Remote Sensing Analysis for Pipeline Incidents Risk Evaluation

Alexandre Agaian, PhD, Dmitry Vilbaum, Terra Insight Services, Inc

Background

Detection and prediction of stress corrosion cracking (SCC) and other pipeline-disruptive conditions is a challenging task. Existing models and methods cannot economically locate areas susceptible to SCC accurately due to long pipeline distances and access difficulty.

The majority of pipeline damage documentation focuses on the particular aspects of the damage management and prevention process – specifically, various manmade causes of corrosion and mechanical damage, or the methods of location, assessment, and remediation of such damage post factum. Little has been done to provide a comprehensive overview of the issues associated with the natural phenomena and processes substantively leading to SCC, CF, or any other type of change of integrity. Typically, the sources of pipeline damage such as landslip, stress, tectonic processes, erosion, mud flows, faults, underground water flows, etc. are excluded from the studies, falling into the "other causes" category. Geological (heat gradient, soil composition and aggressiveness) and electromagnetic (subsoil currents, cosmic radiation influence, etc.) factors typically also fall outside of the root-cause analysis scope.

According to the U.S. Department of Transportation's Pipeline and Hazardous Materials Safety Administration (PHMSA), depending on the remoteness of the pipeline path and the country's specific landscape, population density, climate, etc., the natural and other (including unknown) causes of damage may represent a significant part of all possible causes – up to 50% and more (combined).

In 2011, Terra Insight Services (TIS), a New York based natural resources exploration and technology company, and Transportadora de Gas del Sur S.A. (TGS), an Argentine operator of a 9,000 kilometre gas pipeline, agreed to undertake a R&D study, intended to assess certain subsurface and near surface conditions ("Negative Causes"), which negatively influence the pipeline and may lead to Stress Corrosion Cracking (SCC) or Fatigue Corrosion (FC) and determine the locations of the elevated SCC and FC risk.

The world history of pipeline exploitation is filled with incidents of a different magnitude which occurred due to both known and undetermined causes, which are often "blamed" on a factor of a known quality. Despite well developed and practiced systems and policies of risk management, monitoring, maintenance, prevention, new technologies, testing, etc. ruptures do occur forcing the companies to spend millions of dollars every year on pipeline repairs and incident recovery.

Some gas transporters made significant progress by trying to analyze the correlation between SCC risk and the levels of the cathode protection and electrical resistivity, traditionally used by the industry. The analysis conducted by TIS showed little, if any, correlation between the level of corrosion/metal loss in the pipelines and the values of the aforementioned customary protection parameters.

The corrosion itself is unavoidable, though its rate of development can be controlled. Our analysis of the incidents asserted that in most cases the corrosion by itself only "aided" the incidents, which were triggered by various factors of a different nature. The same holds true in relation to existing dents, cracks and other pipeline defects, including those due to the manufacturing and construction faults.

In light of the absence of certain correlations and dependencies, there arose a need to determine and analyze natural negative factors in order to determine a set of the most probable causes of pipeline incidents. Some negative factors are known (and some are even intuitive), however there isn't a model which can assess the level of influence of each individual factor, correlate and group them rendering an actionable, practical and applied solution which can be utilized on a pipeline pre-emptively and in advance of a rupture.

For example, since SCC is found in operating pipelines where the loads are not static, it is intuitive that within the areas of active surface movements, for instance, due to subsurface displacements (karst formations, local secondary faults, underground water reservoirs and rivers influence, etc.), pipeline damage should be more probable and frequent. Even without a major mechanical impact, the pipeline areas with pre-existing cracks or deep erosion spots could become easily penetrated as a result of minor pipeline displacements or stress. The question is – how to practically determine the areas of probable surface movements or negative subsurface conditions and, moreover, monitor the situation development in those areas.

Due to the inevitable aging process of pipelines, monitoring them must be continuous, predictive, accurate, economic, and incorporate natural negative factors. New remote sensing-based and analytical methodologies addressing the aforementioned demands were developed by TIS and are presented in this paper.

Aims of the Research

TIS understands that it cannot assess all the possible negative causes, especially those of a manmade nature. The goal of the Company is rather to determine *natural* factors, material to the pipeline condition, which can be observed and assessed remotely, as well as to create a model and the methodology of measuring and monitoring of such negative factors on the basis of satellite, geological and analytical data interpretation, providing the industry with an additional efficient methodology.

The research was carried out on a limited pipeline fragment of 20 km length (Test Distance). The following has been determined as the major goals of the study:

1. Assessment of geological and tectonic conditions associated with the Negative Causes;
2. Collection and processing of high resolution satellite data over a 20 km distance of the pipeline ("Test Distance") in order to assess surface and near surface conditions associated with Negative Causes;
3. Using the spectrometric analysis, creation of a model consisting of a set of spectral criteria and parameters which individually indicate for negative influences on the pipeline, test their relevance and correlation over the Test Distance;
4. Perform paleo-reconstruction of the Test Distance;
5. Develop a generalized/composite set of criteria and a model of Negative Causes for the Test Distance;
6. Analyze and correlate the locations of known SCC cracks, past incidents/ruptures with the generalized model applying such an analysis to the Test Distance.

Methodology

The proposed approach was based on several concept remote sensing and analytical methods, designed to evaluate and identify certain pipeline areas with an elevated incident risk level as well as to detect and predict SCC.

TIS was supplied with the following data on the Test Distance: pipeline technical parameters, schematic, properly adhered to marker coordinates. High resolution spectral data was selected as the basis for research. Multispectral satellite data covering RGB and near- through far-IR channels have been utilized. Satellite radar data was utilized to address several specific issues - assessment of soil moisture, texture and surface morphology, identification of shifts and displacements of soil, structural correlation with spectral and thermal anomalies, searching for thermal anomalies of the man-made nature.

Detailed digital elevation data and topographic maps were imperative for the studies related to the geomorphological analysis as well as relief plasticity studies.

The buffer zone of 3-5 km in both directions from the pipeline was covered via satellite data. Time of data acquisition was considered to capture stable vegetation patterns.

TIS applied a multi-factor integrated approach to the analysis of the natural negative causes, which subsequently could be used for the development of the efficient pipeline monitoring/incident prevention system. The importance of different factors was unknown *a priori*. Moreover, it was obvious, that in different geographic areas and conditions (climate, weather, geographical location, elevation, etc), each given factor alone or in combination with other factors could influence the acceleration of corrosion, SCC or other mechanical damages, differently (from a “catalyst” to the cause of an incident). TIS’ general approach was to:

1. Create a list of negative factors, applicable to the project, which can be detected and assessed remotely;
2. Collect the data which will be used to identify, measure, and determine the presence of such negative factors on the Test Distance;
3. Measure and analyze each negative factor (“Factor”) individually and input its values into the model;
4. Determine the existence and analyze the type of correlation between each of the Factors and the technical data on the pipeline provided by the customer in the model (i.e. corrosion and metal loss). More importantly, establish correlation between each Factor and the locations of the past ruptures;
5. Analyze the Factors, their combinations and patterns of values distributions, variations and dependences; deduce the highest combined risk values and analyze their correlation with the known negative pipeline conditions provided by the customer, linking them to the extensive or accelerated corrosion or SCC;
6. Include all of the values in the model for statistical and mathematical analysis.

Although a onetime analysis of the Test Distance is an evidently important undertaking, the ultimate goal of this project was to extend beyond the onetime assessment and design a system, which can rank Factors and Causes (as a combination of several factors), assess the intrinsic natural dynamics of each Cause and its technical/economical considerations. TIS’s goal is to develop an integrated model of negative factors and causes as well as a monitoring system able to periodically update with respect the Factors and Causes, their anticipated rate of development/progress. Such a product would provide regularly updated, actionable datasets used for decision making, planning, and risk management. The system would also alert operators of critical conditions developing in the pipeline as the basis for immediate or scheduled application of preventive measures. The overall system is planned as a 360 degree view of the pipeline: from helping act on the immediate problem elimination at the problematic areas to a longer term improvement of the overall health of the pipeline.

The following analyses have been carried out in this study:
- Relief plasticity analysis
- Spectrometric analysis
- Radar interferometry and polarimetry
- Mapping of temperature gradients
- Risk ranking.

Negative Causes. In a course of this project TIS considered many natural factors and phenomena for inclusion into the remote acquisition, processing and analysis. Some of them represent natural processes or conditions, which may potentially, physically or chemically affect the pipeline corrosion, some in direct, some – in indirect way. The factors of this class are usually slow moving processes or long existing conditions of non-disruptive character, which are responsible for continuous pipeline corrosion. At the same time, main accent in this report was made on studying factors of the stress or displacement character, representing a class of abruptive causes, potentially responsible for the sudden breakages, sharp relative movements of the pipeline parts, bending, walls or welding points penetration, thus – a class of immediate causes of pipeline incidents.

Several causes may lead to gas pipeline damages; each "cause" may be a result of several risk factors (***Figure 1***).

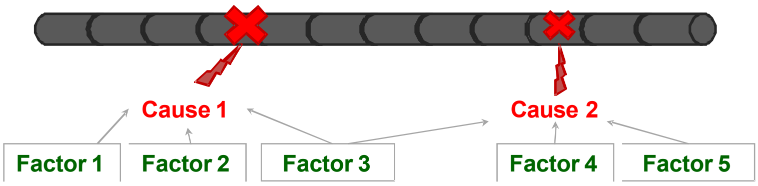

Figure 1: Each pipeline incident "cause" may be a result of several risk factors

Corrosion is one of major, but not necessarily the only, factor playing a role in pipeline integrity disruption. Published international and national standards provide extensive guidance in relation to risk factors, which are related to respective causes, but there are major flaws associated with these published standards:

- Lack of practical and economic solutions to detect Causes
- Lack of practical and economic solutions to detect Factors
- Not all of the Factors are known or can be detected by traditional tools

The actual cause of the incident or high corrosion, or accelerated corrosion rate, as well as mechanical damages, is often unknown as a result of the absence of technology for natural factors analysis, measurement and monitoring.

Important aspect of the negative factors analysis is a natural pace of their development. Elements of local and regional tectonic structure and surface and near surface dynamics represent a class of extremely slow progressing factors compared to the lifetime of the pipeline (surface medium flows, lineaments, hidden major and secondary faults, stress fields, etc). From the first sight, there is no practical reason in identifying these factors, measuring them and interpreting their potential impact on the pipeline integrity. At the same time, stresses accumulated through millions of years of those processes existence might well become a sudden disruptive cause of the pipeline damage and eventually – an incident, as is schematically demonstrated on the Figure 2 below.

