# PIPELINE OUT OF STRAIGHTNESS AND DEPTH OF BURIAL MEASUREMENT USING AN INERTIAL GEOMETRY INTELLIGENT PIG

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## ABSTRACT

With an increase in the development of high temperature and high pressure fields where smaller diameter subsea flowlines are specified, the potential for line upheaval is increased causing a general tightening of the design specifications for out-of-straightness during pipe-lay operations and for depth of cover measurement.

One such project where out-of-straightness and cover heights are of particular importance to pipeline stability, is the ongoing Norsk Hydro Troll West field development in the Norwegian sector of the North Sea. The need for accurate depth of cover and out-of-straightness measurements for the trenched lines are indeed so critical, that Norsk Hydro is using a hydraulic operated Remotely Operated Vehicle (ROV) based mechanical stabbing system. The interval of the accurate mechanical stabbing is 5-10 m and if cover height and out-of-straightness result are outside specified requirements, remedial work by sand/ rock dumping is required. The trench depth is too deep to obtain acceptable results with existing pipe-tracking systems.

Whilst the system using mechanical stabbing has proven to work well during the successful installation of the existing Troll B flexible flow-lines, the method is both time consuming and relatively costly. As a result, during the installation of the K1 and K2 flowlines in January 1999, Norsk Hydro embarked on a unique project to determine whether an Inertial Geometry Inspection Tool could, in addition to provide improved pipeline curvature or out-of-straightness data, determine depth of cover by overlaying measured pipeline shape and position (in 3-dimensions) on highly accurate seabed topographical profiles. If an adequate level of accuracy in determining cover height can be achieved using this method, then the frequency of ROV “stabs” could be reduced significantly, or even eliminated with clear benefits to project cost and schedule. Furthermore, the use of this type of inspection tool offers the benefit of through-life pipeline out-of-straightness and movement monitoring.

This paper describes the project undertaken, the field operations and explores in detail the results and comparison of the data obtained independently from the ROV and Inertial Geometry Survey. Additionally, conclusions are drawn on the effectiveness, potential benefits and accuracy of Inertial Geometry Surveying for both depth of burial, backfill cover and out-of-straightness/ excessive curvatures.

## NORSK HYDRO TROLL WEST DEVELOPMENT

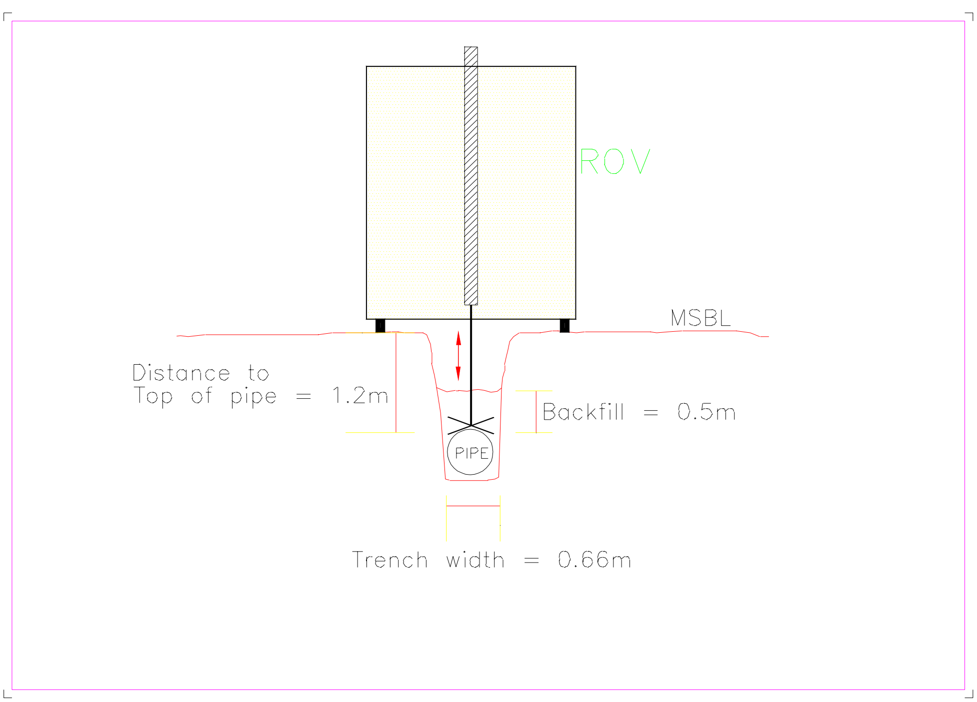
The Troll West area is developed by use of flexible flow-lines hooked up to the floating platforms Troll B and Troll C. All flow-lines run as pairs, one test line and one production line, alongside a third Integrated Service Umbilical (ISU). The lines are laid several kilometres on the soft clay seabed out to a no. 1 template structure (e.g. K1) and further out to a no. 2 template structure (e.g.K2). Round-trip pigging is then possible. The lines are trenched and partly rockdumped.

## PROJECT OVERVIEW – DEPTH OF BURIAL & OUT-OF-STRAIGHTNESS MEASUREMENTS

In order to stabilise and insulate each of the flexible flowlines, a minimum backfill requirement of **0.50m** has been specified. This level of critical backfill is relatively small in terms of backfill for most pipelines installed in the North Sea. Further, an out-of-straightness requirement of less than 30 cm over 30 m has been established as trenching target to prevent upheaval-buckling problems Finally a total trench depth requirement of 1.2 m is defined, measured from seabed to top of pipe. The actual depth obtained for most of the lines were in the range of 1.5m – 1.8m, out of range for traditional pipe tracking devices.

In response to this, Norsk Hydro used a ROV based hydraulic mechanical measurement device, (constructed by Stolt Comex Seaway) as shown in Figure 1, to ensure that measurement of backfill, out-of-straightness and total burial depth was guaranteed to an accuracy of greater than 0.10m. Minimum dimensions for trench and burial of pipe are also shown. The actual depth obtained for most of the lines were in the range of 1.5m – 1.8m, out of range for traditional pipe tracking devices. The trench width was in most cases also much wider, and the trench walls were less steep than indicated.

