EFFECTIVE MANAGEMENT OF GEOHAZARD THREATS IN PIPELINES

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Abstract:

Geohazards in the form of earthquakes, landslides, mining subsidence, etc., will typically result in ground movement and where a pipeline crosses such areas, it will be subjected to additional stresses that may lead to its failure. The geohazard related pipeline failures often drive operators to include rigorous geohazard mitigation strategies in their pipeline integrity management programs. Ensuring and managing the integrity of the pipeline in such cases requires frequent monitoring by In-Line Inspection (ILI) or by above ground surveys (e.g. line walking); however, these activities can be costly and ineffective to identify all geohazard threats if they are not performed to relevant standards and at the correct frequencies.

This paper describes the use of ILI technology employing Inertial Mapping (IMU) technology, in combination with satellite borne Synthetic Aperture Radar (SAR) technology, to monitor ground movement near a pipeline. This integrated approach represents a powerful dual-method measurement technique to support geohazard mitigation.

ILI-based IMU systems provide a continuous measurement of the pipeline's centreline coordinates (X, Y, Z), from which pipeline curvature can be derived. The data can then be used to calculate the magnitude and nature of bending strain in the pipeline.

Differential Interferometric SAR (DInSAR) processing allows for accurate measurements of changes in terrain conditions, which can be of the order of millimetres in terms of accuracy. In addition, we look at how pipeline strain can be determined and efficiently managed using ILI-based inertial mapping in conjunction with the DInSAR system.

1. Introduction

In 2018 Inspipe Integrity Ltd. performed a combined geometry and IMU survey of a 28" gas pipeline in southern Sumatra to inspect for geometric anomalies and possible abnormal strains caused by land movements. The entire pipeline route is prone to significant seismic activity that can displace the pipe from its intended position. In addition to seismic events, a coal mine close to the line added to the risk of ground movement.

Sumatra is located on the northwest edge of the Australian tectonic plate, where it is vulnerable to major seismic disturbances arising from differential movements of the fused Indo-Australian tectonic plate. The Great Sumatran fault, a strike-slip fault, and the Sundra megathrust, a subduction zone, run the full 1,790 km length of Sumatra's west coast (Figure 1). They have been responsible for many major earthquakes in the past, many of them exceeding magnitude 9.0.

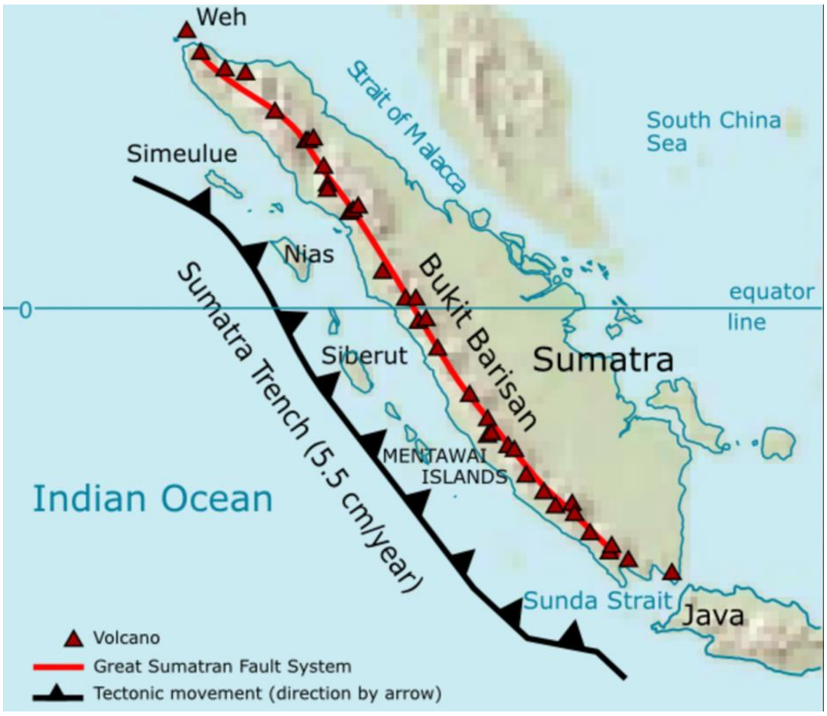


Figure 1: Major Tectonic Features of Sumatra

The Australian part of the fused plate moves northward at 5.6 cm per year while the western part in India moves only at 3.7 cm per year due to the impediment of the Himalayas. This differential movement causes compression of the plate near Sumatra and frequent releases of plate stresses cause earthquakes and associated land movements (Figure 2). Such land movements can impair the integrity of pipelines in the region.

