Evaluation of Stress-Relief Excavation for Pipeline Affected by Landslide – Case Study

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Abstract

Stress-relief excavation is a widely used mitigation method for pipelines affected by landslides. This approach involves removing soil above and around the pipeline in the impacted area to enable pipeline rebound and release a portion of accumulated elastic stresses. This paper examines a case study in the United States where stress-relief excavation was implemented as the mitigation measure. Data collected include pipe rebound measurements using survey laths, strain changes monitored during and after excavations using strain gauges, and comparisons of pipeline rebound and strain changes before and after excavations. These findings provide valuable insights into the effectiveness of stress-relief excavation, enhancing our understanding of its impact on pipeline integrity.

Introduction

Pipelines cross diverse regions with varying geologies, geometries, and subsurface conditions and are susceptible to geohazards such as landslides. Ground movement from a landslide can induce strains on pipelines that may not have been accounted for during their design, particularly in older or vintage pipelines. If the strain demand exceeds the pipeline's ultimate strain capacity, failure becomes inevitable. Therefore, maintaining a strain capacity greater than the strain demand is essential for ensuring pipeline integrity and safe operation.

Various mitigation measures can be employed to either increase the strain capacity of pipelines or reduce the strain demand they experience. The strain capacity of a pipeline can be improved through the replacement of vintage pipe with modern pipe, adherence to well-designed welding procedures, or the reinforcement of girth welds. Conversely, strain demand can be reduced by stabilizing landslides, rerouting pipelines, or performing stress-relief excavation. Stress-relief excavation is one effective method for reducing strain demand on pipelines. This approach involves controlled excavation of the soil surrounding the pipeline in landslide-affected areas. By removing external earth pressure, the pipeline is allowed to rebound, thereby releasing a portion of the elastic stresses accumulated due to ground movement. Research (e.g., Ahmadipur et al., 2022) indicates that stress-relief excavation can relieve between 30% and 60% of the elastic strain in steel pipelines. It is usually recommended to monitor pipeline rebound during stress-relief excavation. Survey laths can be used to measure pipeline movement and changes in curvature, while strain gauges installed beforehand can track strain variations resulting from the excavation. In cases where Inertial Measurement Unit (IMU) bending strain data is available both before and after excavation, it can provide valuable insights into the performance and effectiveness of the stress-relief process.

Since stress-relief excavation exposes the pipeline, it provides an opportunity to combine this technique with other mitigation measures. These may include reinforcing girth welds, installing enhanced drainage systems, placing non-cohesive, deformable backfill around the pipeline, and installing strain gauges for ongoing monitoring. Additionally, construction equipment can be used during excavation to improve site conditions, such as enhancing surface water management and runoff control, as well as reducing water infiltration—measures that can potentially improve landslide

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stability.

Despite its benefits, stress-relief excavation is generally considered a short-term mitigation solution because it does not address the root cause of ground movements. Landslides often continue to move over time; therefore, it is recommended to monitor ground movements and pipeline strain changes following the completion of stress-relief excavation. If necessary, stress-relief excavation should be repeated periodically, based on the data collected from monitoring.

Stress-relief excavations are relatively simple and potentially cost-effective, making them a popular mitigation measure in the pipeline industry. However, despite the straightforward concept, designing, planning, and implementing stress-relief excavations require careful consideration of numerous factors. These include landslide characteristics in relation to the pipeline, geotechnical stability, and the condition of the pipeline itself. These aspects have been extensively discussed by various authors (e.g., Ahmadipur et al., 2022, and Mckenzie-Johnson et al., 2020).

Despite the widespread application of stress-relief mitigation in the USA, there is limited quantitative information available to the pipeline industry regarding its performance. This paper addresses this gap by summarizing and evaluating a stress-relief mitigation project. The evaluation is based on several parameters, including site conditions, pipeline strain conditions, instrumentation monitoring data collected before, during, and after the excavations.