**Figure 1 ROV Used For Stabbing**



The system consist of a hydraulic ram mounted vertically in front centre of the ROV, the length of the ram is just over 2 m. A steel cross at the end of the ram (diameter=40 cm), makes it easier to locate the line in the trench. A wire is attached to the cross and is pulled out as the ram is extended, the measuring wire is divided into 5 cm divisions with coloured tape. When the ram is fully retracted the wire at the measuring point will read zero. On extension of the ram, the ROV personnel, by use of camera and light looking directly at the measuring point, compare the observed colour coding with a prepared reference sheet showing colour coding and distance. These readings and simultaneous taken high accuracy cross profiles of the trench give cover depth and total depth, seabed to top-of-pipe, at each measuring location. Furthermore, this stab data, collected at 5-10m intervals along the entire pipe length, is used to provide “out-of-straightness data” or curvature for the purpose of upheaval buckling analysis.

Whilst the technique has been effective and achieved good results during the installation of the existing Troll flexible flowlines, the method (Løtveit, Bryn, Hjermann, 1994) was both intensive in terms of schedule (approx. 1.5 km per day), and consequently costly. The old technique also gives no method for monitoring pipeline position / stability throughout the life of the pipeline.

With a significant proportion of planned flowlines yet to be installed, Norsk Hydro decided to investigate alternative methods that could provide depth information at less cost, less time, or potentially both.

Following discussions with BJ Pipeline Inspection Services based in Aberdeen, Scotland, Norsk Hydro concluded that an Inertial Geometry Surveying technique offered a potential solution. Inertial surveying using an intelligent inspection tool is a well established method for determining very accurate pipeline out-of-straightness within the North Sea construction environment, however the technology had not been used specifically to determine pipeline depth of burial. Inertial surveying can provide an accurate as-built pipeline curvature or make shape data available, but fixing the pipeline position relative to the seabed topographical profile offered challenges as did confirmation of the accuracy of the system.

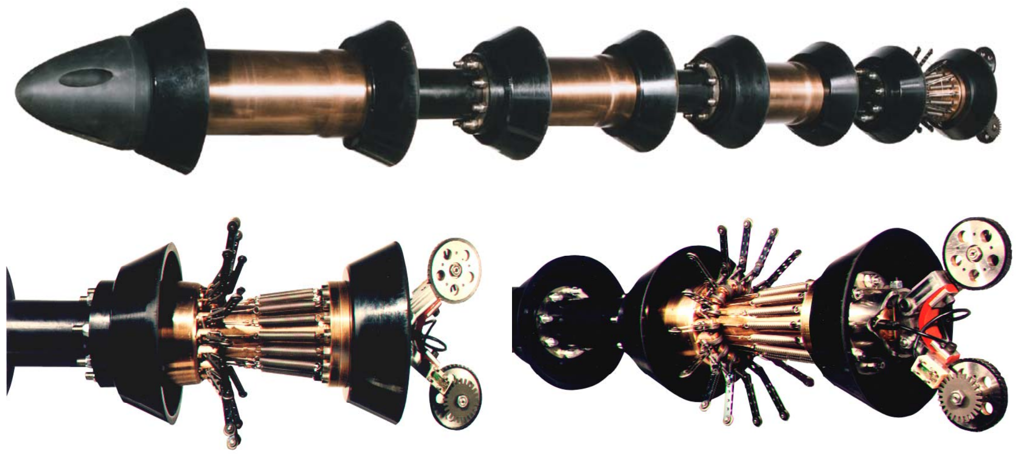
## THE INERTIAL GEOMETRY TOOL

The patented BJ Geopig Inertial Geometry Tool has been continually developed over a twelve year period. The ability to interpret the complexities of inertial data to give accurate and meaningful results has been made possible through the continual feedback of tool results with those obtained by the operators using alternative survey techniques.

The Geopig is equipped with the following sensor systems:

- The *Inertial Measurement Unit (IMU)* comprises angle rate gyros and linear accelerometers. The system measures the precise path the pig has taken during its traverse of the pipeline. This system is used to produce a detailed map of the line, measure curvature, and to identify any significant out of straightness features.

- *Odometers* measure the pig's distance moved along the line (chainage) and instantaneous speed in the line.
- *Pressure and Temperature Sensors* measure the pressure and temperature in the line during the pig run.



- *Mechanical Callipers* measure pipeline internal diameter, ovality, dent size and shape and perform weld detection.

**Fig 2 10-inch Geopig**

## PIPELINE POSITION AND CURVATURE

The pipeline position and bending strain are computed from the odometer and inertial measurements. The odometers measure the distance travelled by the Geopig, while the strap-down inertial system provides the acceleration and rotation of the Geopig about three orthogonal axes (with respect to an inertial reference frame, which is fixed in space).

The processed inertial data is rotated into the selected tie-points on the pipeline with known Universal Transverse Mercator (UTM) co-ordinates. The purpose of the tie-points is twofold. First, they are used to adjust the inertial system biases in such a way that the pipe centreline shape fits the tie-points the best over long distances. Then, when the adjustment is completed the pipe centreline co-ordinates are tied to those points, which prevent accumulation of the absolute position error and transforms the pipeline co-ordinates into the required UTM mapping projection. Usually, for off-shore pipelines the UTM of the tie points are obtained from the ROV as-built survey.

The minimum spacing between the tie points depends on the required absolute accuracy. The specified accuracy is 1:2,000 of the distance to the nearest tie point. Table 1 below specifies the maximum error for selected distances between the tie points in the range from 100 m to 5 km.

| Distance Between Tie Points [m] | Absolute Accuracy [m] |
|---|---|
| 5,000 | 1.25 |
| 1,000 | 0.25 |
| 500 | 0.13 |
| 250 | 0.06 |
| 100 | 0.03 |

Table 1 Geopig Accuracy between Tie-points

Beside the UTM co-ordinates, the azimuth and pitch of the pipe centreline in the local level frame are also computed. 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 changes $\Delta P$ and $\Delta A$ of pitch and azimuth over a distance $\Delta s$ along the pipe centreline allow for computation of the pipeline total curvature $\kappa$ and its vertical $\kappa_v$ and horizontal $\kappa_h$ components (Czyz, Adams, 1994):

a) $\kappa = \sqrt{\kappa_v^2 + \kappa_h^2}$

b) $\kappa_v = \dfrac{\Delta P}{\Delta s}$ (1)

c) $\kappa_h = -\dfrac{\Delta A}{\Delta s}\cos(P)$

## DEPTH OF BURIAL ASSESSMENT

As described above, collecting highly accurate pipeline shape (curvature) data with the Geopig is routine. The challenge with the project was to locate the absolute position of the pipe accurately relative to the 3-D seabed topographical profile so that depth of burial could be determined.