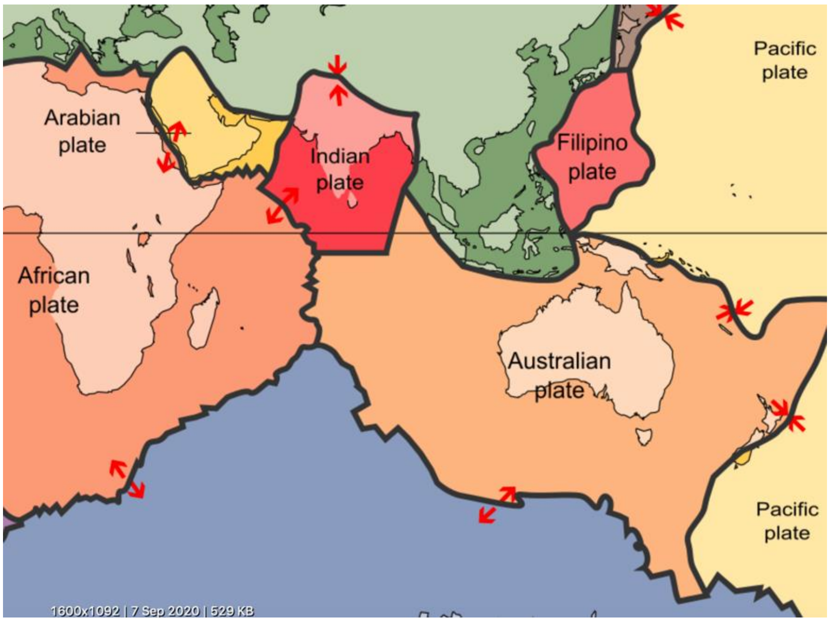


Figure 2: Indian and Australian (Indo-Australian) Tectonic Plates
(Arrows show relative movement)

The Sumatran 28”gas pipeline was newly constructed and was in the process of being commissioned. Therefore, the operator’s main ILI requirement was to perform a base line survey to check for geometric anomalies using a high resolution geometry inspection tool.

When running geometry inspection tools, it is common practice for Inspipe to fit an Inertial Measurement Unit (IMU) in order to enhance the identification and accurate positioning of girth welds and other location references on the pipeline. An IMU was fitted in this case and precise measurements were obtained of the XYZ position of the pipeline's centreline.

In conjunction with the ILI survey it was decided by Inspipe to investigate the effectiveness of complementing the IMU data analysis with a DInSAR study of ground movements near key parts of the pipeline. The DinSAR study was conducted by Satsense Solutions Limited (SSL), based in London, and the survey was conducted by an earth orbit satellite. The twin data sets were correlated and interpreted to provide a dual-method investigation of pipeline movement and associated strain anomalies.

2. ILI Survey and Results

2.1 Geometry Inspection

The geometry tool was retrieved from the pipeline in good condition, with minimal wear to the discs and no mechanical damage to the tool (Figure 3). No debris was collected.

The average run speed was 4.37 ms^{-1}, well within the tool's specified speed range of 0.1 to 5.0 ms^{-1}. All sensors and sensor arms had functioned correctly and the tool had acquired high quality data throughout the inspection run.

Figure 3: Receiving the 28" High Resolution Geometry + IMU Survey Tool

Inspection data was downloaded and reviewed onsite, to confirm that complete information had been obtained for the entire length of the pipeline. A secure internet link was used to transmit the inspection data to Inspipe HQ for detailed analysis.

No significant geometry reductions were found that exceeded the set thresholds of 3% ID for reductions/dents, ovalities and ovalities with dents.

The most significant geometric features found in the pipeline are summarised in Table 1.