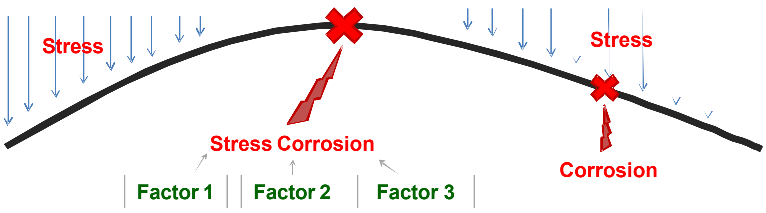

Figure 2: Stress as a cause of incidents

In many cases, **the real Cause of ruptures is NOT corrosion, but Stress**. It is not currently understood how cracks initiate under a coating disbondment environment. There are stress/microstructural features responsible for the initiation process. While the corrosion detection is fairly simply, although expensive, the real challenge is detection of the elevated Stress in certain sections of the pipeline. The hypothesis developed in this report is that a high percentage of corrosion related pipeline breaks is due to Stress, accumulated within the containing medium and exerted on the pipeline over time.

TIS used the following list of the Groups and Factors/processes (directly or indirectly impacting the pipeline) which the Company was capable to collect, and analyze using its "remote" capabilities (*Figure 3*).

Designation and name of the factor		Content/Presence
1	2	3
Group 1: External anthropogenic impact		
$(F)_{11}$	The level of anthropogenic activity	Construction density
$(F)_{12}$	The level of anthropogenic activity	Roads density
Group 2: Corrosion		
$(F)_{21}$	Soil corrosive aggressiveness	Soil resistivity (provided by TGS)
$(F)_{22}$	Soil corrosive aggressiveness	Types of soils, geomorphology (provided by TGS)
$(F)_{23}$	Soil corrosive aggressiveness	Depth of groundwater (provided by TGS)
Group 6: Natural effects		
$(F)_{61}$	Effect of water-slopes processes	Value of the day surface sloppiness (prepared based on the data from SRTM and ASTER GDEM. Also provided by TGS). Processed and integrated in CIR SRTM and ASTER GDEM.
$(F)_{62}$	Territory moisture degree	Marshiness
$(F)_{63}$	Temperature contrasts	Soil own thermal radiation (obtained from Landsat-5, 03-04 2011).
$(F)_{64}$	Tectonics	Density of the lineaments network (prepared based on SRTM)
$(F)_{65}$	The nature of vegetation	Based on high-resolution satellite imagery.
$(F)_{66}$	Landslides	Landslides and other sharp land moves (prepared based on the data from SRTM and ASTER GDEM. Also provided by TGS – file ELEVATION_DEPTH.xls)
$(F)_{67}$	Seismic activity	Resonance seismic waves
$(F)_{68}$	Lithodynamic Stress	Surface stress fields due to the lithodynamic flows pattern (prepared based on the elevation maps 1:500,000 and 1:50,000)
$(F)_{69}$	Lithodynamic Lineaments	Deep lineament structures due to lithodynamic flows (prepared based on the elevation maps 1:500,000 and 1:50,000)
Group 8: Pipeline defects in welds and pipe walls		
$(F)_{81}$	Defects Density 1	Metal loss and defects, manufacturing (provided by TGS)
$(F)_{82}$	Defects Density 2	Metal loss and defects, corrosion (provided by TGS)
$(F)_{83}$	Defects Density 3	Metal loss and defects, corrosion, other factors (provided by TGS)

Figure 3: Factors analyzed during the study

TIS uses an integrated suite of several independent remote sensing and analytical methods under the Sub-Terrain Prospecting (STeP®) technology umbrella. Within the scope of this project, the Litho-dynamic analysis (LDA) and Spectrometric analysis (SMA) were used supported by the optical, multispectral and radar image sophisticated processing and interpretation.

The full descriptions of LDA and SMA can be obtained on the TIS web-site www.terrainsight.com.

LDA entails creation of maps which identify the specifics of vertical and horizontal movements of the surface and ground masses (litho-dynamic flows), responsible for creation of surface and near-surface stress. SMA represents a set of proprietary and industry standard algorithms of processing of remote sensing data for identification of the surface and subsurface features, anomalies, and spectral deformations indicative of specific natural phenomena and processes. To achieve the objectives, a number of satellite images were selected, prepared and thematically processed at various resolutions, presenting a set of optimal remote sensing materials from regional to local scale of remote information. Thematic processing of the remote sensing data was carried out using ArcGIS (9.x-10), Mapinfo (9-10), ERDAS (9.x-2011), ENVI (4.7-4.8) with SarScape (3.4-4.4), Global Mapper (v.13), Matlab (R2009b-R2010b), Mathematica (5.x-8.x), and certain proprietary software developed by TIS.

The maps and graphs for each negative factor were compiled based on the acquired and processed data. Examples of such results are provided below.

Factor F_{22}:

Corrosion aggressiveness	Soil type	Score
Low	Sandy and sandy-clay	1
Medium	Clay, saline, poor in black earth	4
Elevated	Rich in black earth, lime	7
High	Seeded with lime, slag, waste	9
Very High	Turf	10

Figure 4: Soil types influence scores

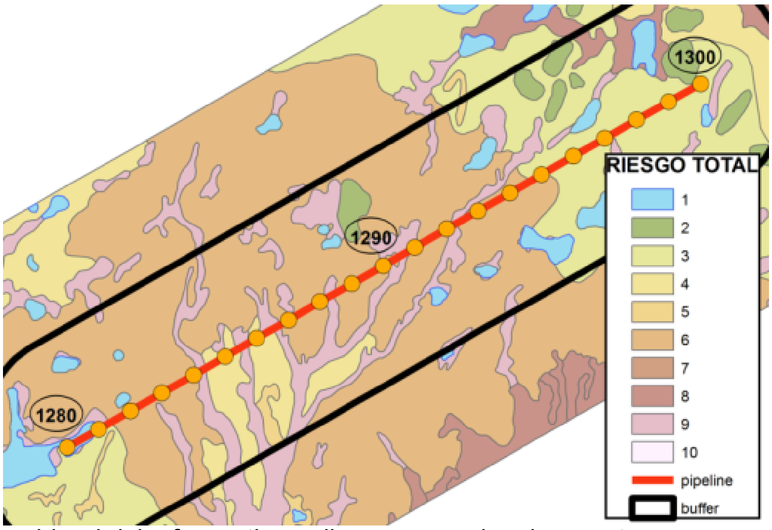

Figure 5: Map of combined risk of negative soil processes development

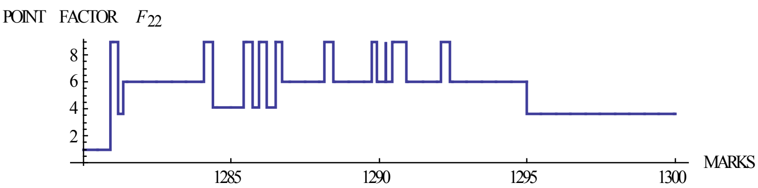

Figure 6: Score graph for the soil processes influence risk distribution along Test Distance

Factor F_{61} :

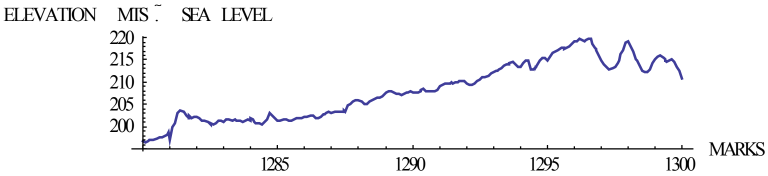

Figure 7: Absolute elevation profile along the Test Distance

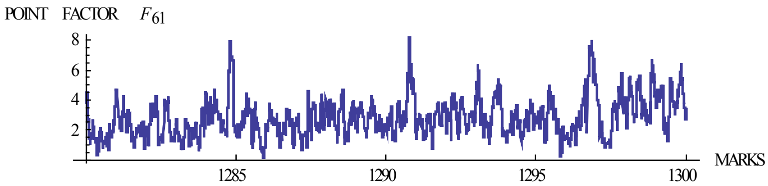

Figure 8: Risk score graph of the sloppiness of the day surface along Test Distance

Factor F_{63} - Assessment of the rate of change of the thermal field over the research area using the satellite imagery is based on the measurements of temperature as one of the most effective parameters in the pipeline diagnostics. The F63 values were derived from the temperature maps over the Test Distance using the thermal band satellite data from LANDSAT – 5, obtained on 03/30/2011, and 04/15/2011; the difference of temperature readings for these two dates have been calculated.

Thermal anomalies, recorded on the map of the temperature difference, are caused by both active geological processes and the changes of the pipeline conditions (physical and/or chemical). Therefore, the highest value of the temperature gradient should correspond to the greatest risk.

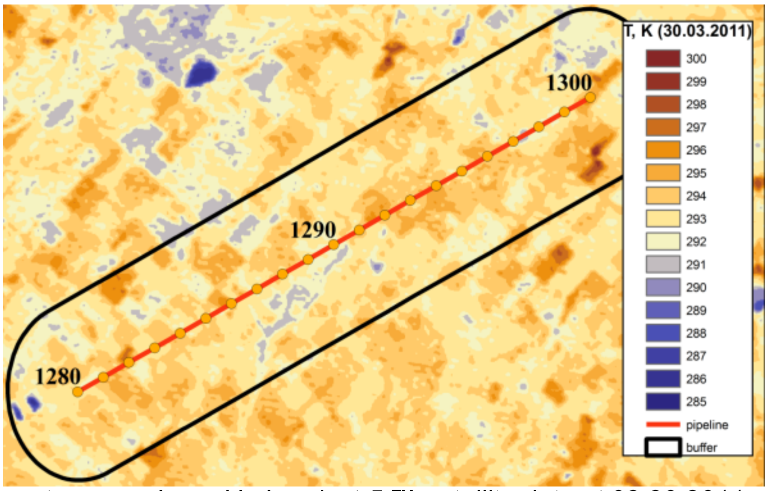

Figure 9: The temperature map based in Landsat-5 ™ satellite data at 03.30.2011

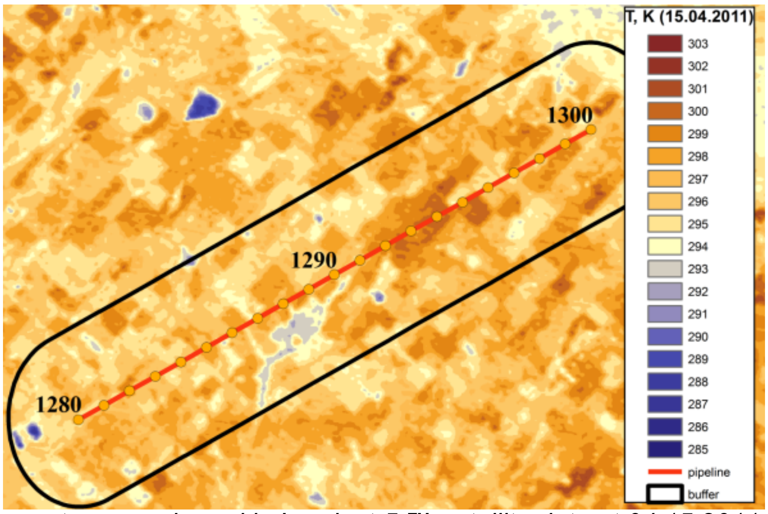

Figure 10: The temperature map based in Landsat-5 ™ satellite data at 04.15.2011

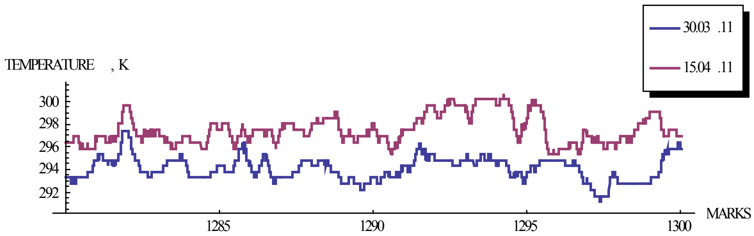

Figure 11: Surface temperature graphs above the pipeline for chosen dates

The maximum temperature difference (in absolute values) amounts to 3°K per 16 days. The temperature gradient graphs and the corresponding scores are shown in Figure 12 (the series of temperatures were first centered relative to the average values).

