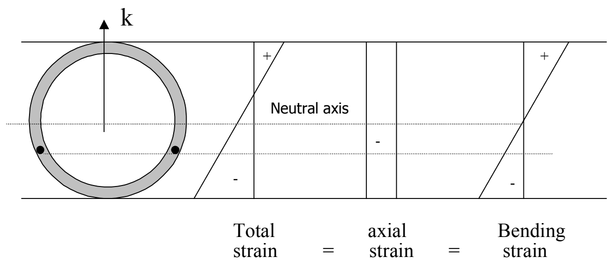
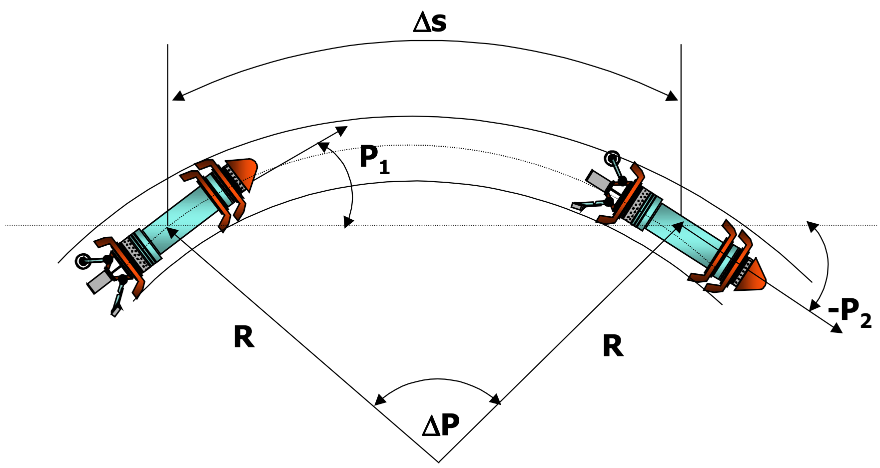


Fig 3 Components of Strain



Pitch Change : $\Delta P = P_2 - P_1$

Curvature : $\kappa\nu = \Delta P / \Delta s$

Strain : $\varepsilon\nu = \kappa\nu \; D/2$

Radius of Curvature :