Feature No.	Distance, m	Reduction		Remaining ID, mm	Velocity, ms^{-1}	Remarks
		mm	%			
6	2.69	7.78	1.16	661.42	1.26	Valve
11	5.33	3.71	0.55	665.49	3.77	Tee
13	7.38	9.12	1.36	660.08	3.75	Tee
22	29.57	8.11	1.21	661.09	3.43	Tee
1923	22,393.86	4.52	0.68	664.68	1.21	Tee
1935	22,413.72	10.45	1.56	658.76	1.92	Tee
1938	22,415.86	4.96	0.74	664.24	1.44	Valve

Table 1: Most significant geometric features found in the pipeline

2.2 IMU Data and Calculation of Bending Strains

A complete record of inertial data was acquired and was used with odometer data to calculate the pipeline’s 3D shape and pipeline bending strains. To support geographical referencing, inertial survey positions were tied to the GPS coordinates of 45 points along the pipeline.

All calculations and graphical plots were performed using a proven inertial measurement software package. In calculations, bending strain is proportional to the curvature of the pipe, however, curvatures obtained from the tool’s IMU data can measure only the bending component of the pipeline’s longitudinal strain. Axial components cannot be measured and care needs to be exercised in the analysis process because the axial strain may be higher than the bending strain in cases where the pipeline direction is close to the direction of ground movement.

Intentional bends and girth weld angular misalignments were excluded from the strain analysis. A girth weld misalignment generates elevated curvature that typically does not correspond to real bending strain in the pipeline.

In an IMU survey performed shortly after pipeline construction, the initial curvature of a bend is not precisely known. For this reason, it is difficult to estimate how much it has changed since the construction. Although the curvature of intentional bends can usually be clearly identified, in some rare cases it can be difficult to distinguish them from any curvature that was imposed unintentionally. Making this discrimination is particularly challenging when the strain of an intentional bend is superimposed on strain induced post construction, especially when it is induced over a distance longer than the length of the field bend [1].

The IMU recorded large vibrations in several locations with the amplitude reaching 60 degS^{-1}, which generated large noise in the bending strain data. In order to filter out this noise, the bending strain was calculated using a linear regression line fit over a relatively long gauge length of 5 m.

The IMU data was analysed to identify strain features that extended for more than one pipe joint, with a peak value exceeding 0.2% strain, excluding bends and angular misalignments at girth welds. Five bending strain areas meeting these criteria were identified, all of them in the vertical plane. Their details are given in Table 2.

Feature ID	Distance (m)	Peak Strain			Main Orientation	Start Distance (m)	End Distance (m)	Length (m)	UTM Zone 48 (CM 105)			Comments
		Vertical (%)	Horizontal (%)	Total (%)					Latitude (deg)	Longitude (deg)	Height (m)	
BS1	5875.996	-0.32	-0.06	0.33	Vertical	5850.981	5920.332	69.351	-3.38429424	104.08386910	31.808	0.17% Strain at GWD
BS2	9568.113	-0.20	-0.03	0.20	Vertical	9536.697	9576.321	39.624	-3.40005962	104.10993357	32.814	0.19% Strain at GWD
BS3	11353.440	-0.25	-0.01	0.25	Vertical	11317.710	11380.690	62.980	-3.40921303	104.12276949	47.940	0.24% Strain at GWD
BS4	14938.750	-0.20	0.02	0.20	Vertical	14916.950	14953.240	36.290	-3.41608719	104.15379112	43.705	At GWD
BS5	15314.910	-0.17	-0.01	0.22	Vertical	15283.650	15322.570	38.920	-3.41707100	104.15699527	53.160	

Table 2: List of Bending Strain Areas Identified from IMU Analysis

The maximum reported value of the bending strain was 0.33% and this occurred at a distance of 5,876m from the beginning of the line. Plots relating to this maximum bending strain area (B51) are shown in Figure 4, which displays the following data:

- Pipeline elevation with overlaid girth weld locations and joint lengths
- Horizontal (green) and vertical (blue) bending strain in the range +0.35% calculated using a regression line fit over a gauge length of 5m
- Pipeline Pitch Angle (degrees)
- Pipeline Azimuth (degrees)

The following colour coded abbreviations have been used for displaying features on the plots:

BS	Bending Strain
B	Bend
WM	Weld Misalignment

Welds are shown as black vertical lines.