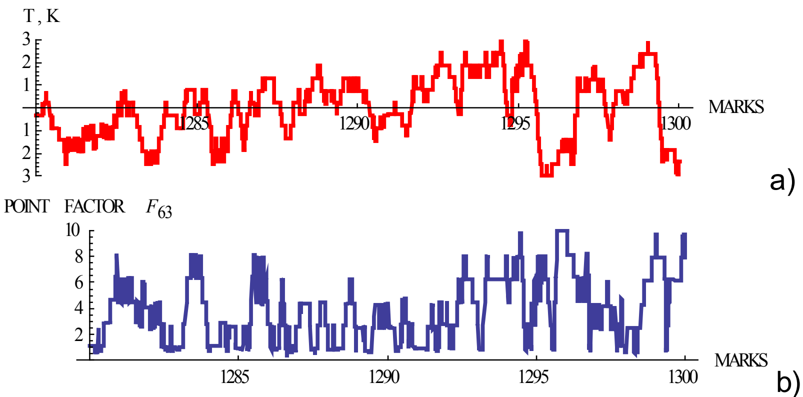

Figure 12: Temperature gradient along the profile (a) and scores of the incident risk due to uneven heating/cooling of the different parts of the pipeline (b)

After constructing the maps, graphs and tables for all selected factors along the entire Test Distance of the pipeline, the process of the pipeline division into the fragments was applied consistently and independently for each influence factor $\mathbf{F_{ij}}$ or the factors group $\mathbf{G_i}$. Criterion for determining the borders between different segments, based on factor $\mathbf{F_{ij}}$, was a notable enough (perhaps, gap), change in the factor value. The increment of the analysis in length was selected equal to 1m, and the values of all the factors were defined along the pipeline in increments of 1m.

A specific score $\mathbf{B_{ij}}$ (on a 10-point scale) is assigned to each factor $\mathbf{F_{ij}}$, which is basis of the calculation or expert opinion and reflects the intensity of its influence. Based on the score assessment of each factor, the factor weight within its Group and the weight of the Group (relative "contribution" of each group $\mathbf{G_i}$, i = 1, 2, 6, 8) in the summary statistics of incidents, it becomes possible to obtain estimates of the local frequency of incidents on the given fragment of the pipeline.

Upon completion of the evaluation of the individual risk Factors, the integrated risk score values have been calculated. These scores incorporate the level of impact (weight) of each factor within the Group and the Weight of the entire Group, as shown on Figure 13:

Group, $\mathbf{G_i}$	Factor, $\mathbf{F_{ij}}$	Factor's weight in its group, $\mathbf{q_{ij}}$	Group's weight, $\boldsymbol{\rho_i}$
G1	F11	0.5	0.21
	F12	0.5	
G2	F21	0.34	0.14
	F22	0.33	
	F23	0.33	
G6	F61	0.3	0.21
	F62	0.2	
	F63	0.2	
	F64	0.3	
G8	F81	0.33	0.44
	F82	0.33	
	F83	0.34	

Figure 13: Weights of the negative factors and groups

Combined influence of all factors at any point *n* on the pipeline was calculated using the following formula:

$$R_n = \sum_i \sum_{j=1}^{l_i} \rho_i q_{ij} B_{ij,n}$$

where $B_{ij,n}$ is the value of the factor F_{ij} in point n. As previously stated, the calculations were performed for all of the points on the 20km Pipeline fragment with 1 meter resolution. Thus, the assessment of risk is represented as a function of the combined/correlated individual risk factors for any specific point (coordinate) on the pipeline. The map and the graph showing the results of such calculations are presented on Figure 14 and Figure 15.

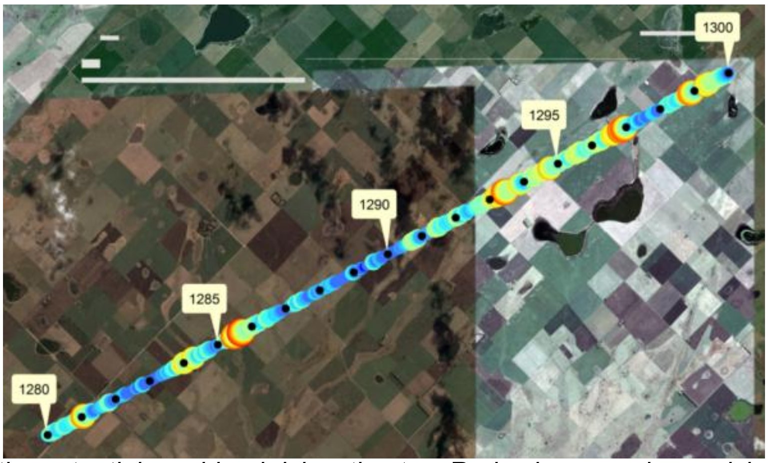

Figure 14: Map of the potential combined risk estimates. Red color – maximum risk values, blue color – minimum risk values

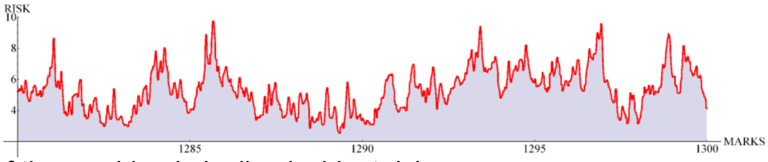

Figure 15: Graph of the combined pipeline incident risk scores

Clustering

Clustering is a method of data sets classification based on an aggregate set of attributes without pre-creation of standard training samples and "training" (parameter tuning) of classificators. Within this research, a Kohonen's artificial neural network has been used as a clustering tool.

In this case, the data set is a set of vectors, whose components are the previously determined Factors (often called in literature as the "feature space"). The number of factors-features generally could be arbitrary. It is recommended to select the factors that cannot be correlated. Such factors in our case were: the value of the area's inclination value (F_{61}), temperature gradients (F_{63}), lineament density (F_{64}), soil electrical resistivity (F_{21}), the total risk of dangerous ground processes (F_{22}), corrosion (F_{81}) and corrosion (F_{83}).

Several clustering procedures were performed for a different number of classes. The analysis revealed that the optimal number of classes was between 4 and 10. For the illustration purposes, Figure 16 shows the results of clustering for 9 and 4 classes respectively. Colors designate particular classes, spatial localization of which is determined by the distance (in meters) from the pipeline marker 1,280. Semantic content of colors for the upper and lower graphs is not the same, i.e. the same colors in the graphs (above and below) do not imply the same class. Differentiation of classes by height in the lower figure is shown for a better visual perception and has no other substantive meaning.

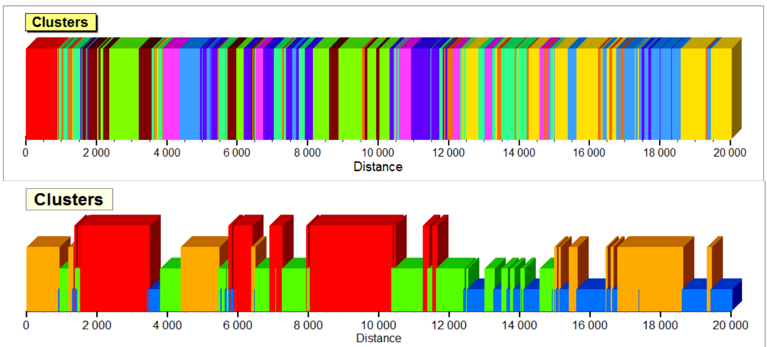

Figure 16: Clustering result for 9 (upper graph) and 4 (lower graph) classes.

Analyzing the results, we can notice some correlation between classes in the upper and lower figures. In particular, in the distance range 2,000-4,000 and 8,000-10,000 meters from mark 1,280, red color at the bottom of the figure are correspond to brown and green colors at the top; in the range of 15,000-20,000 meters, blue and orange colors of the lower picture correspond, respectively, to yellow and blue color of the top graph.

Comparing the assessment of the overall risk of the pipeline incident, calculated as a linear combination of risk factors, with the clustering results (Figure 17), a certain correlation can be observed. The division into 4 classes correlates with the low frequency component of the combined risk score graph, while the 9-class clustering correlates with the high-frequency component on the risk score graph.

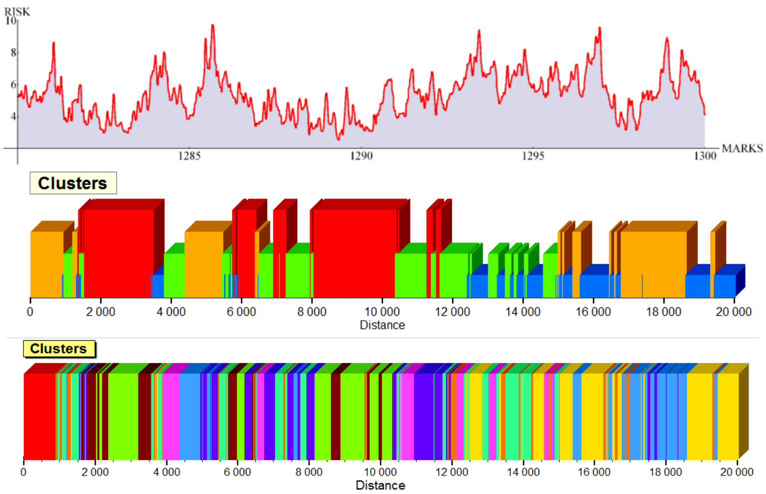

Figure 17: Comparison of the combined risk estimates and clustering

The principle of interpretation of the results of clustering is in the assignment to the pipeline parts with the same colors (belonging to the same class) of the same properties. For instance, if we leave aside the combined risk assessment and consider only the results of clustering, then, keeping in mind that there was an incident in the past at the mark 1,290 (10,000 m from mark 1,280 on the clustering graphs), it can be assumed that at intervals of 2,000-4,000 m, and 8,000-10,000 m, similar incidents may also occur, since these ranges belong to the same class as mark 1,290. But this suggestion has merit only if the cause of the incident at mark 1,290 was one (or several) of the factors, included into the clustering.

