Maximising value from single run IMU inspection data

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Ground movement associated with landslides, subsidence, erosion or seismic events can damage or fail pipelines. This article, from ROSEN Group, explores the importance of identifying the presence and activity of geohazards on pipeline routes as an element of pipeline integrity management.

Terrain has a major influence on the likelihood and nature of geohazards, together with factors of geology, hydrogeology, climate and human activity. Robust investigation and assessment during the design phase should minimise exposure to geohazards during the operational life of the pipeline; however, this is not always carried out to the appropriate level, in some cases not at all.

Extreme events, climate change, anthropogenic factors or an unforeseen chain of events all can contribute to the development of new geohazards.

Pipeline operators are increasingly aware of the need to identify and address ground movement threats. In the US, there is increased regulatory scrutiny and the US Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA) has proposed to expand the safety requirements that apply to gas pipelines, particularly under Section 192.9.[1]

Under the regulations, threats to the pipeline must be identified, including external loads. This has had significant repercussions on the demands for bending strain assessments from inline inspection (ILI).

In addition, a forthcoming ISO standard on geohazard management[2] sets out requirements to identify, evaluate and manage geohazards. The responsibility of the plan to control hazards will lie with the operator and apply throughout the design phase and operational life.

The standard is also intended to apply to existing pipelines. Where the operator considers a management plan unnecessary, this must be supported by documentary evidence.

IMU INSPECTION

ILI using an inertial measurement unit (IMU) has been used for many years to identify external loading on pipelines.[3] These tools work by recording centreline angle and distance information along the pipeline route. This information provides a profile of curvature. Curvature associated with formed bends in the pipeline is readily identified, so that any remaining curvature represents bending developed during construction and installation or from external loading sources such as geohazards.

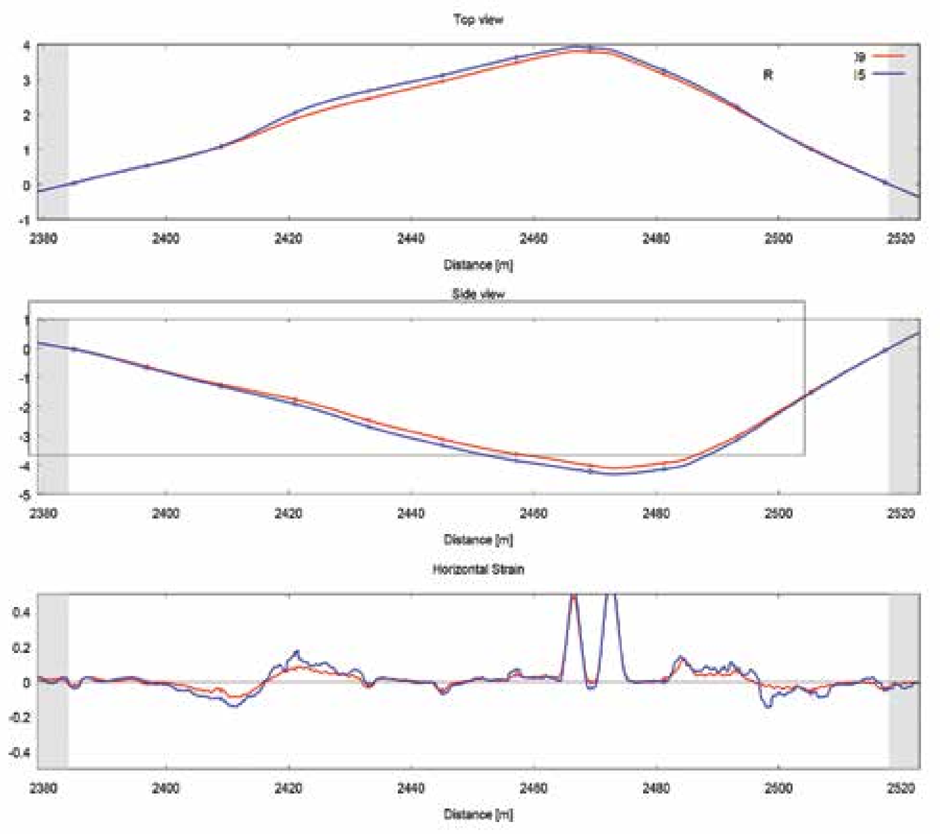

FIGURE 1: Location of pipe movement identified from repeat inspection.