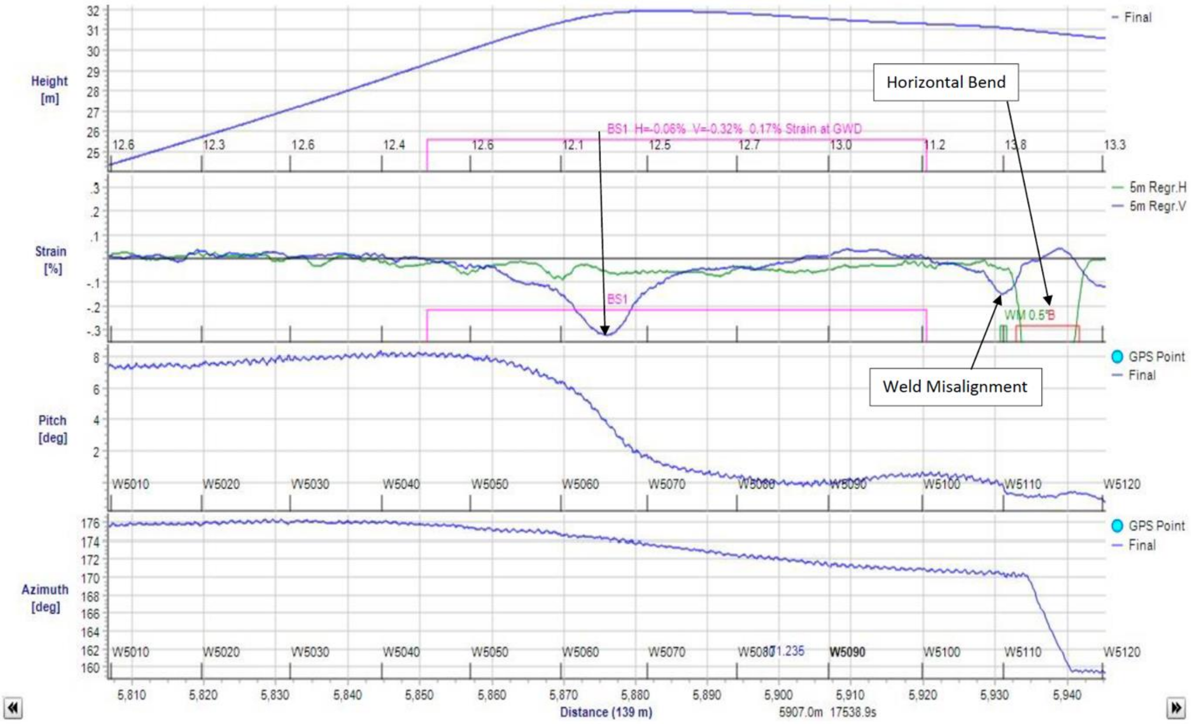


Figure 4: Plots of Bending Strain for Feature B51 (Max. Bending Strain 0.33%)

Based on a single IMU survey it can be difficult to determine if any reported strain was induced during construction or was a result of pipeline movement following construction. A future inertial survey can determine with high accuracy if there has been any pipeline movement between two inspections, however, the use of a complementary SAR survey together with DinSAR processing can greatly strengthen the confidence of ground movement assessments based on a single IMU survey.

3. Satellite Remote Sensing and DinSAR Data Processing

Satellite borne Synthetic Aperture Radar (SAR) data and Differential Interferometric SAR (DInSAR) processing techniques are used to detect and measure ground disturbances over certain time frames.

Synthetic Aperture Radar (SAR) is a microwave imaging system. Interferometric SAR or InSAR, allows accurate measurements of the radiation travel path.

Measurements of travel path variations as a function of the satellite position and time of acquisition allow measurement of millimetric surface deformations of the terrain (Figure 5).

While measuring changes in terrain motion, i.e. ground disturbances, we can note that points that scatter radiation from a SAR sensor will slightly change their relative position in the time interval between the SAR observations [2], for example in the event of subsidence, landslide, earthquake and similar geohazards. In such cases the interferometric phase variation (Δφ) representative of terrain motion or ground disturbances can be calculated.