In order to achieve the accuracy levels required, it was clear that simply using the known positions of the riser base connection PRBN (Production Riser Base North) close to Troll B and the K1 (5.9 km from PRBN) & K2 (2.5 km from K1) templates would be insufficient. Cumulative random drift error in the inertial measurements would be significantly greater than the desired burial depth accuracy, and therefore, the data in terms of pipeline position, meaningless.

With a need for additional accurate tie-points, it was concluded that a number of stabs using the current ROV technique would be required for tying the relative Geopig data to the accurately to the absolute seabed data. Clearly, as a combination of methods would be required. There was a critical trade-off between the number of and cost of the additional ROV stabs required (for tying the Geopig data) and the use of the ROV for the entire survey.

By virtue of the accelerometer data collected, the Geopig can, under good operating conditions, give significantly higher accuracy data in the vertical plane by analysis of the additional pitch data resulting from measurement of the gravity vector. Should an accuracy of greater than 1:2000 be achievable in the vertical plane, a direct cost and schedule saving could be realised as the number of stabs could be decreased. It was therefore decided that as part of the survey of the K1 / K2 flow-line, that the accuracy of the data in the vertical plane would be assessed to determine tie-point spacing requirements.

## FIELD PIGGING OPERATIONS

The Geopig survey of the 10" Test and Production Flowlines was successfully performed with seawater as the propelling medium. The survey of the two flowlines was performed in a single run with the Geopig launched from the Test Line temporary trap on Troll B, returned through the loop at K2 template, and recovered at the Production Line temporary receiver on Troll B.

The entire inspection operation, including a pre-survey gauging run through to receipt of the Geopig, was completed within a 15 hr period.

On receipt of the Geopig, the data was downloaded. Initial data processing demonstrated good data within 24 hrs.

## DATA PROCESSING

In the case of the K1 & K2 flowlines, a stabbing programme at 5-10m intervals was completed in order to verify the accuracy of the inertial data, and furthermore to independently assess the capability of the Geopig for depth of burial measurement. Therefore, to verify the Geopig performance, the following staged approach to data processing was adopted:

Stage One – inertial data processed using only the PRBN, K1 and K2 template locations as tie-points for absolute position, with the reference position co-ordinates being obtained from the as-built ROV survey. Typical plots of the Geopig system data after Stage One of processing are presented in Figures 3, 4 and 5.

Stage Two – inertial data was re-processed with additional stab data at varying intervals.

After completion of Stage One of the Data processing and delivery of the results to Norsk Hydro, three sets of stab data were returned to BJ in order to complete Stage Two of the processing. One data set contained tie points spaced every 100 m, the second at 250 m intervals, and the third, at 500 m spacing, was a subset of the other two sets. The data for each tie point consisted of 3 stab points at 10 m intervals in order to minimise the effect of outliers in the stab data. The inertial survey elevation was adjusted at the tie point in such a way that the average height at those 3 locations was the same as the average height of the corresponding three stab points.

## COMPARISON OF INERTIAL DATA & ROV STAB DATA

ROV stab data for every 5-10m along the lines were acquired and processed on board the Geofjord survey vessel, and were then wired ashore over Internet for further processing and comparison with the inertial pig results. Measurements in the trench gave burial depth, backfill depth, trench width and kilometre position (Kp) for each stab.

Illustrations of the Stage One comparisons are given in Figures 6 and 7.

Suspicious stab points were removed or had been replaced by re-stabs down to every 5m position. This was typically for cases when the stabbing tool completely had missed the pipe, e.g. when the pipe had moved to one side of the trench, such as in bends. Examples of stabs, re-stabs and inertial data are given in Figures 8, 9 and 10. These are examples of areas with the largest discrepancies between the stab data and the Geopig data in the Stage One processing.

Other sections of the pipeline did however show excellent agreement between the two methods, as shown in Figure 11, although a shift in height is observed.

It is seen that the main problem with the Stage One processing is the absolute position drift, or determination of the vertical level of the line. The local relative measurements of the pipe behaviour seem to be trustworthy. Additional stab points will therefore aid in locking the inertial ROV data to a more correct level.

When all three sets of data from the Stage Two measurements were re-processed and available as complete lines, Norsk Hydro made maps allowing a direct comparison with the ‘manually’ obtained stab data for every 10m.

Illustrations of the Stage Two comparisons are given in Figures 12 and 13, showing the original ROV stab data in comparison with the tied in data at 250m intervals. The accuracy is seen to be far better than that obtained in Stage One. One may now note, that between the crossing of the two existing pipelines at Kp 1.8, the inertial ROV data show a correct pipeline position over the seabed, not below or too far above as in Figures 6 and 7.

A general conclusion had to be drawn upon studies of the three sets of data, as this would be the only time where manually obtained ROV data are available for estimating signal drift along a complete line. A subset of the 10m interval data had to chosen in order to reliably tie in future inertial data.

Selection of a suitable density to be used for future stab points is a matter of cost and accuracy. The evaluation process considered the inertial data tied to three 10m points every 100, 250 or 500m. In short, the 100m estimate was accurate, but also prone to errors in the selected stab data. Such errors were indeed observed, and one, two or even all three data-points had to be left out at some intervals in order to make the line fit with measurements at neighbouring intervals. Using stabs every 100m, the stab intensity will still be fairly high and costly.

The 500m estimate still showed signal drift, causing deviations from the other signals of more than +/- 20cm.

The 250m estimate was sufficiently accurate, with a deviation of max +/- 10cm from other measurements. Stabs here could also be prone to errors in the selected stab data. An increase of the 10m stab points from three to five stabs at every 250m interval was recommended in order to minimise the effect of stabbing errors. A local plot of the re-processed inertial pig data is shown on Figure 14.