This is extremely useful data, as it can reveal areas of high bending strain that arise from displacement of the pipeline due to ground movement. Displacements arise from a range of geohazard mechanisms or engineering activities. Pipe movement is confirmed when a repeat inspection is carried out and the two centreline profiles of the pipeline are compared while taking account of the positional measurement accuracy, as seen in Figure 1.

In many cases, a repeat inspection is not available and there is only a single curvature profile for the pipeline. This presents a difficulty in interpreting whether locations of high bending strain are due to external forces such as ground movement or are created during the construction and installation phase.

Understandably, many operators are unsure of the value of measuring the magnitude of bending strain in their pipeline if the origin and significance of the bending strain is unknown. Bending strains measured in a single IMU inspection can help identify the geohazard threats on a pipeline and the likelihood of ground movement can be estimated from the magnitude of bending strain and the classified terrain on the pipeline route.

SINGLE IMU INSPECTION

Where only one IMU inspection is available, it is still possible to identify the presence of ground movement loading.

A key starting point in the evaluation of IMU data is to identify the locations of high bending strain in the pipeline. This requires a threshold value to be set and the locations of bending strain that exceed this value to be listed.

An analyst will identify the length of the pipeline that contains elevated strains considered to be associated with the specific maximum strain event and this defines the bending strain area. An initial indication of the likely source of the loading can be made from the profile of bending strain and the pipeline out-of-straightness, seen in Figure 2.

This example shows a distinct horizontal out-of-straightness of about 300 mm accompanied by a localised increase in pipeline strains. The features suggest displacement loading on the pipeline; therefore, the site would be prioritised for more detailed evaluation.

LINK WITH TERRAIN

A methodology developed to link reported bending strain to the likelihood that it is caused by ground movement allows a measure of significance to be assigned to the reported bending strain, which assists in the prioritisation of sites for further evaluation.

The estimated likelihoods of ground movement are classified according to the nature of the terrain where the strain develops, as certain types of terrain are more prone to instability than others. An obvious example is hill slopes and landslides.

In general terms, high steep slopes exhibit increased levels of instability compared to low shallow slopes; this point is clearly demonstrated by Sweeney[4] for pipeline failure frequencies due to landslides. The method is based on IMU inspection data together with publicly available digital elevation data, where a basic terrain classification is derived from the IMU data. Currently, the classifications represent a simple and rough initial breakdown and comprises five basic terrain classes: mountains, upland hills, upland plain, lowland hills and lowland plain.

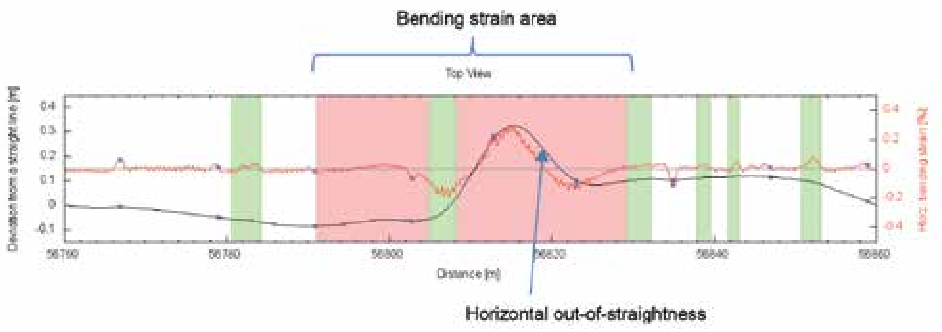

FIGURE 2: Location of pipeline movement identified from a single IMU inspection.

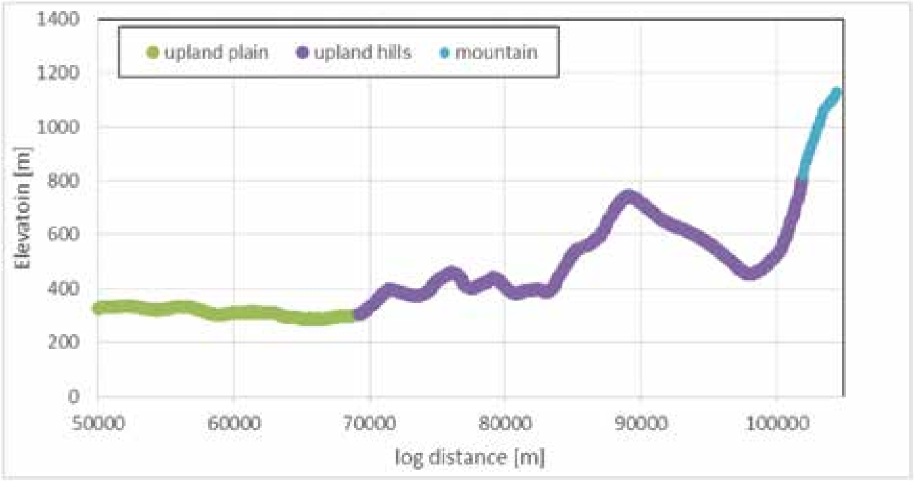

FIGURE 3: Classification of terrain along a pipeline route based on IMU and DEM data.