$R = 1 / \kappa\nu$

Fig 3b Calculation of Curvature

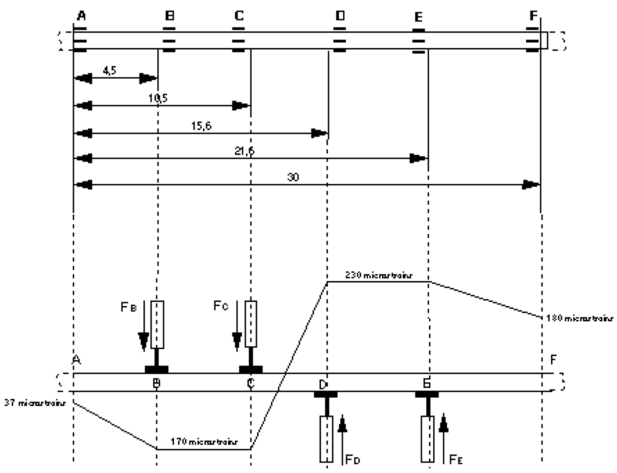


Fig 4 Induced "Unknown" Horizontal Displacement

Fig 5 Strain Gauge Monitoring

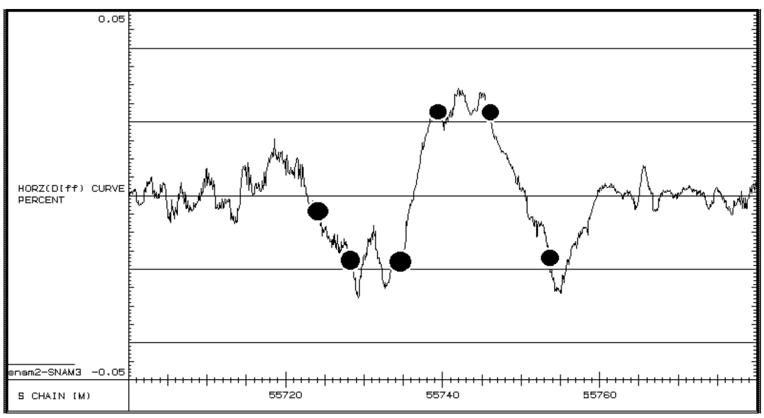


Fig 6 Phase 1 Test Results - Survey Data versus measured strain

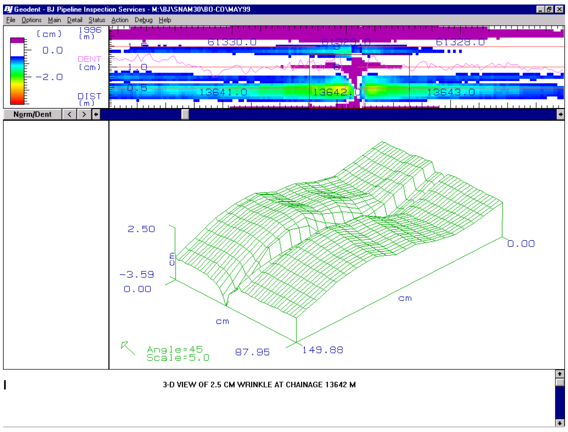


Fig 7 3D Plot of Wrinkle at Chainage 13642

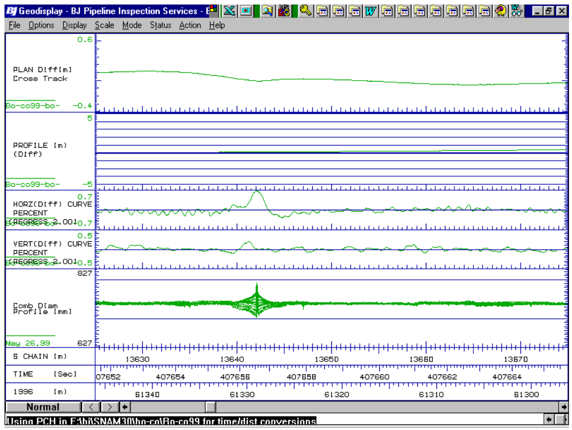


Fig 8 Strain Plot at Chainage 13462

Fig 9 Verification of Wrinkle Dimensions in Cut-out Section

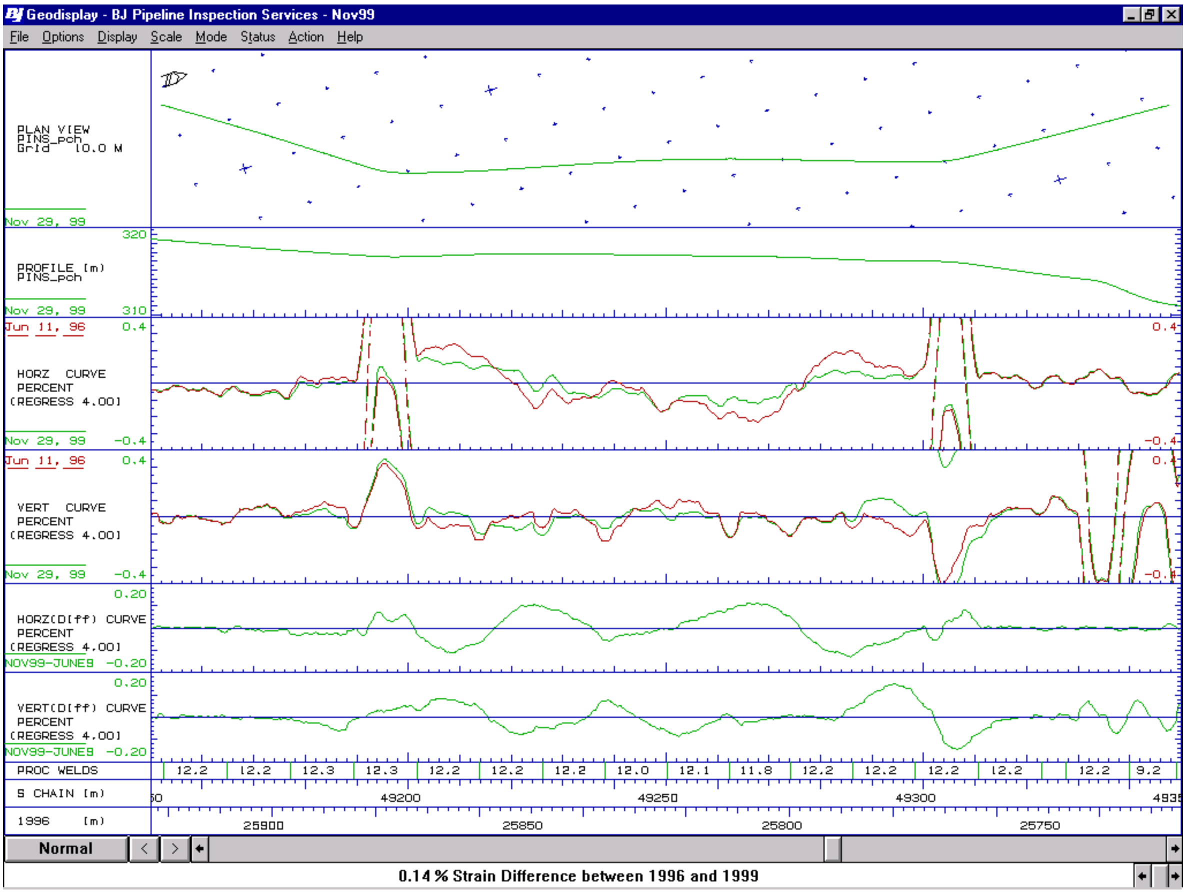


Fig 10 1996 and 1999 Geopig Data Comparison