## USE OF INERTIAL DATA & ROV STAB DATA IN UPHEAVAL BUCKLING PREDICTIONS

When installed and buried pipelines are pressurised and heated after production start-up, it is from time to time observed that pipelines buckle vertically and penetrates the backfill cover (0.5m here) in the trench. Such loss of thermal insulation is not acceptable, and further buckling out of the trench (here 1.2m deep) is not permitted.

It is however possible to predict and identify points where such upheaval buckles may occur. This may be done by observing the vertical curvature of the pipe, or indirectly, by controlling the pipe out-of-straightness after trenching and burial.

Upheaval buckles are avoided if the vertical curvature is kept within certain boundaries. A typical boundary for a 10" Wellstream flexible pipe with a 0.5m backfill cover on top, is a maximum curvature of 0.010 (1/m), or a minimum bending radius of 100m. The boundaries are found by FEM computer analyses of typical vertical anomalies, using non-linear soil properties in modelling resistances to pressure and temperature induced pipe motions. Vertical curvatures are calculated from the same ROV data as obtained for the depth and burial checks. Or, when inertial pig measurements are made, a more detailed and accurate curvature is directly available from the pig Pitch and Azimuth data, as shown before.

Vertical curvature from the two different methods are presented and compared in Figure 15. It is seen that even in the Stage One processing as presented here, the less accurate ROV results display an amazing resemblance to the inertial data, even for the smallest details. As curvature is determined by local changes in pipe geometry, and less by signal drift over large distances, the Stage One processing will be sufficiently accurate for the curvature. Further signal processing in Stage Two will not improve the curvature estimates, but is necessary for accurate depth-of-burial and backfill estimates.

## CONCLUSIONS

The ‘manual’ and mechanical method for obtaining positioning data for a buried pipeline has over five years proven to be a reliable and sufficiently accurate method, even though both the additional positions of the surface vessel and the ROV must be determined. Due to the large resources required, and time needed for data collection and processing, alternative methods for data gathering were sought.

A new ‘high accuracy’ use of an inertial pig, combined with a number of tie-in points, has given promising results. It is however concluded that known data points only at the riser base and at the templates several km’s away does not tie down the inertial pig measurements adequately to determine cover height to the specified level of accuracy.

A sufficiently accurate vertical position of +/- 0.10m is obtained by use of additional ROV stab points every 250m along a pipeline. In order to minimise the effect of possible errors in the ROV stabs and measurements, a total number of five stabs, 10m apart, are specified at every 250m stab interval.

The selected procedure will result in a reduction in mechanically obtained ROV stabs from 100 to 20 for every km of pipeline. A five-fold reduction of the number of necessary stabs is estimated to give a significant reduction in processing turn-around time, and in time spent offshore.

The first results from the mechanical stabbing (250 m stab interval) in September 1999 indicate a survey/ stab performance of approximately 8 km/day compared to the previous 1.5 km/day (5-10 m stab interval).

To illustrate the potential gain in cost, approximately 40 km of flowline was installed in the Troll West area in 1998, an additional 40 km in 1999, and 37 km will be installed in the year 2000.

## REFERENCES

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

Løtveit, S.A., Bryn, P. and Hjermann, B.K., “Upheaval Buckling of Flexible Pipes, Method Selected at the Troll Olje Field”, Advances in Subsea Pipeline Engineering & Technology, Aberdeen 1994.