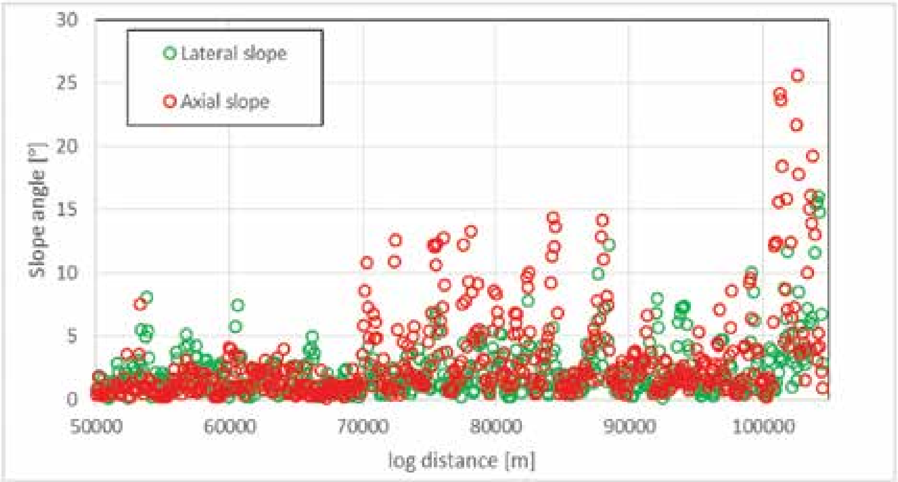

FIGURE 4: Comparison of lateral and axial slope angle.

There is no universal definition of these terrain types, although the United Nations Environment Program[5] does provide some guidance on the description of mountainous terrain, differentiating between more developed and cultivated lowland areas and upland areas that experience comparatively harsh winters with seasonal snow melt.

Two important planned developments are the inclusion of rainfall data, which is a key factor in many forms of ground instability, and the addition of river crossings as a separate terrain class, because these are active geohazard environments.

Terrain classification is based on elevation and slope gradient. If it is assumed that the pipeline is laid at a constant depth of cover, the gradient of the centreline trajectory is a good approximation of the ground in the same direction.

However, pipelines are also routed across the side slopes of hills, so the transverse gradient must also be taken into account, which is extracted from a publicly available Shuttle Radar Topography Mission (SRTM)[6] digital elevation model. The spatial resolution for lateral slopes is lower than for the axial data from the IMU; while this effect may result in an underprediction of the slope gradient by missing localised steeper variations, it provides a good first approximation.

Following the pipeline in the inspection direction, the classified terrain type transitions from upland plain to upland hills and then mountains. An example of classified terrain for an IMU run is shown in Figure 3, with corresponding measured axial and lateral direction slope angles shown in Figure 4.

There is strong correspondence between the terrain type and slope angle. In addition, there are a number of locations where the lateral angle is higher than the axial angle, indicating that the pipeline is routed across side slopes and possibly vulnerable to slope instability.

LOCATIONS OF PIPE MOVEMENT

There is a large database of pipe movement events recorded on pipelines using IMU tools. The locations of pipe movement can be related to the terrain, based on the above classification process. The proportion of detected pipe movement locations distributed across the five terrain classes recorded by a number of inspections within one geographic shows a clear trend that most events occur in mountains and upland hills.

The selected geographic area covers approximately 250,000 km² and contains a major mountain chain that experiences significant earthquake events. More than 2,000 km of IMU data has been evaluated and the breakdown of terrain classes is mountain, 31 per cent; lowland plain, 26 per cent; upland plain, 23 per cent; and upland hills, 19 per cent. For the selected region, at just 1 per cent, only lowland hills are not significantly represented.

ESTIMATED PROBABILITY OF PIPE MOVEMENT

When a new inspection is carried out, the bending strains are measured and reported and the terrain class is automatically assigned along the pipeline route based on the IMU data. The estimate of the likelihood that the recorded bending strain is associated with pipe movement is based on both the magnitude of bending strain and the nature of the terrain.