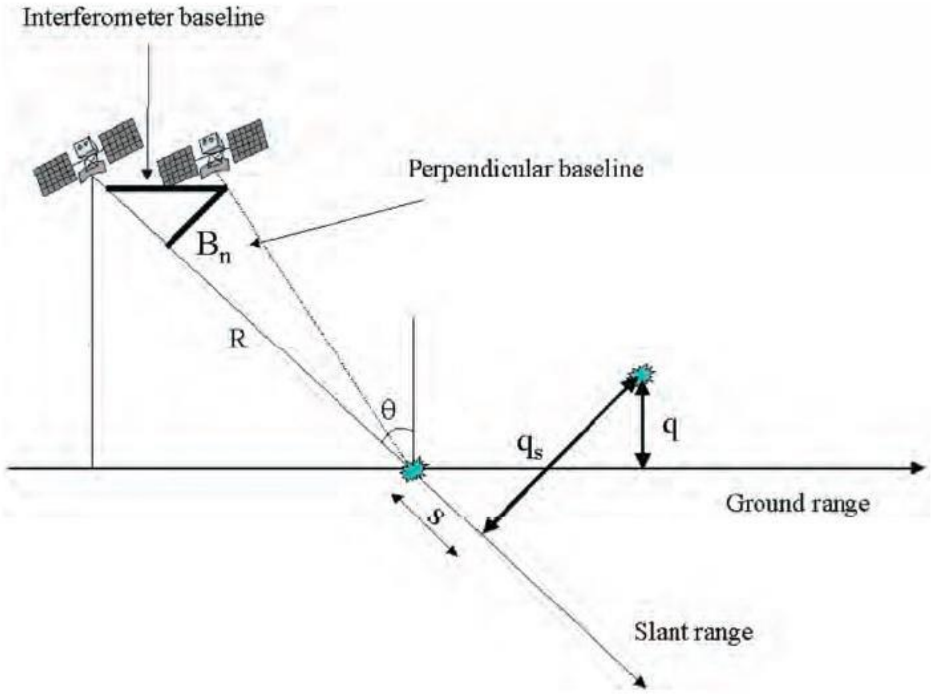


Figure 5: Geometric parameters of a satellite interferometric SAR system

SAR survey data relating to the 28” gas pipeline was examined in relation to the five bending strain areas, identified from the IMU data, that had peak values exceeding 0.2% strain. In comparing the SAR and IMU data sets there was a good correlation in terms of total displacement and calculated total strain (Figure 6). Four were close to the coal mine and were in areas that had experienced displacement from 7 cm to 14 cm. This fact was highlighted in both the IMU survey and the satellite displacement analysis. The fifth bending strain area was near a riverbed, which could also be regarded as a potential geohazard threat to the pipeline [3].

In terms of seismic threats to the pipeline, no seismic activity was reported for the area by geological monitoring services, nor were any seismic impacts seen in the SAR data for the area. SAR data visualisations and analysis relating to previous tsunami and landslide events were sensitive enough to reveal minor ground disturbances in the town near the end of the pipeline. However, there were no disturbances of structural importance around the pipeline’s start and end locations.

SAR surveys were conducted by an earth orbit satellite equipped with high resolution microwave imaging radar. To facilitate Differential Interferometric Processing (DinSAR), data were gathered during successive orbits of the satellite on different days, while maintaining the same altitude.

As anticipated, dense forest cover in the region led to radar signal coherence loss in some areas. In heavily forested areas, radar has difficulty in penetrating to the ground level because forest canopies disperse the signal. Nevertheless, it was clearly seen that there was no ground disturbance in or near to the start and end of the pipeline.

Ground disturbance adjacent to the coal mine was clearly seen in the DinSAR data analysis, revealing an uplift of up to 13 cm between August 2016 and August 2018. This kind of uplift is often seen when there is subsidence or geotechnical forces in an adjacent area.