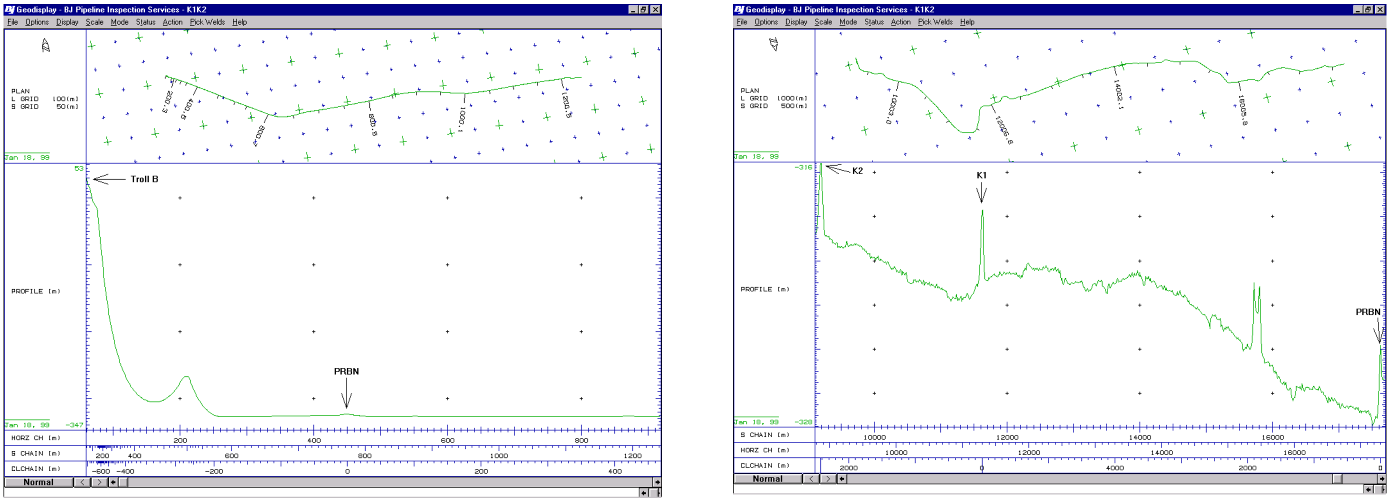



**Fig. 3 Test Line Plan and Profile from Troll B towards PRBN (1200 m) and from PRBN to K2 ( 8.5 km)**

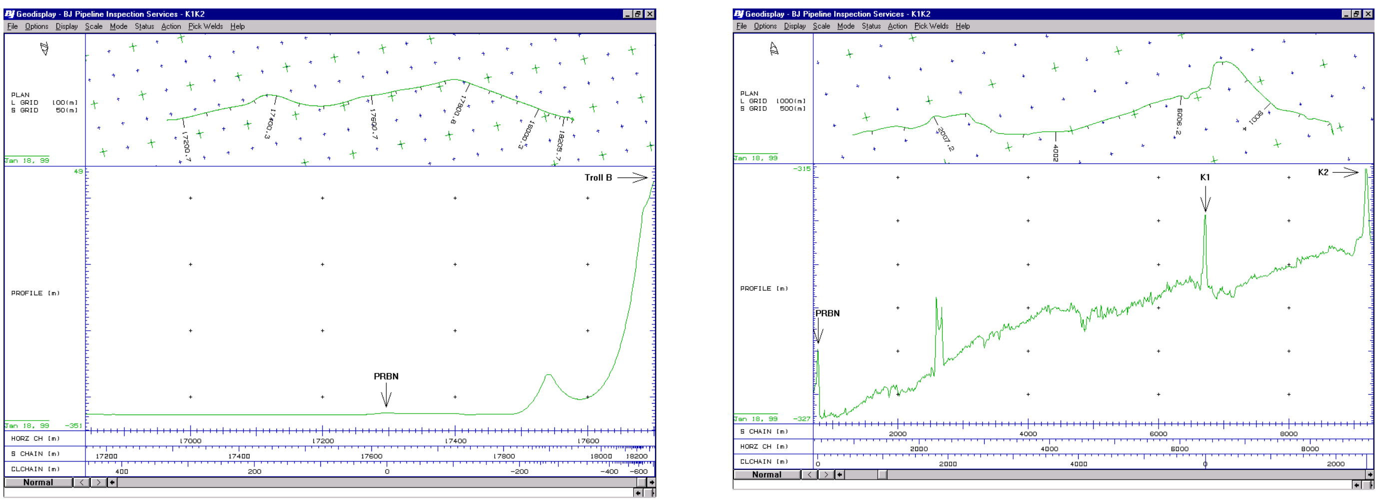



**Fig. 4 Production Line Plan and Profile from PRBN to Troll B (1200 m) and from K2 to PRBN (8.5 km)**

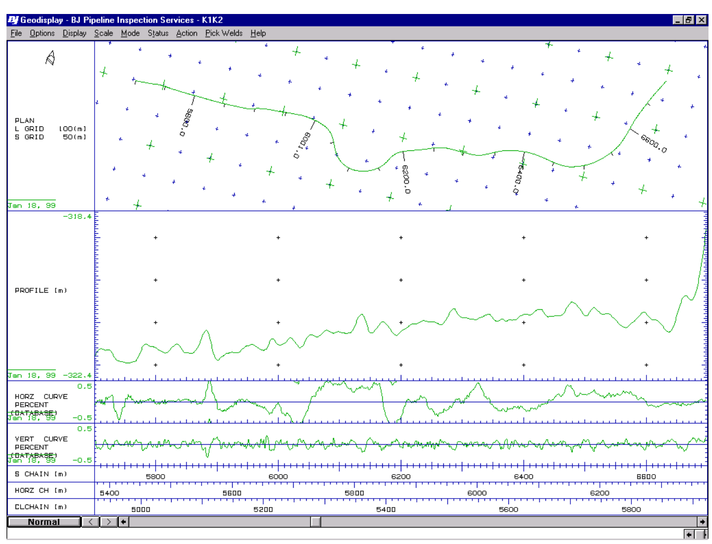


**Fig. 5. Sample plot of pipeline plan, profile, horizontal and vertical strain**

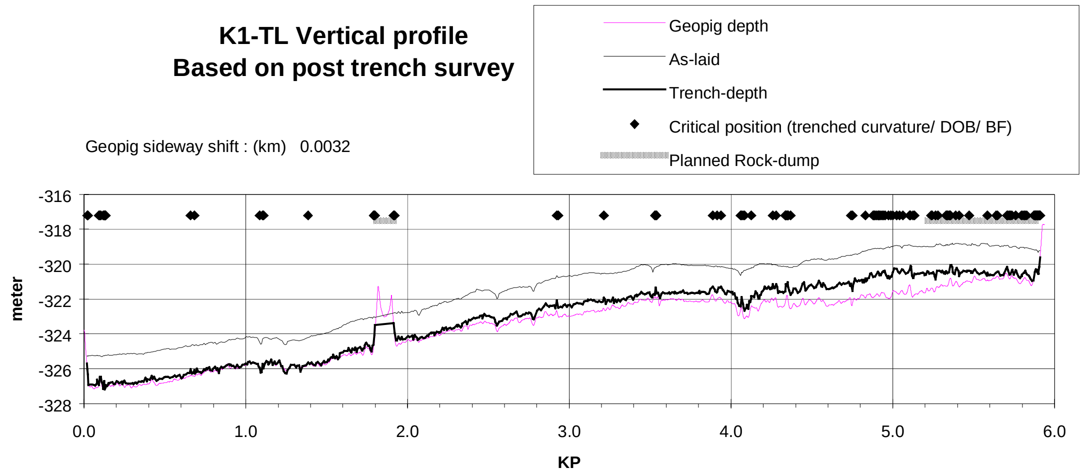



**Fig. 6 Stage One comparisons for the K1- Test Line (outward pig travel).**
The upper line is the seabed level. The bold line with ROV data is compared to the inertial pig data. Note that a crossing of two existing pipelines take place at Kp 1.8. The inertial data are generally seen to **undershoot** the ROV data.