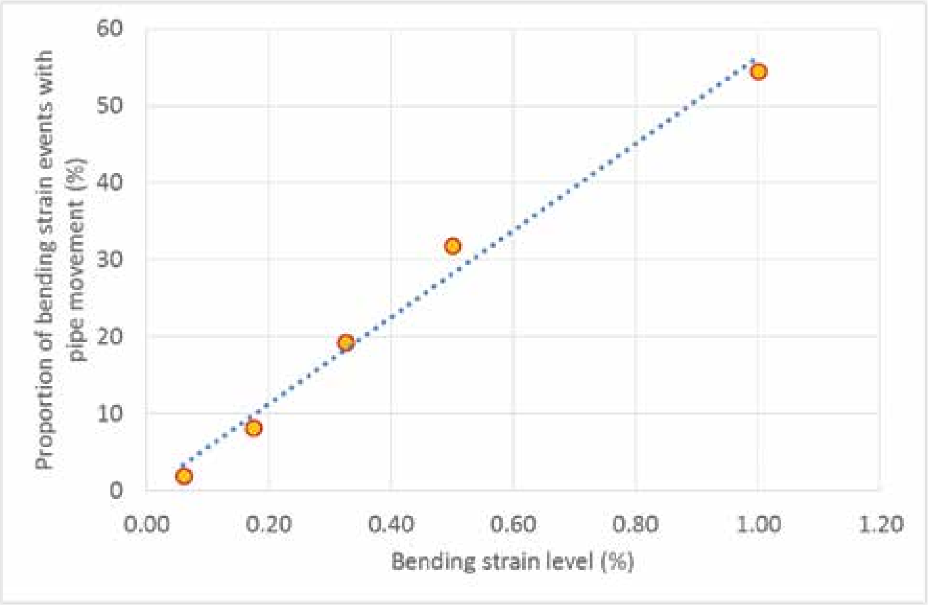

FIGURE 5: The relationship between bending strain and pipe movement for the region.

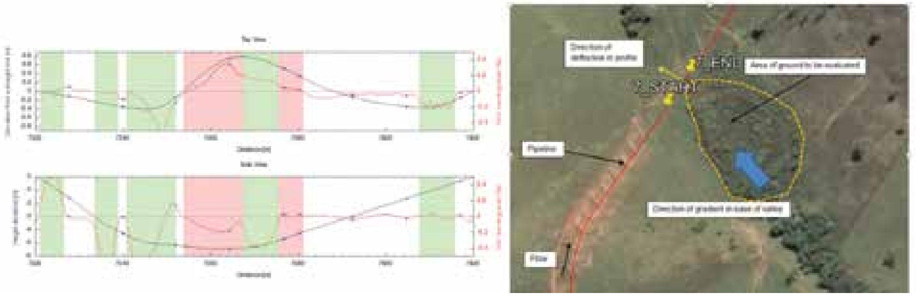

FIGURE 6: Interpretation of the loading source within an integrity assessment of bending strain.

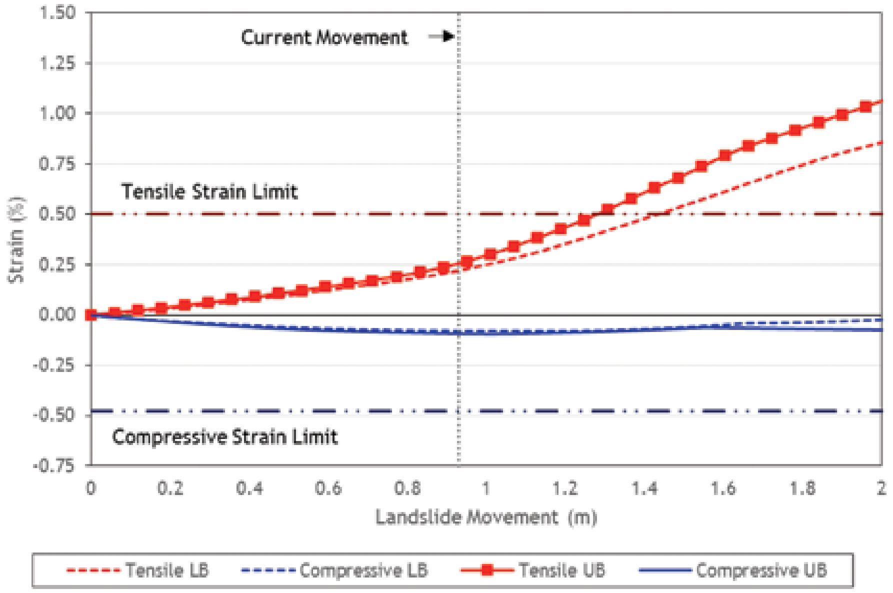

FIGURE 7: Interpretation of loading source within a Level 2 bending strain assessment; LB = lower bound soil, UB = upper bound soil.