Lithodynamic Analysis

In addition to the direct satellite images processing and interpretation, performed in the previous section, TIS' special analytical tool, LDA, was applied to the Test Distance. The aim of this part of TIS' LDA analysis was to identify potentially dangerous zones along the pipeline from the point of view of stress fields created by the lythodynamic flows:

Positive flows (also called convexities) represent the inherited tops of deep seated flows of a lighter terrestrial matter, and negative flows (concavities) represent the flows of the heavier terrestrial matter, trending downward. Positive flows are slow shifts/movements; however they are relatively large in terms of scale: their height ranges from a few meters to several hundreds of meters, or kilometers in mountainous areas. Only the very tops of convexities can be observed, analogous to "tips of icebergs". Negative flows move faster than the positive ones, and the volume of the matter carried by such flows is also quite large. The areas of negative flows are characterized by substantial land subsidence and flooding, potentially resulting in ruptures of the pipeline. As a result of the difference in the movements of the positive and negative flows, the contact areas of such flows pose a higher incident risk.

Typically, only two-dimensional geological and engineering profiles are used by the pipelines constructors. Lithodynamic analysis produces highly informative more accurate space-time (matter in motion) maps, as shown for example in Figure 18.

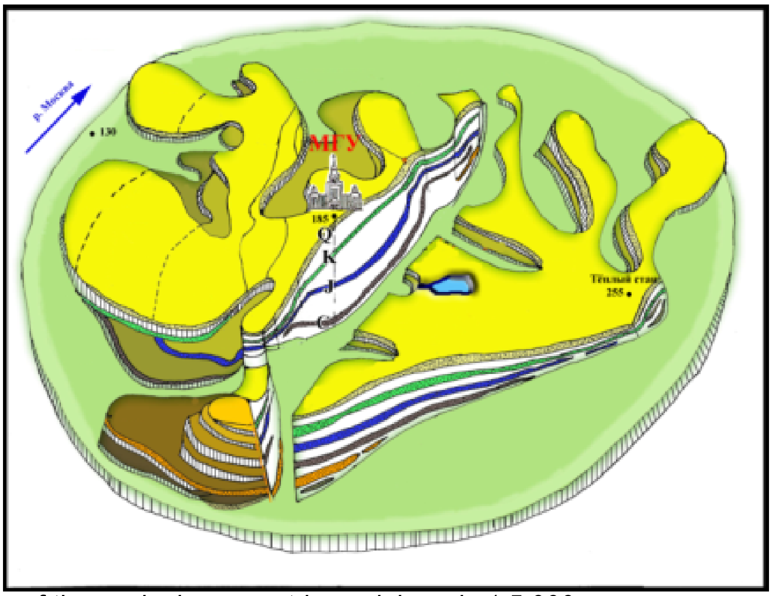

Figure 18: Example of the geologic-geometric model, scale 1:5,000

As seen on Figure 19, the boundary zones between the rising and subsiding flows are the zones of stress risk.

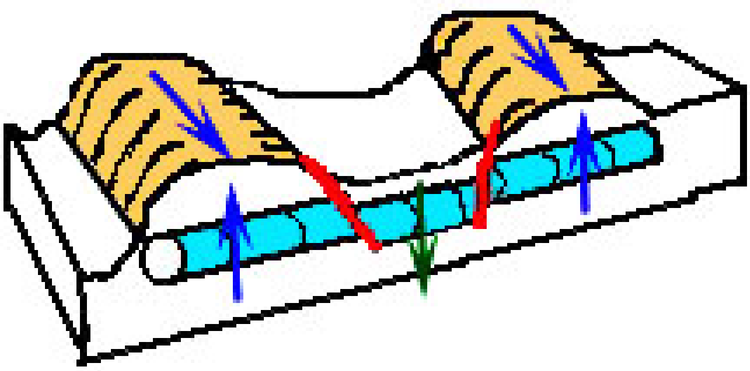

Figure 19: Example of the pipeline position relative to the positive (light brown) and negative (white) flows.

Through the pattern of the relief plasticity flows, the directions of the distribution of geological, geochemical and water masses in the Earth's gravitational field could be seen. Through LDA deep linear tectonic structures (lineaments) were identified, see Figure 20 below.

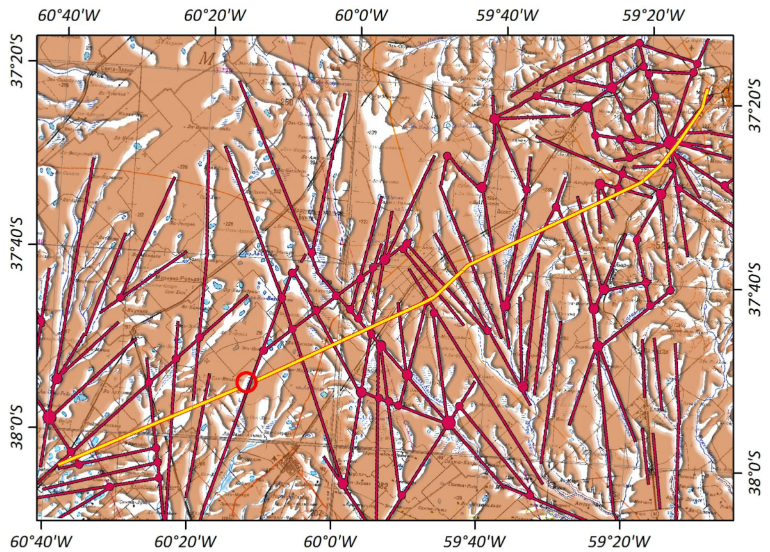

Figure 20: Map of the linear tectonic structures, located in the vicinity of the pipeline, scale 1:500,000. Positive flows - brown, faults – red. Red dots - nodes of intersection of faults.

The map (Figure 20) shows the faults that are located in a close proximity to the object. On the map below (Figure 21) the areas, which require a heightened attention (though not in a pre-incident state) are shown. We can't exclude the situation that the pipeline at those areas is already in the dangerous or pre-incidental condition.

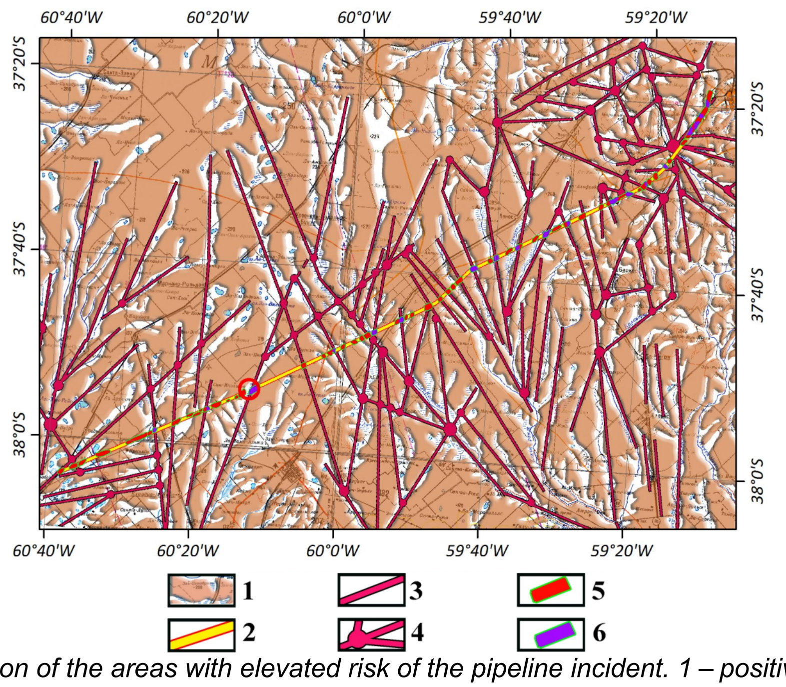

Figure 21: Prediction of the areas with elevated risk of the pipeline incident. 1 – positive flows, 2 – pipeline location; 3 – lineaments; 4 – nodes of the lineaments intersection; 5 – pipeline parts, located in endangered zone; 6 – pipeline parts with the highest risk of incident

According to the lithodynamic analysis, the elevated risk fragments on the pipeline can be classified into two categories: A - elevated risk areas (red) and B - danger areas (purple). The red category includes those areas which are affected by only one Factor (the dynamics of hydro-lithologic flow or a stress zone caused by the linear fault), while the purple category denotes the areas of both negative Factors coinciding. The process leading to the red and purple zone determination is demonstrated on Figure 22.

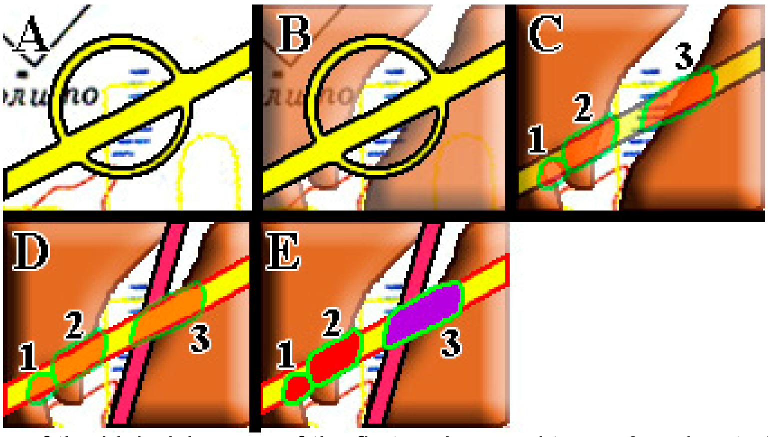

Figure 22: Selection of the high risk areas of the first and second type. A – elevated risk spot location on the topographic map; B - the risk site location in respect to the existing lithodynamic flows; C – identification of the pipeline point with a high degree of risk, on the border of the lithodynamic positive flows (## 1-3); D – depicting the lineament on the map (red line, according to the legend to the map in Figure 21); E – the final map. Selection of two categories of risk zones: 1 and 2 - high risk (red), and 3 – highest risk zone (purple).