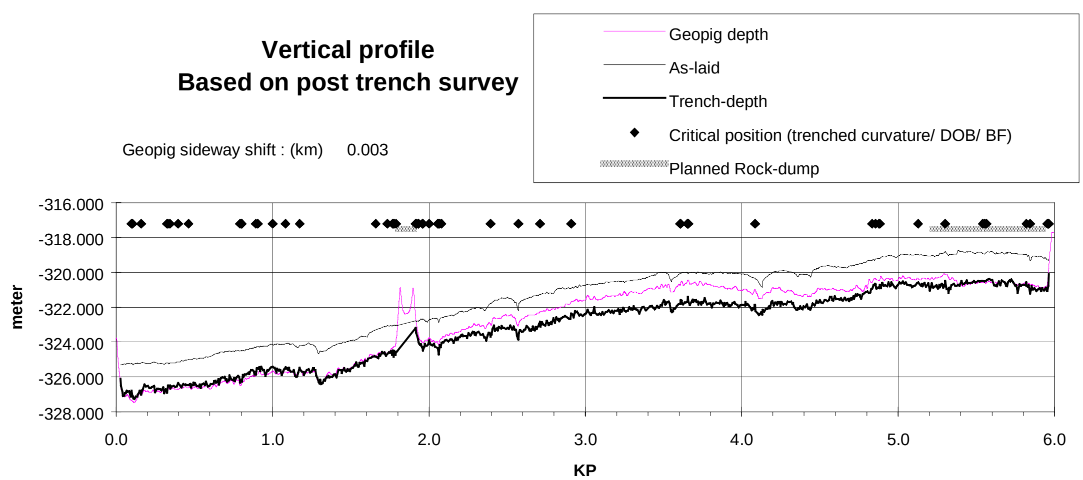



**Fig. 7 Stage One comparisons for the K1- Production Line (inward pig travel).**

The upper line is the seabed level. The bold line with ROV data is compared to the inertial pig data. Note that a crossing of two existing pipelines take place at Kp 1.8. The inertial data are generally seen to **overshoot** the ROV data.

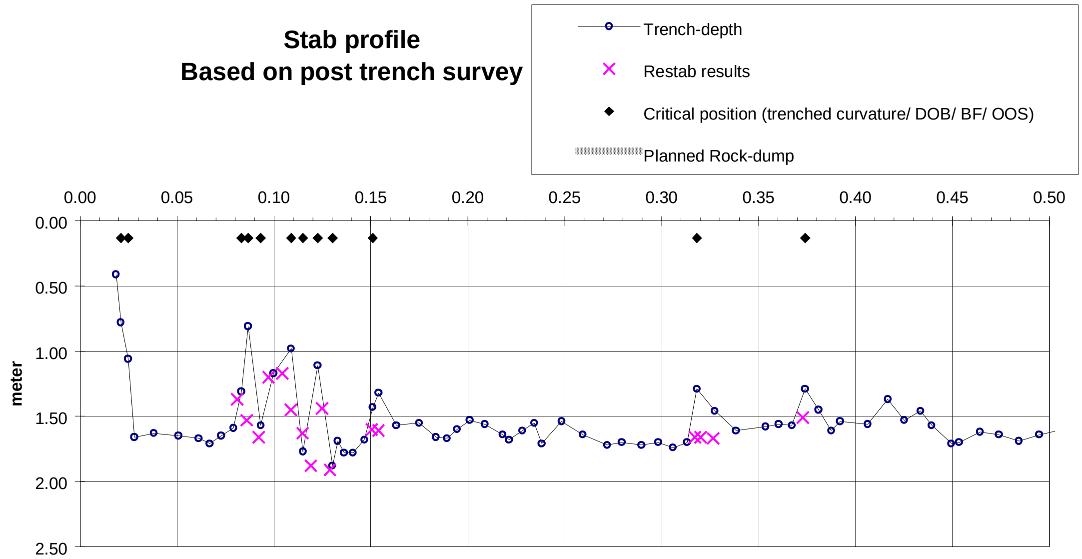



**Fig. 8 Stabs obtained from the start of the K1- TL (Test Line).**
Note particularly uneven results for the stretch Kp 0.070 - 0.130. Re-stabs were specified for this section, and the results are shown as X's.

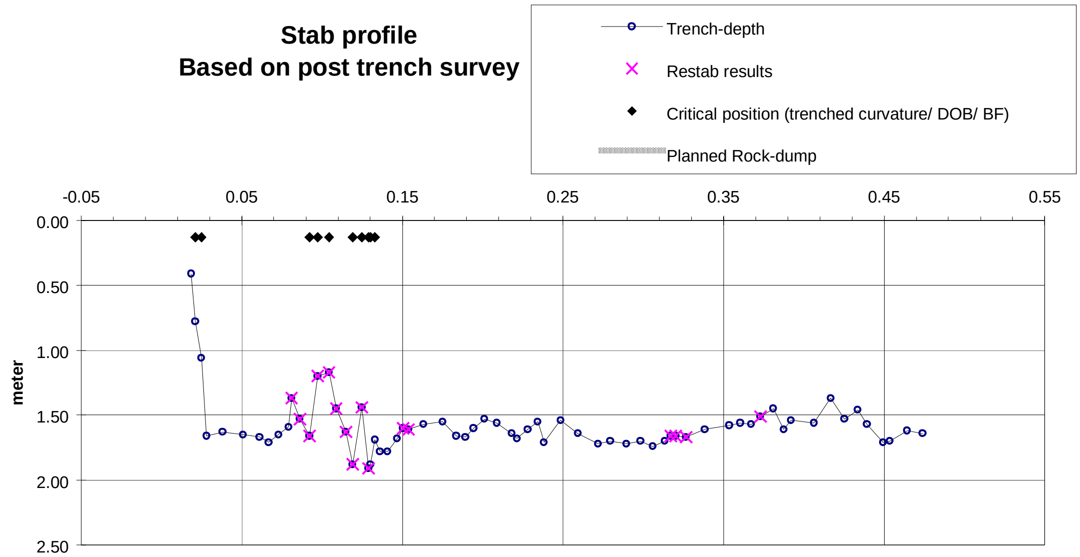



**Fig. 9 Original stabs replaced by re-stabs in the start of the K1- TL (Test Line).**
An uneven behaviour of the pipe is still measured for this stretch.