The influence of the magnitude of bending strain for the geographic area used in this study is shown in Figure 5; similar relationships are constructed for the other terrain classes relevant to the geographic area of interest. Unique relationships are established from historical data for the other distinct geographic areas across the world.

INTEGRITY ASSESSMENT AND LOCATION PRIORITISATION

The detection and listing of areas of bending strain and pipe movement is essentially the first level of pipeline strain assessment. This can include an initial prioritisation of strains due to the likelihood of pipe movement based on the strain magnitude and assigned terrain class as described.

A detailed evaluation determining whether the measured magnitude of bending strain is acceptable and what is causing the reported strain is carried out in the second level of pipe strain assessment. It is especially important to identify whether the source of strain is an active ground movement mechanism.

Industry recognised standards or approaches have been used to define the tensile and compressive bending strain limits and methods appropriate to the pipeline (Canadian Standard CSA Z662[7] and European Pipeline Research Group guidelines)[8] are selected considering both the tensile and compressive strain limits. While this assessment is based on bending strain only and does not include the influence of axial force, it provides an indication of the acceptability of the strain magnitude.

The detailed assessment also takes account of the presence of metal loss and whether any geometric features have been reported in the bending strain area. Locations found unacceptable are investigated to determine the probable cause of the high bending strain.

The assessment of the cause of the high strains involves review of vertical and horizontal bending strain profiles; vertical and horizontal pipeline profiles; ground topography; ground surface features; and available soil information.

Figure 6 shows a deflection of 1.2 m in the pipeline horizontal out-of-straightness profile, where the direction of deflection is downslope and inspection of imagery shows an area of potentially unstable ground.

Consequently, a ground movement source is considered credible, and this site would be scheduled for field verification by geohazard expertise.

The outcome of an integrity assessment of bending strain is the prioritisation of sites based on the magnitude of strain, presence of metal loss or geometric features and ground movement or other pipeline defects possibly active at the location. The prioritisation level defines what further action is necessary to investigate or remediate the location.

SITE-SPECIFIC GROUND MOVEMENT ASSESSMENT

Ultimately, if ground movement is identified to be present, the effect on the pipeline at that location must be established in order to make decisions on the future protection strategy.

The evaluation of active ground movement effects on pipelines requires structural analysis using finite element methods to fully define the current integrity of the pipeline from the ground movement event, including operational loads. It also involves evaluating axial forces from ground loading, which can be significant and are not recorded by the IMU tool.

IMU data is used in structural analysis to improve the accuracy and confidence in the modelling by providing an accurate centreline geometry for constructing a model by including all curvature in the pipeline. The recorded changes in pipe trajectory or bending strains by the IMU tool can also be simulated by the modelling, which is particularly helpful in defining a representative ground movement profile. When the predicted changes adequately match the measured changes, the model is considered robust.

A key output of the modelling establishes how pipeline integrity changes with the magnitude of the ground movement, as seen in Figure 7, where the strain associated with the current movement level lies within the compressive and tensile strain acceptance limits.

In this example, a further 300 mm of movement will generate tensile strains above the limit. This provides a framework for monitoring and planning the intervention strategy to avoid damage or failure.

SUMMARY

Evaluating the bending strains in pipelines from IMU inspection tools is an important and valuable method to detect, assess and monitor the presence of geohazards that affect pipelines. This is expected to form a key part of the geohazard management strategy as defined by the upcoming ISO standard.

The early identification of geohazards on pipeline routes forms an important and cost-effective element of pipeline integrity management. A staged approach to the assessment of bending strain is possible and results in a progressively more detailed evaluation of the pipeline condition from geohazard loads.

The first step is the detection and listing of the bending strains in the pipeline. This article describes terrain classification and the link between measured bending strains and pipe movement. This provides a measure of significance for the reported bending strain so that decisions can be taken on whether more detailed evaluation is necessary. The two further levels of bending strain assessment examine the acceptability and cause of the bending strain and a detailed site-specific evaluation of integrity where active ground movement has been identified.

Site-specific analysis will typically involve structural assessment using finite element methods; however, this is integrated with bending strain data to generate and validate the modelling and maximise confidence in the predicted behaviour. The outcome is a decision framework for maintaining the pipeline in a safe condition.

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