Lithodynamic Analysis Results on the Test Distance

Lithodynamic analysis, due to its nature and specifics of its application was performed on the areas covering longer than 20 km of the Test Distance of the pipeline. The spatial extend of areas tectonic elements such as lineaments and upper crust dynamics, such as lithodynamic flows is quite large and requires staged approach from regional to sub-regional to local compilations. To use the results of lithodynamic analysis in conjunction with the data provided by the customer and with the results produced by other methods used by TIS, we separated an area covering the segment of the pipeline within the Test Distance (20 km long, between marks 1,280,000 and 1,300,000) the map of this fragment of the analysis results is shown in Figure 23 below.

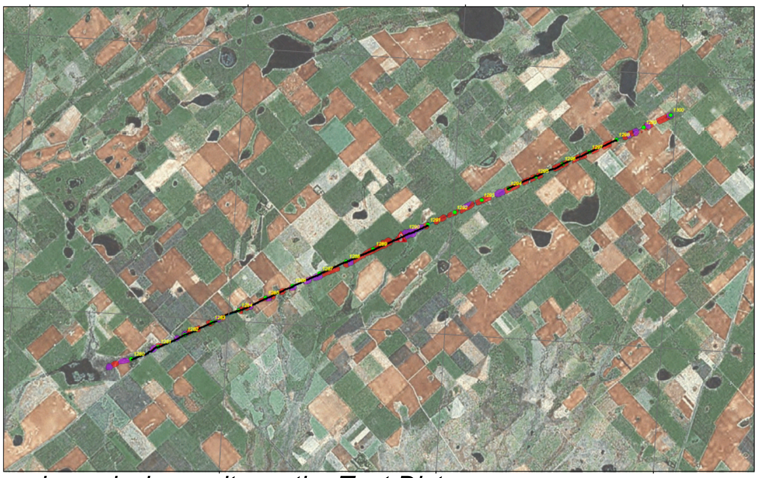

Figure 23: Lithodynamic analysis results on the Test Distance

Several areas of “red” (elevated risk) or “purple” (high risk) have been identified using the lithodynamic analysis, as the study of stress at the contact zone between different lithodynamic flows and physical displacement along the tectonic faults/lineaments. Many of the “purple” zones coincide with the pipeline segments which sustained the substantial metal loss or the above average deep defect density. Such zones are, for instance, between the markers 1,280,650 and 1,280,690; near mark 1,282,000 and clearly between the markers 1,298,140 and 1,299,140. All of these pipeline segments require attention and more frequent monitoring, especially if the other negative Factors correlate with the lithodynamic analysis results with their high values.

It is of note that two of the high risk areas which were located using the special satellite image processing (one of which also coincides with the recent point of rupture), in turn coincide with one of the areas of a very high lithodynamic risk (approximately between the markers of 1,290,000 and 1,290,120).

Spectrometric Analysis Risk Evaluation Results

The incident risk scale was calculated by TIS' proprietary SMA for local points separated 125 meters from each other. Combined weighted incident probability values were assigned for all local points within the Test Distance. The respective map is shown in Figure 24.

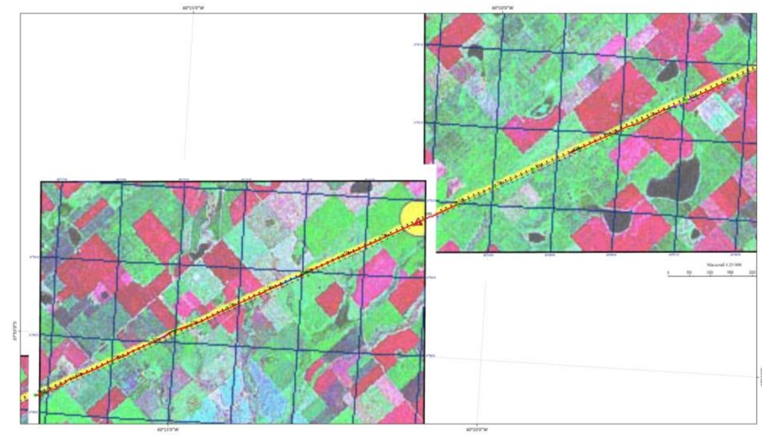

Figure 24: SMA risk level estimates for the Test Distance

Optical Satellite Images Processing of the Test Distance

Based on the visual interpretation of the space imagery materials (QuickBird-2) on 10/10/2010 (4 months before the Incident at mark 1,290), TIS discovered a clear anomaly precisely over the mark 1,290. Moreover, the presence of the same anomaly, although not as explicit, can be observed on the image hosted on the Google Earth Installer service (photo taken in 2003).

It is obvious, that this anomaly is an indication of a negative process associated with the pipeline at this location. The registered incident is a testament to that. Therefore, analogous anomalies detected directly over the pipeline can be considered as areas of note, or even concern, and are to be recommended for observation or an in-field inspection, depending on the intensity/contrast characteristics of the spectral anomaly. In short: similar spots must be noted, monitored, and analyzed.

An analogous area was noticed 120m upstream from the rupture site. Because the anomaly is located over the pipeline, and is largely in similar engineering and geological conditions as the 1,290 mark, closely resembling its anomaly prior to the rupture, TIS suggests that this area may be critical and requires an inspection.
The following images illustrate the newly discovered point of contention (Figure 25 through Figure 27).

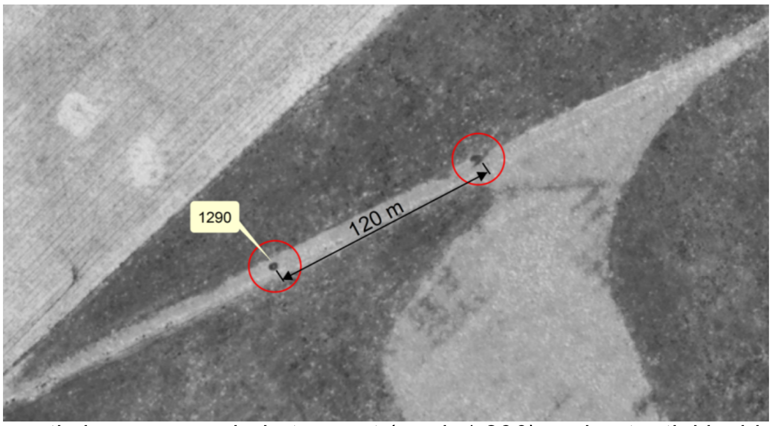

Figure 25: Panchromatic image recorded at recent (mark 1,290) and potential incident locations (date 10.10.2010 - 4 months before the incident

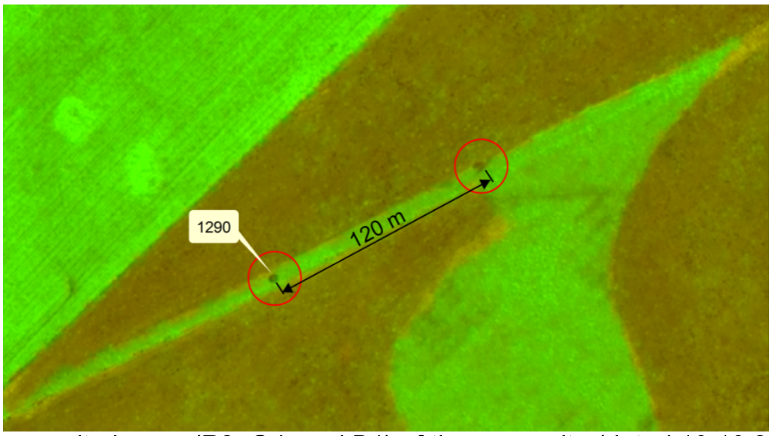

Figure 26: Color composite image (R2, G4, and B1) of the same site (dated 10.10.2010 - 4 months before the incident)

Figure 27: Image taken in 2003 (from the Google service)

The hypothesis is that the colonies of cracks have been developing at the location of the Pipeline marker 1,290 over a number of years prior to the rupture. It is currently difficult to assess whether these cracks developed steadily over time or went dormant for some time, however it is very likely that these cracks continued to propagate and lead to an incident in 2010. It could also be concluded that the spectral anomalies similar to this one are to be excavated for further study, testing, and confirmation. Should the excavation and other tests confirm the presence of SCC or other types of cracks, it is recommended to monitor and study the development of the situation at such “high-risk” locations no less than every 6 months or in case of the accelerated development, every 3 months.

The monitoring using the satellite data approach is believed to be advantageous, as compared with field methods. Although it is not exactly understood how cracks initiate under the coating disbondment environment, the hypothesis leads to the micro-structural features responsible for the SCC initiation process. The general assertion is that the remote sensing analysis may be more accurate and informative than the traditional analysis and testing methods, in such situations.

At present, significant portions of the Pipeline are managed by in-line inspection or by hydrostatic testing. Either of these techniques provides protection from in-service failures for a number of years and then the process has to be repeated. The testing cycle is particularly troublesome for gas pipelines since only relatively large flaws and cracks that fail at SMYS (specified minimum yield strength) are detected by the hydrostatic testing technique, potentially leaving out the micro-cracks. These procedures are also enormously expensive.

Indeed, the anomalies identified herein may serve as a better early detection mechanism of SCC crack initiation and propagation leading to more accurate prediction of the locations of significant SCC. This knowledge would also reduce the rupture rate and hence prevent the associated large gas fires (releasing clouds of carbon dioxide and smoke) that accompany these failures. In SCC or CF (corrosion fatigue) processes, there are generally three stages for the cracking process: (i) generation of an environment that causes cracks to initiate; (ii) initiation of cracks; and (iii) propagation of cracks until failure occurs. This present study and the spectral anomaly depicted on Figure 25 through Figure 27 are believed to have addressed the environment generation or/and the crack initiation stages. Periodic monitoring of these anomalies may help assess the types of cracks, crack behaviour, role of crack initiation sites, and factors governing crack growth.

Is it of note that certain spectral anomalies (vegetation, soil changes and such other similar effects) taking place and developing over a significant duration of time reflect a cumulative effect of certain physical and/or geochemical anomalous behaviour, which has the ability to accumulate micro effects otherwise undetectable if measured at an instant. This phenomenon may be the primary advantage advocating the use of remote sensing for this application.

For the length of the Test Distance analysis, we have ordered images in Bundle format: Pan (0.61 м/pixel) + MS (2.44 м/pixel). This choice was motivated by the fact that the images, delivered in such format and high spatial resolution, have undistorted spectral characteristics. At the same time, they are very easy to process for obtaining useful for visual interpretation Pan-Sharpened images - artificially produced colored images in natural colors with a resolution of 61cm per pixel.