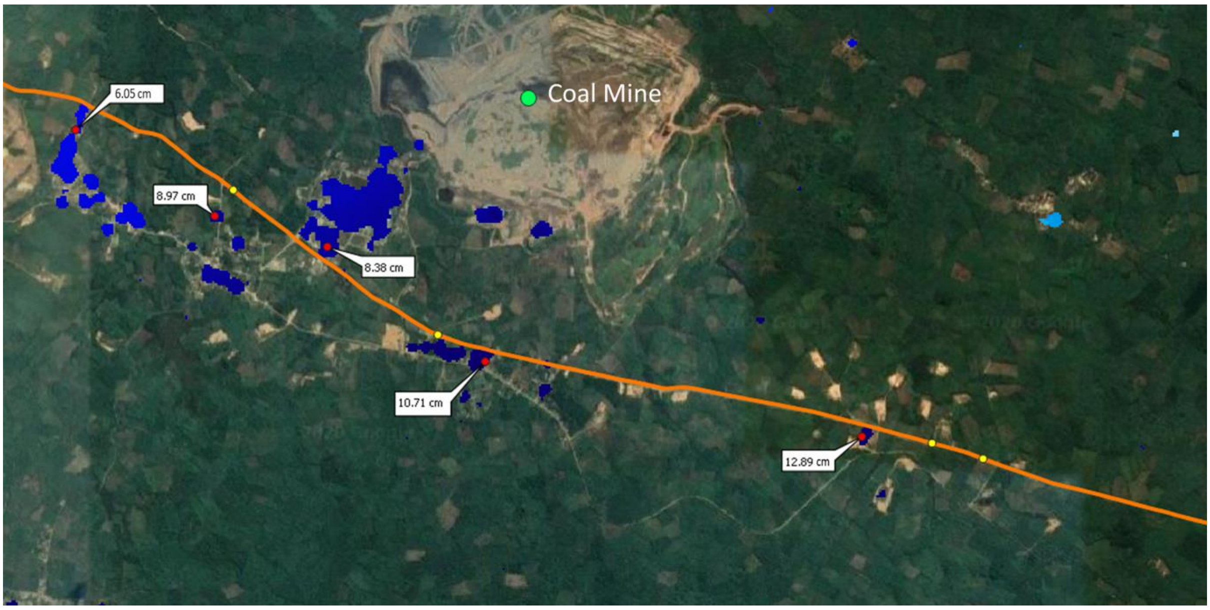
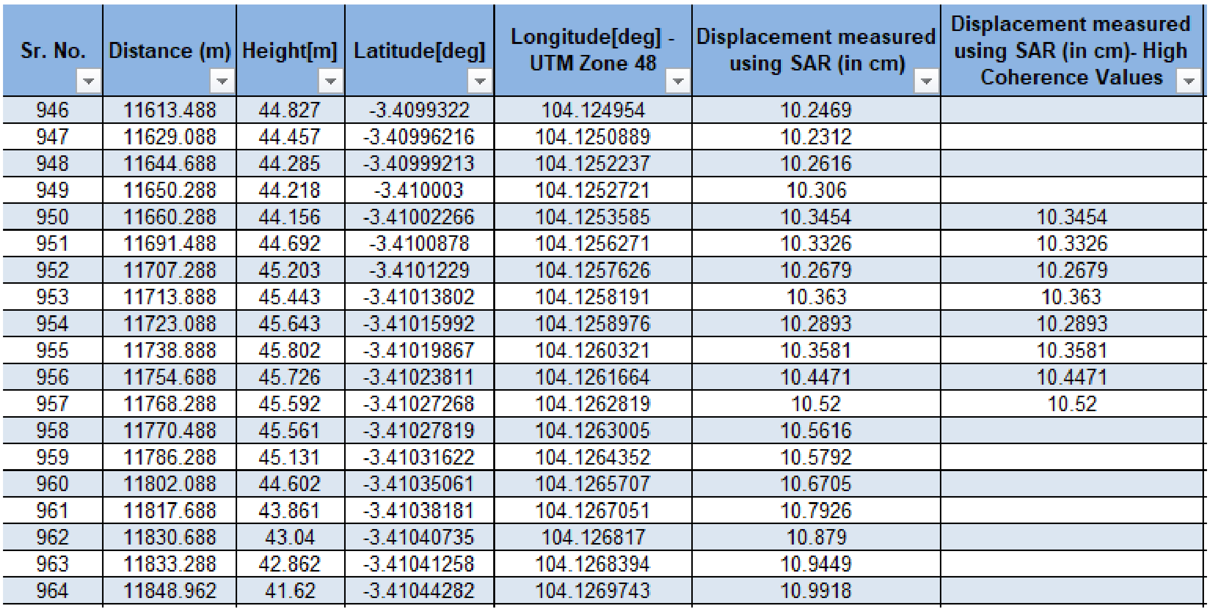