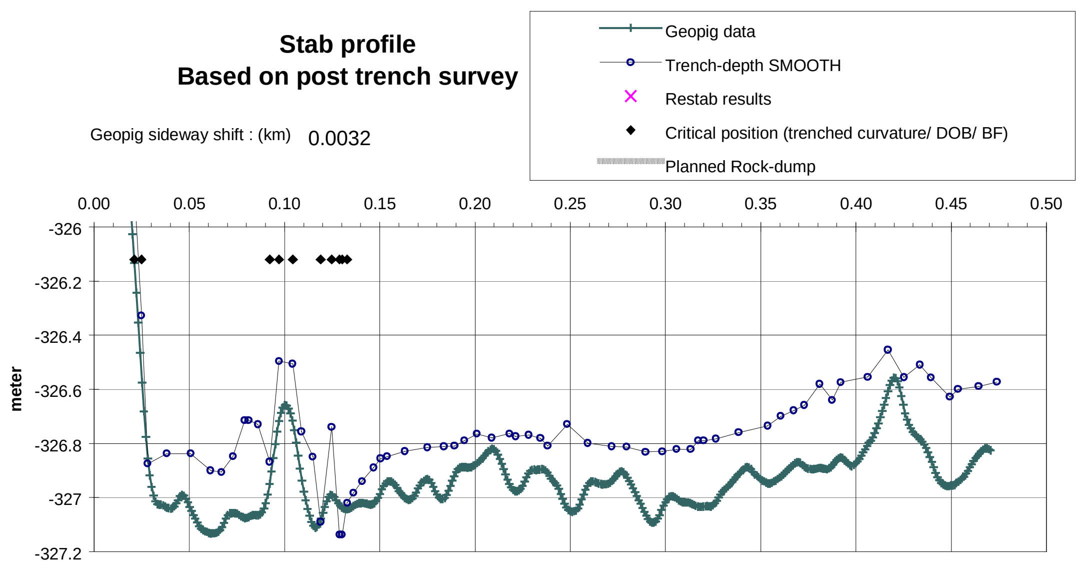



**Fig. 10 Stab points are overlaid by Stage One inertial measurements in the start of the K1-TL (Test Line).**
The Geopig results confirmed very uneven pipe behaviour for this stretch.

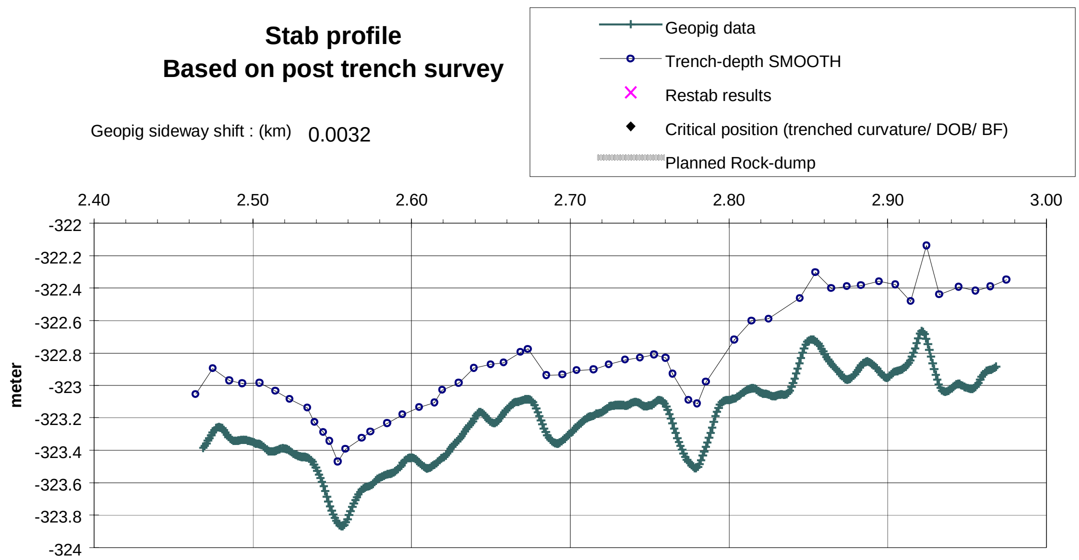



**Fig. 11 Stab points overlaid by Stage One inertial measurements along sections of a line.** The mechanically acquired data can be said to be amazingly accurate, although a shift in height is observed.

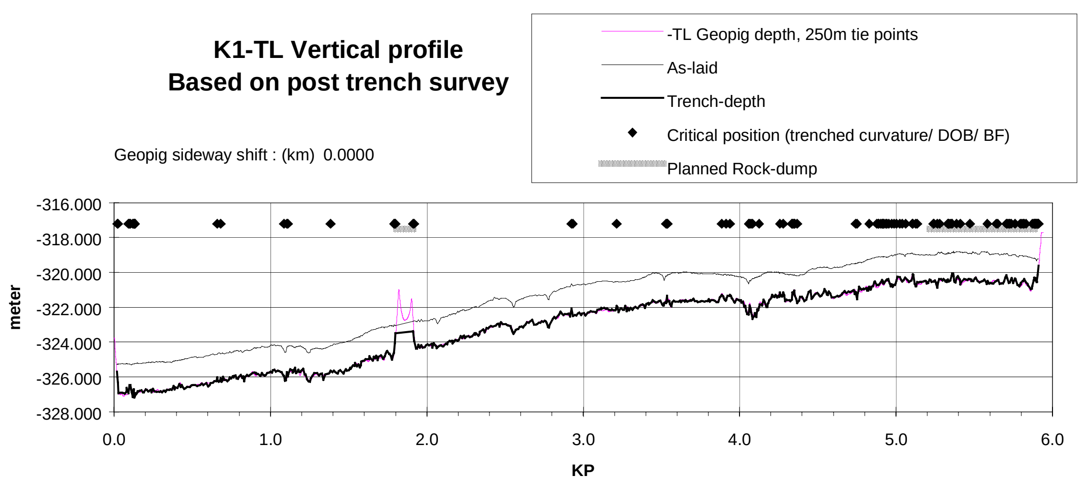



**Fig. 12 Stage Two comparisons of the K1- Test Line.**

The upper line is the seabed level. The bold line with ROV data is now level with the inertial pig data line. Note that between the crossing of the two existing pipelines at Kp 1.8, the inertial ROV data now show a pipeline position of half a diameter over the seabed.