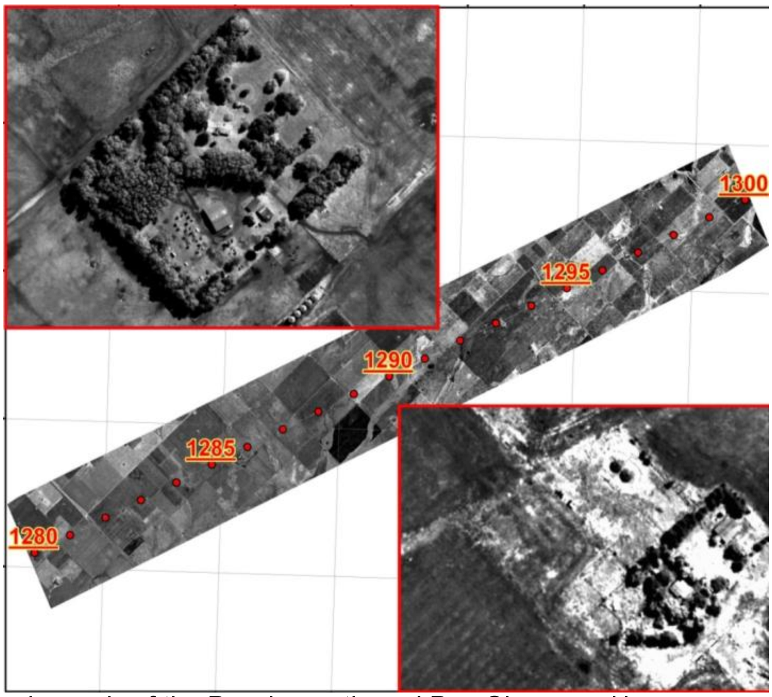

Figure 28: Combined mosaic of the Panchromatic and Pan-Sharpened images

The next Figure 29 shows an image in Multispectral mode with a spatial resolution of 2.0m per pixel. The dots depict the pipeline marks with a step of five kilometres.

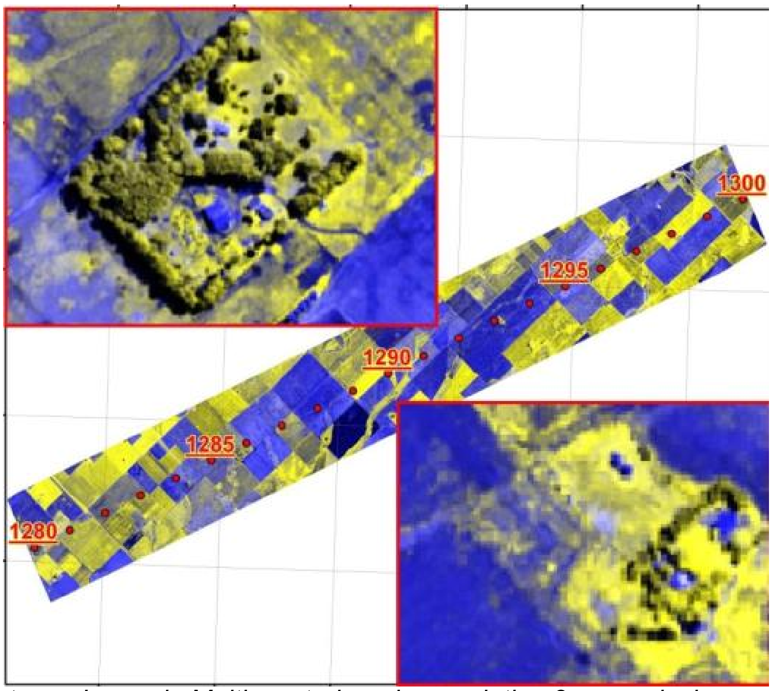

Figure 29: Test Distance Image in Multispectral mode, resolution 2m per pixel

Using the multi-spectral images above, the normalized vegetation index over the Test Distance was calculated: NDVI (Normalized Different Vegetation Index). NDVI is one of the most common and actively used indices for researches utilizing quantitative estimates of vegetation cover, such as vegetation anomalies as the indications of the potential pipeline damages or negative trend in its condition (Figure 30).

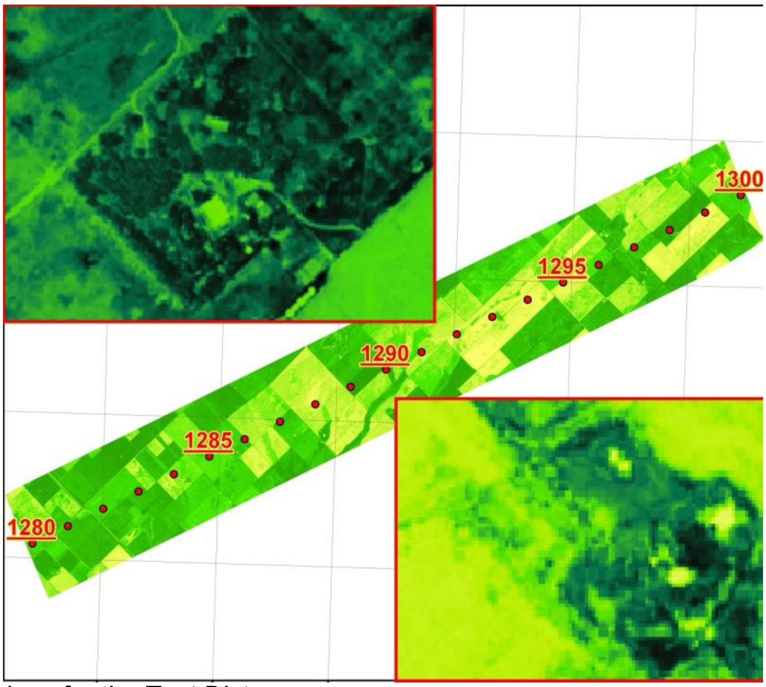

Figure 30: NDVI values for the Test Distance

Interpretation of Images

Anomalous zones at the pipeline were allocated and classified according to the following criteria:

1. Disruptions in the integrity of the vegetation and soil as a result of human intervention;
2. Abnormal changes in vegetation;
3. Elevated moisture or even the presence of water on the surface;
4. Changes in the landscape.

Examples of type 1 anomalies are pits, which are present along the pipeline as Figure 31 below shows in a snapshot, in the panchromatic mode. The pits locations are shown on the image as red rectangles. Pits appear as small dark patches of a right geometric shape with smooth edges. Their size is usually no more than 2x2 and 3x3 pixel. The magnified fragment in Figure 32 shows how the pits look like in close-up mode.

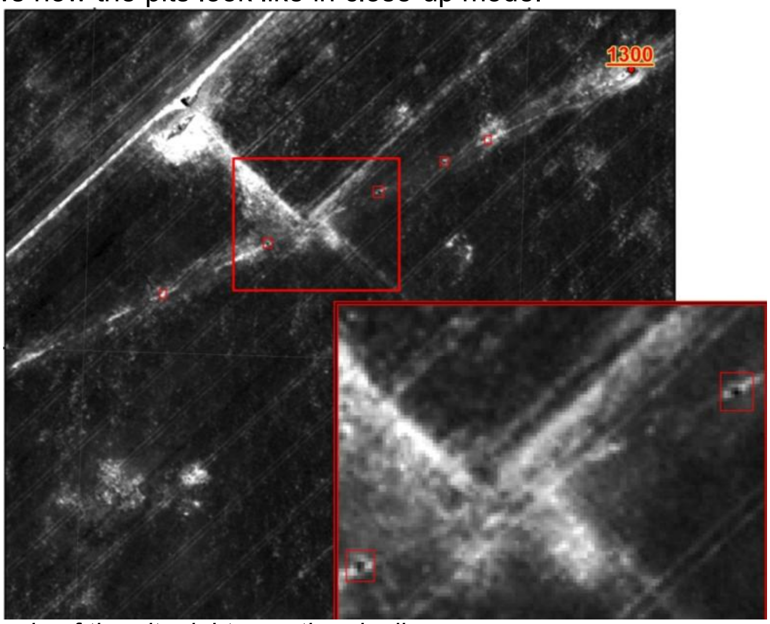

Figure 31: An example of the pits right over the pipeline

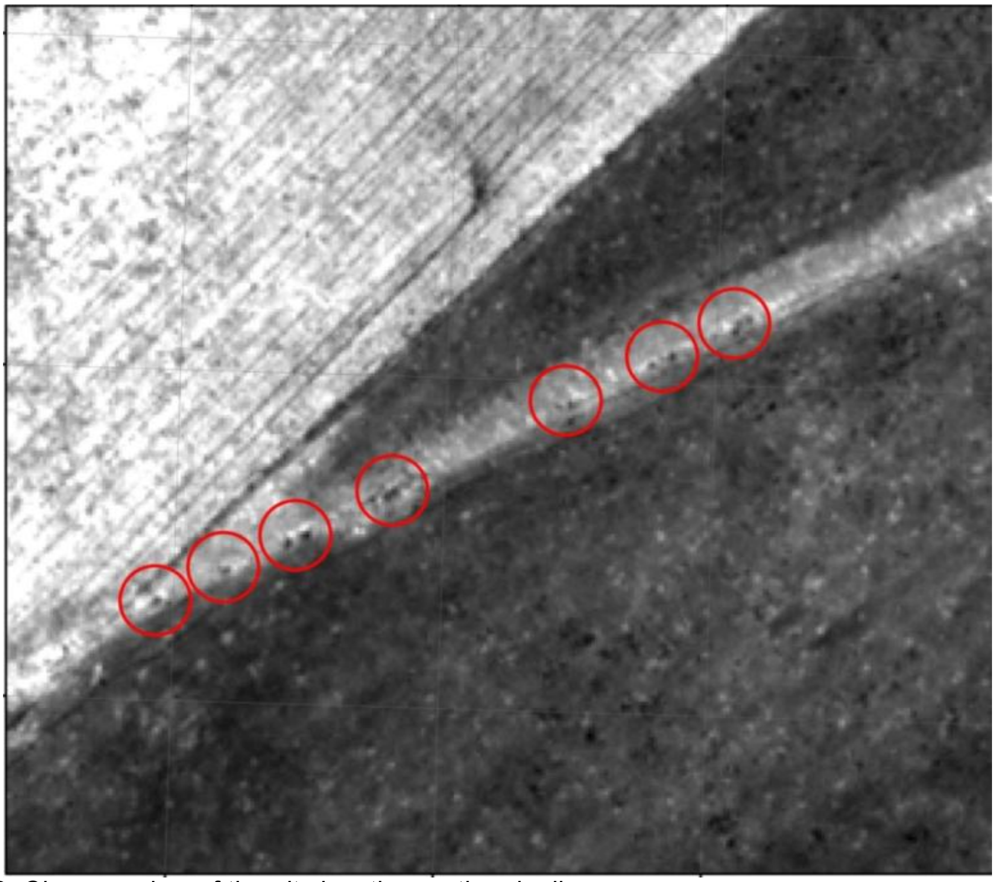

Figure 32: Close-up view of the pits location on the pipeline

Places where the water is accumulated and “stored” for a long time are also potentially dangerous. Water can accumulate in pits, trenches, deepened tracks. Water is characterized by dark tones in panchromatic image and its NDVI value is close to "-1".