Figure 6: SAR Pipeline Image of 4 high strain points near the coal mine and one near the river

The greatest pipeline stresses/strains will tend to be in sections that lie at the interface of extreme ground disturbance differentials [4]. In this case, due to SAR coherence loss in forested areas, it was difficult to determine where the interface differentials were located. To assist in this situation the SAR and IMU data sets were correlated to produce two lists of ground displacements. One displacement list contained all the measured ground displacements along the pipeline. The second displacement list was a subset of the first list and contained only coherent displacements where the SAR data sets from successive satellite orbits were in close agreement (Table 3). The coherent list was judged to possess a high level of confidence in terms of identifying ground displacements.



Sr. No.	Distance (m)	Height[m]	Latitude[deg]	Longitude[deg] - UTM Zone 48	Displacement measured using SAR (in cm)	Displacement measured using SAR (in cm)- High Coherence Values
946	11613.488	44.827	-3.4099322	104.124954	10.2469	
947	11629.088	44.457	-3.40996216	104.1250889	10.2312	
948	11644.688	44.285	-3.40999213	104.1252237	10.2616	
949	11650.288	44.218	-3.410003	104.1252721	10.306	
950	11660.288	44.156	-3.41002266	104.1253585	10.3454	10.3454
951	11691.488	44.692	-3.4100878	104.1256271	10.3326	10.3326
952	11707.288	45.203	-3.4101229	104.1257626	10.2679	10.2679
953	11713.888	45.443	-3.41013802	104.1258191	10.363	10.363
954	11723.088	45.643	-3.41015992	104.1258976	10.2893	10.2893
955	11738.888	45.802	-3.41019867	104.1260321	10.3581	10.3581
956	11754.688	45.726	-3.41023811	104.1261664	10.4471	10.4471
957	11768.288	45.592	-3.41027268	104.1262819	10.52	10.52
958	11770.488	45.561	-3.41027819	104.1263005	10.5616	
959	11786.288	45.131	-3.41031622	104.1264352	10.5792	
960	11802.088	44.602	-3.41035061	104.1265707	10.6705	
961	11817.688	43.861	-3.41038181	104.1267051	10.7926	
962	11830.688	43.04	-3.41040735	104.126817	10.879	
963	11833.288	42.862	-3.41041258	104.1268394	10.9449	
964	11848.962	41.62	-3.41044282	104.1269743	10.9918	

Table 3: Example of data listing all SAR Displacements and those with High Coherence Values (Distance, Height, Lat. & Long. are IMU data)

Data in the list of all SAR displacements was found to be very valuable because it indicated where high displacement differential interfaces might lie. Therefore, in this case, SAR data helped to validate the IMU data and vice-versa.

4. Conclusions

In addition to successfully surveying the pipeline’s geometric profile, this project represented an appraisal of an integrated, two-method approach to the measurement of ground movements and other geohazards near a pipeline. The integrated approach was judged to be highly successful.

Based on a combination of IMU and SAR data, small ground movements that did not adversely affect the pipeline’s integrity, were used to calculate bending strains in the ground-disturbed areas. Although no structurally significant pipeline strains were found, the project clearly confirmed the value of integrating IMU and SAR data to increase the confidence of the data analysis.

Further development of the combined IMU/SAR methodology is already underway in a partnership between Inspipe Integrity Ltd and Satsense Solutions Limited. Future work will focus on further refining the technologies and methods involved, in addition to investigating a range of new developments. These will include the correlation and combined analysis of historical data records for each method in order to enhance the predictive capabilities of the integrated analysis.

References:

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[2] InSAR Principles: Guidelines for SAR Interferometry Processing and Interpretation (ESA TM-19, February 2007), Alessandro Ferretti et al.

[3] Development of a Risk Rating Matrix for Assessing Onshore Pipeline Geohazards, IChemE, Hazards 26, 2016, C Ashton et al.

[4] Impact Assessment of geohazard related Ground Disturbances on Hydrocarbon Pipelines, using satellite remote sensing technology (June 2020), Pranav Pasari and Umang Buddhdev, Satsense Solutions Ltd.