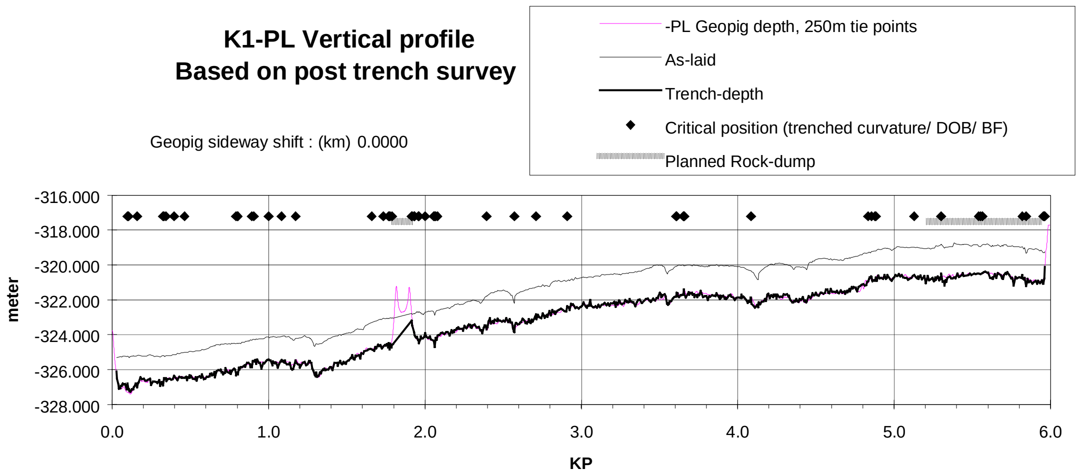



**Fig. 13 Stage Two comparisons of the K1- Production Line.**

The upper line is the seabed level. The bold line with ROV data is now level with the inertial pig data line. Note that between the crossing of the two existing pipelines at Kp 1.8, the inertial ROV data now show a pipeline position of half a diameter over the seabed.

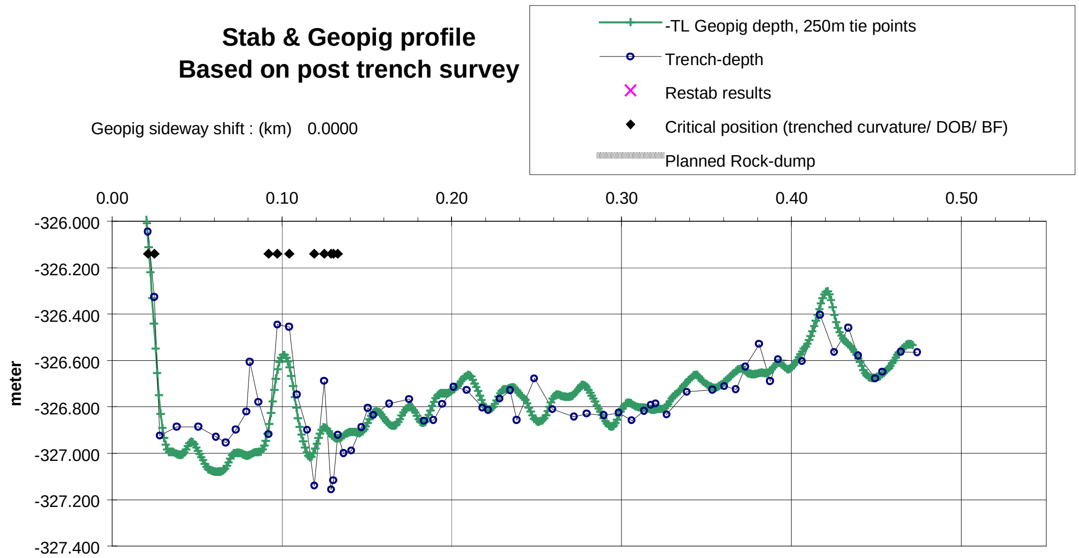



**Fig. 14 Stab points are overlaid by Stage Two inertial measurements in the start of the K1-TL (Test Line).**
The Geopig results generally confirmed the depth level for the pipe, even for this very irregular stretch.

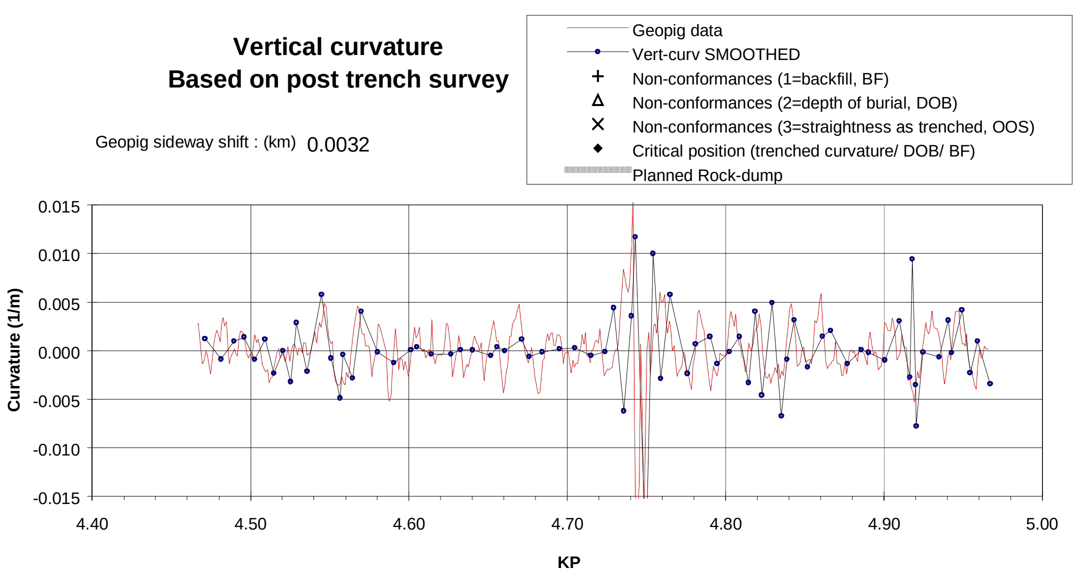



**Fig. 15 Identification of Up-heaval buckling potentials by use of Vertical curvatures.**
Note that vertical curvatures generally are below 0.010, but a disturbance is found at Kp 4.75.