Figure 33 below shows that the pipeline is crossed by the trodden track. At the time of the image acquisition in its deepest point there is a slack water (dark black spot).

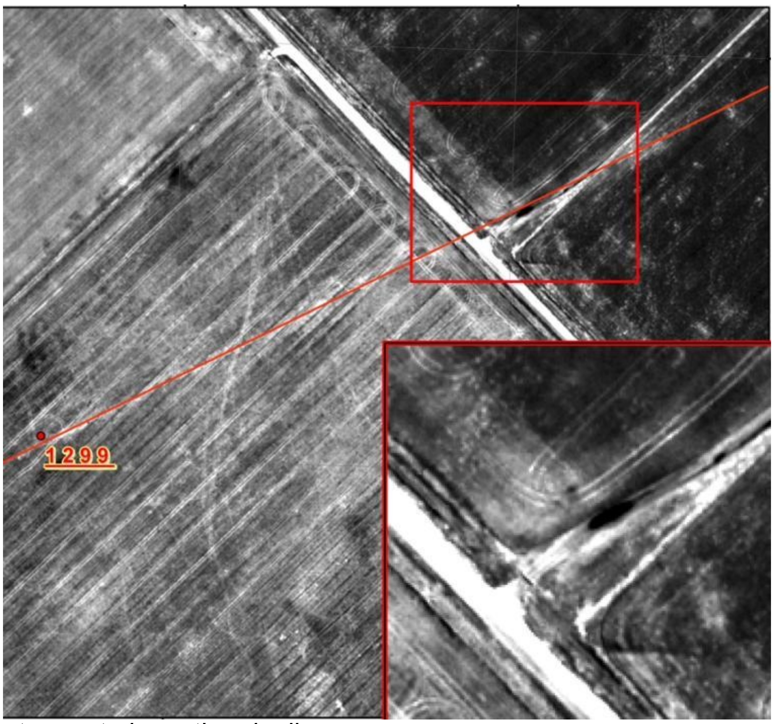

Figure 33: Slack water spot above the pipeline

In general, in the homogeneous areas, the vegetation anomalies are sometimes observed. Figure 34 below shows a circular structure (in the middle of the square) in the center of which there is an increase in vegetation mass, while along the radius of the circle - a sharp decrease in vegetation mass. The path of the pipeline is also hardly traceable within this spot. Perhaps this is a local subsidence in the relief, the so-called micro-depression.

Figure 34: Circular structure on the pipeline with a high vegetation mass in its center and sharp drop in vegetation at its edges

The search and identification of the anomalous zones was carried out within the entire Test Distance. Each zone was characterized by the weight from 1 to 4 (depending on the origin/genesis of the anomaly). The results of the analysis are shown as a graph in Figure 35 and on the image in Figure 36. All anomalous points with their description and coordinates are summarized in Figure 37: Anomalous points along 20km pipeline fragment, identified via optical images processing. The series of numbers representing the weights of the anomalies (factor F93) was also produced for the Test Distance (see table fragment in *Figure 37*.

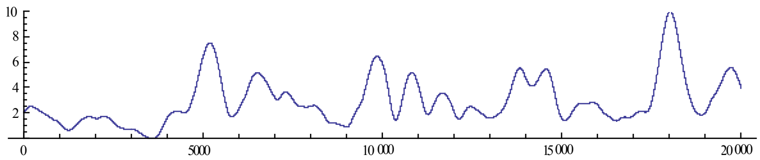

Figure 35: Graph of anomalies density along the 20km pipeline fragment

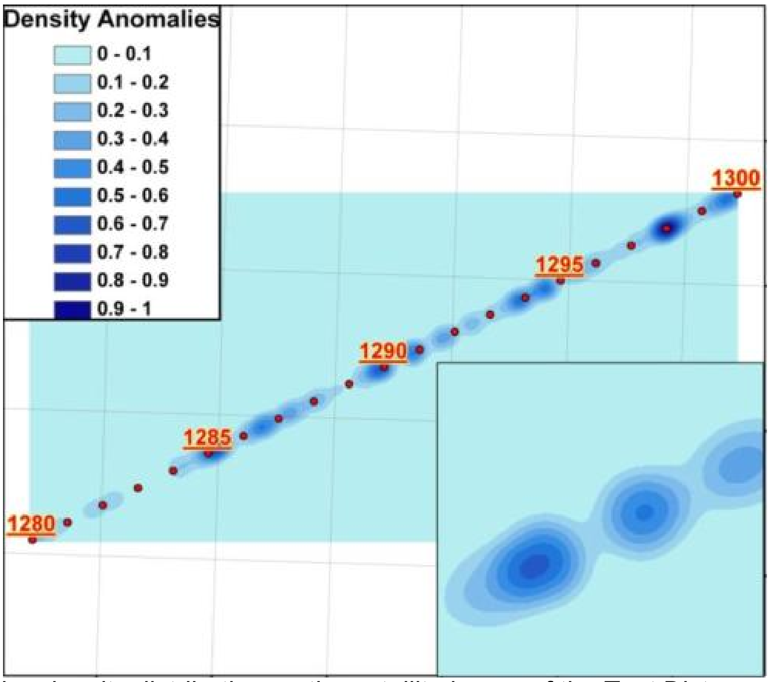

Figure 36: Anomalies density distribution on the satellite image of the Test Distance

Description	**Longitude**	**Latitude**
Vegetation change or Pit		
Pit with water		
Adjacent / crossing linear object		
Bridge / dam / crossing		
Relief change		
Bore pit		
Pit		
Vegetation change		
Bore pit		
Relief change		
Vegetation change		
Bore pit		
Pit		
Vegetation change		

Pit, Vegetation change		
Incident location		
Bore pit		
Oppressed vegetation		

Figure 37: Anomalous points along 20km pipeline fragment, identified via optical images processing

Anomalies, identified by TIS analysis, were recommended to the customer for priority inspection.

Radar interferometry - Identification of Surface Movements

The principle of the possibility of detecting dangerous geological processes development speed and their impact on the man-made objects is based on such tools as radar differential interferometry (DInSAR). This technology allows identifying displacement of the Earth's surface with millimetre precision on the basis of a comparison of two (or more) multi-temporal radar images of the same territory under study.

Causes of the displacement could be different. In the case of evaluation of their impact on the pipeline condition two categories of the displacement should be considered and the most dangerous: 1) "fast", i.e. those that occur in a relatively short time span, such as landslides, avalanches, earthquakes, volcanic eruptions, suffusion-karst and water erosion, etc; and 2) "slow", i.e., the formation of which is subject to internal (endogenous) processes – vertical movements of the Earth's crust, salt blocks diapirism, plate tectonics, etc.

First category, in case of a very rapid and intensive development can cause an incident, which is difficult to predict. The factors of the second category are much slower and their constant unidirectional operation, albeit unnoticeable to the eye, manifests itself in a constant accumulation of stresses in the pipeline. Sooner or later the accumulated stresses will exceed the threshold of the pipeline's hardness and the destruction of the pipeline at the weakest point (-s) will occur. Without knowing the tectonic processes development, which trigger movements of the Earth's surface, which in turn lead to the destruction of the pipeline, it is impossible to establish the true causes of incidents.

To detect movement of the Earth's surface within 20 km of the test pipeline fragment, we have selected radar images of the PALSAR sensor, installed on the spacecraft ALOS. Data registration parameters were as follows: wavelength - 23 cm (L-range), mode – FBD (Fine Dual Polarization Mode), Polarization Processing Level - 1.1, acquisition dates – 07.07.2010 and 10.07.2010.

The original ("raw", not confined to coordinate system) radar imagery data was obtained from the provider. The main and auxiliary images of the interferometry pair are then co-registered with each other and averaged in azimuth and range. The co-registration procedure involves combining of the two images with sub-pixel precision. Filtered differential interferogram needs to be unwrapped to remove phase breaks at the border 2π -interference cycles.

In the final stage, the unwrapped phase is re-combined with the synthetic phase of the relief and then is converted into a matrix of heights, above the ellipsoid WGS-84, after which it is geo-coded into the selected cartographic projection.

To obtain maps of the displacements we also used independent Digital Elevation Model (AsterDEM, v2.0). At the following a surface displacement map is shown with the depicted pipeline location.

The displacements of the Earth's surface within the area of the satellite image are mainly lying within the range from - 0.015m to + 0.015m, i.e. the changes in the absolute heights

within 3 months amounted to ±15 millimetres. Such seemingly minor values of the displacements must not, however, be discarded: the trend is more important than the absolute values. *Figure 38* clearly shows an area of uplifting and subsidence. If this feature of the territory is not random but a trend, one can calculate the size of the displacement for the coming years (subject to the displacement speed remaining constant). In our case the displacement speed was +/- 15 mm/3 months or ± 6 cm/yr. Having knowledge of surface movement speed (normal and tangential components relative to the pipeline) we may assess the degree of bending (curvature) of the pipes and localize the place of maximum curvature of the pipeline; therefore – the place of the maximum stress accumulation.
It should also be noted that areas with right geometric shapes should not be taken into account during interpretation, because the change in their height is likely due to the vegetation growth. Nevertheless, we can trace the boundary between the areas of relative subsidence and relative uplift of the territory (blue dotted line in Figure 38). Interestingly, the location of the pipeline with mark 1,290 (place, where the incident occurred) is right on this border. In the following Figure 39, point at mark 1,290 and surrounding area are significantly magnified.

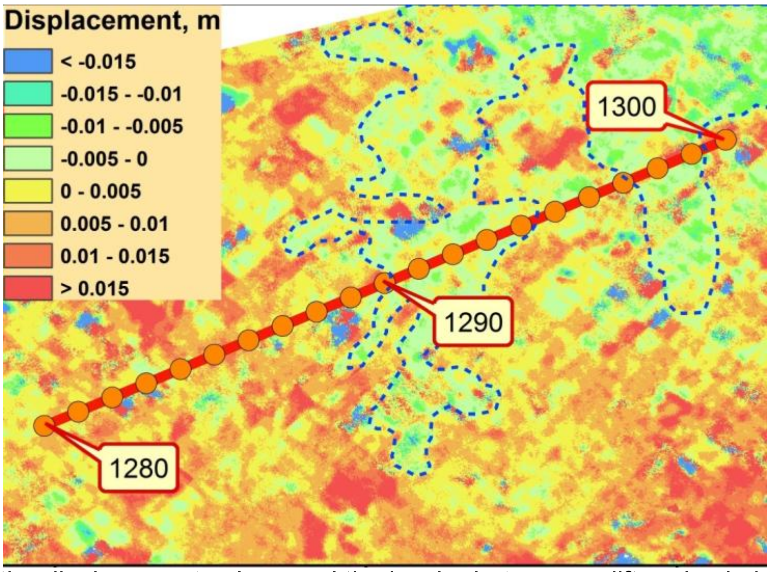

Figure 38: Map of the displacement values and the border between uplift and subsidence areas

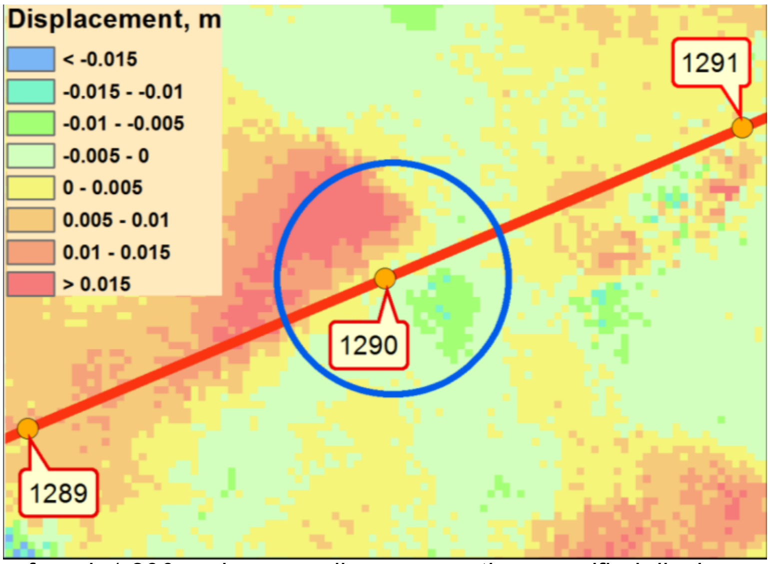

Figure 39: Position of mark 1,290 and surrounding area on the magnified displacement map

Similar situation (in terms of gradients) is also observed in Figure 40: the pipeline marks 1,297 and 1,299 in a same way as mark 1,290 are located right on the borders of the delineated gradient area.

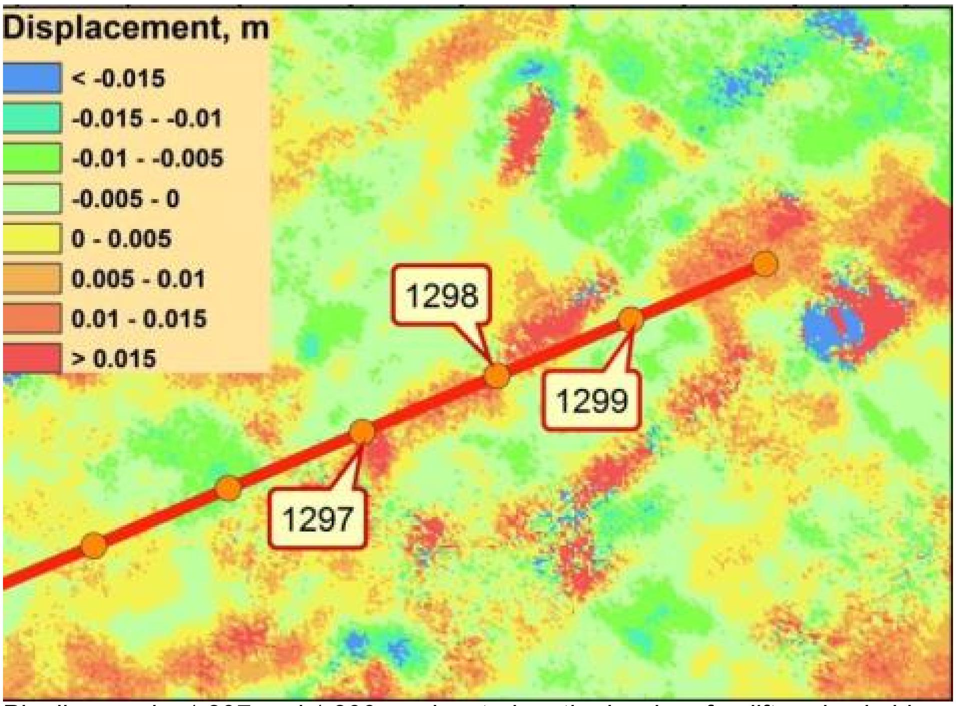

Figure 40: Pipeline marks 1,297 and 1,299 are located on the border of uplift and subsidence areas

Figure 41 below shows the displacement graph along the Test Distance.

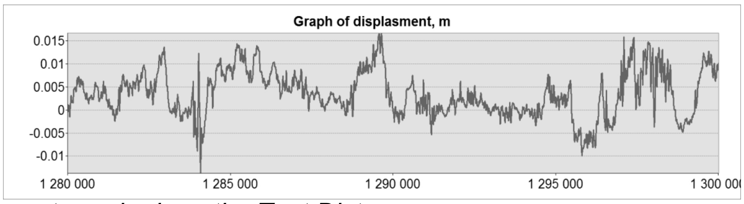

Figure 41: Displacement graph along the Test Distance

If the highest displacement gradients are actually related to the surface displacement and represent a risk of incidents, we can identify the points of the highest risk on the pipeline, as shown in Figure 42

.

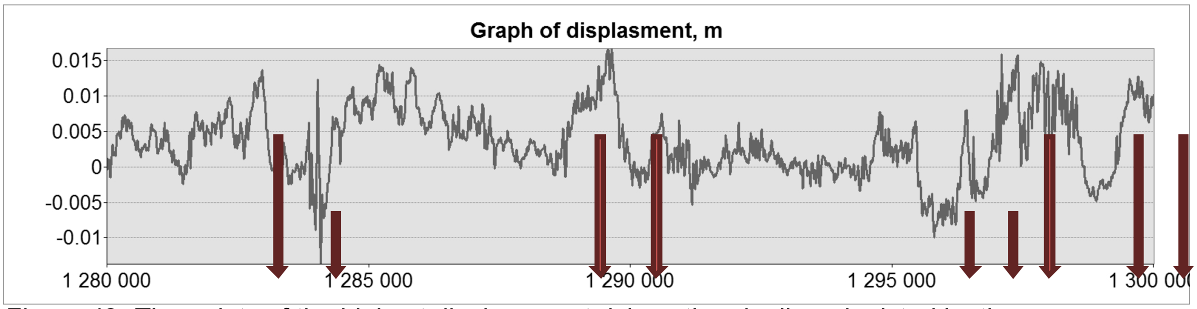

Figure 42: The points of the highest displacement risk on the pipeline, depicted by the arrows.

Analysis Summary and Interpretation

This project was intended to identify any and all negative factors and causes which may be materially responsible for the retardation of the underground gas pipelines. The task was to devise the ways to analyze and quantify such factors and causes using the remote sensing and cartographic data, as well as the analytical models and ideas. Realizing that there is a large number of negative factors, TIS was to systematize them into groups, discover their dependencies and correlations, and develop appropriate mathematical methodologies for their analysis.

TIS has carried out a substantial amount of analytical work which included:

1. Discovery of the Factors and Causes of SCC and CF;
2. Correlation on such Factors and their grouping;
3. Application of the various spectrometric, analytic, physical, and mathematical models which independently produced the uncorrelated datasets;
4. Mathematical processing and predictive modeling of the Factor values;
5. Incorporation of the Factor values into the customer risk assessment model;
6. Development of the methodologies for the risk assessment and Pipeline monitoring.

In summary: TIS applied a set of sophisticated methodologies which can significantly contribute to the cause of preventive maintenance and pipeline monitoring. TIS produced actionable reports, such as coordinates of high risk locations, which can save customers significant funds spent on internal inspection, excavations, and rupture recoveries.

The methods applied within the scope of this project targeted identification, measurement and interpretation of the different sets of natural negative causes of the pipeline integrity loss. Some of the factors, such as the lineament density/pattern in the Test Distance, inclination of the landscape, as well as others were analyzed using more than one method and the results show a strong correlation, although the vastly different approaches and datasets were used to evaluate the same natural causes.

The results produced via each respective method are provided within the appropriate sections of this report, however their integration proves that on the 20 km pipeline fragment, selected for analysis, several concrete areas were identified via several methods as the areas of elevated risk: at the pipeline marker 1,285 (with a reasonable deviation between the markers 1,284 and 1,287) and 1,295 (with a reasonable deviation between the markers 1,293.5 and 1,296.5), as shown on Figure 15, Figure 23, and Figure 24.

It is worth noting that the rupture location at the 1,290 marker was not representative from the standpoint of the regional risk factor analysis, although the lithodynamic and the lineament density factors indicated for it. Utilizing TIS' spectrometric models, however, the rupture point would have been identified four months prior to the accident. Customers may utilize the results and the methods in the following ways:

- Analyze individual negative factors and perform risk assessment;
- Correlate the individual Factor values with the known pipeline conditions;
- Develop repair schedules, strategies, and rules using the analysis information;
- Amend and/or correct the monitoring and preventive maintenance procedures, based on the results of this report;
- Save on maintenance via prioritizing work, reducing the Pipeline distances planned for internal inspection and other diagnostic activities;
- Evaluate the impact of the Pipeline on the environment;
- Where applicable, revise the design, construction, and operation procedures;
- Reduce the insurance and liability premiums due to the accident and injury rate reduction.

Conclusion

The study has been applied over the Test Distance of the pipeline, where SCC occurrences and one serious incident have previously been registered and the criterion developed matched with the existing pipeline conditions demonstrating the high predictive power of TIS's methods in determination of risk areas.

TIS demonstrated the methodology for determination of the natural negative factors using the remote sensing data and identification of the areas of corrosion and elevated external stress, thus predicting the locations on the pipeline where delayed failures are likely to occur due to a combination of external stress and/or other factors.

The implementation of such remote sensing methods reduces the risk of both the non-catastrophic and catastrophic failures, which often endanger human lives, affect the environment and result in significant financial consequences. Such an efficient remote monitoring tool would render substantial savings on standard field work, internal inspection, and other traditional monitoring and prevention activities. Accurate, timely and inexpensive high grading of areas of rupture risk can potentially help limit the pipeline monitoring to specific fragments, concentrating the human and financial resources in the areas of the highest risk and susceptibility to ruptures and other failures, improving the economic bottom line and the health of the pipeline. Over time, such an intelligent approach of the pipeline management and preventive maintenance is expected to significantly reduce the incident rate and increase the overall pipeline health, where routine and planned maintenance would prevail.

The authors of this paper would like to express their special thanks to TGS whose support and recommendations during the execution of this project and preparation of this paper were invaluable.