Site Background

The site includes three gas pipelines, identified as northern, southern and middle pipeline in Figure 1. In 2020, an In-Line Inspection (ILI) conducted by the pipeline operator on the southern pipeline identified a horizontal strain of approximately 0.46% and a maximum horizontal out-of-straightness of about 10 feet based on the bending strain plot shown in Figure 2. ILI was not conducted on the northern and middle pipelines, however, the strain on these pipelines were assumed to be relatively low. Following the ILI, a visual site assessment was conducted by the operator. During the site assessment, two distinct landslides were identified: a smaller landslide, delineated in magenta, and a larger landslide, delineated in blue, as shown in Figure 1. The horizontal strain observed on the southern gas line indicated that the smaller landslide was likely shallow and actively moving southward, hereafter referred to as active landslide, posing a higher threat to the southern pipeline.

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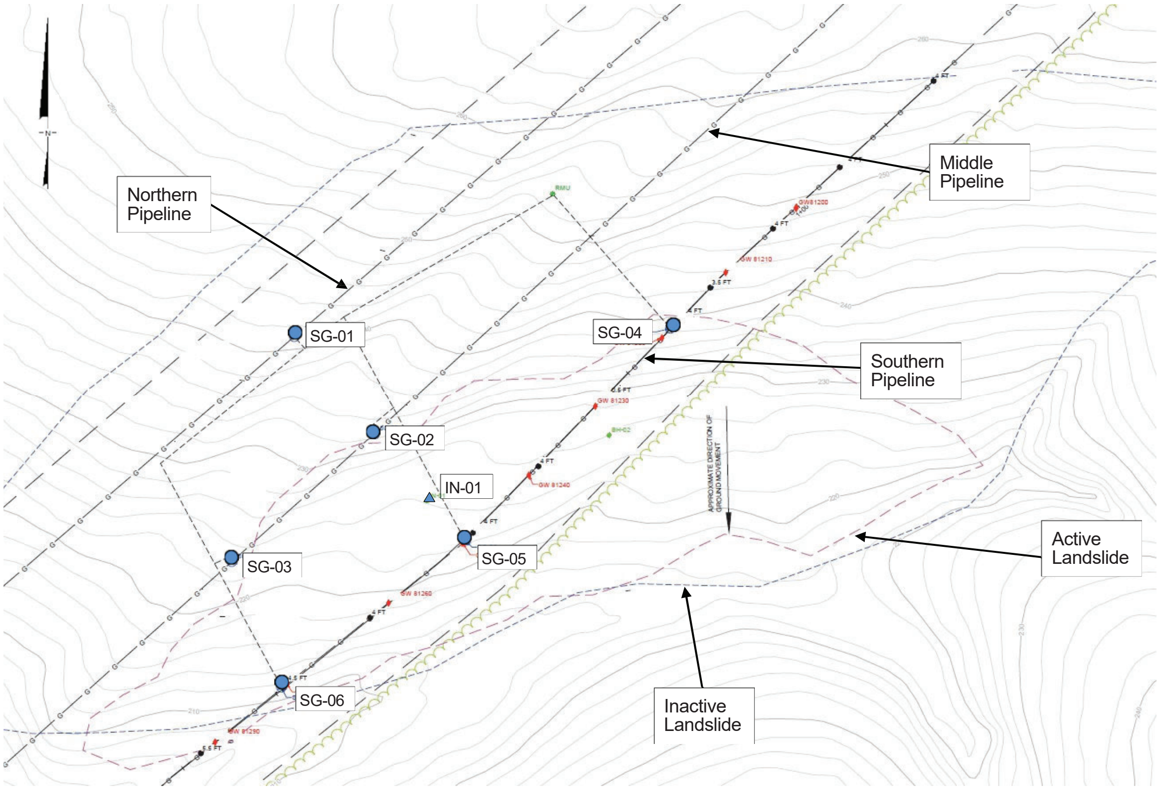

Figure 1: Landslide Boundaries, Pipeline Locations and Instruments Installed Before Stress-Relief Excavation

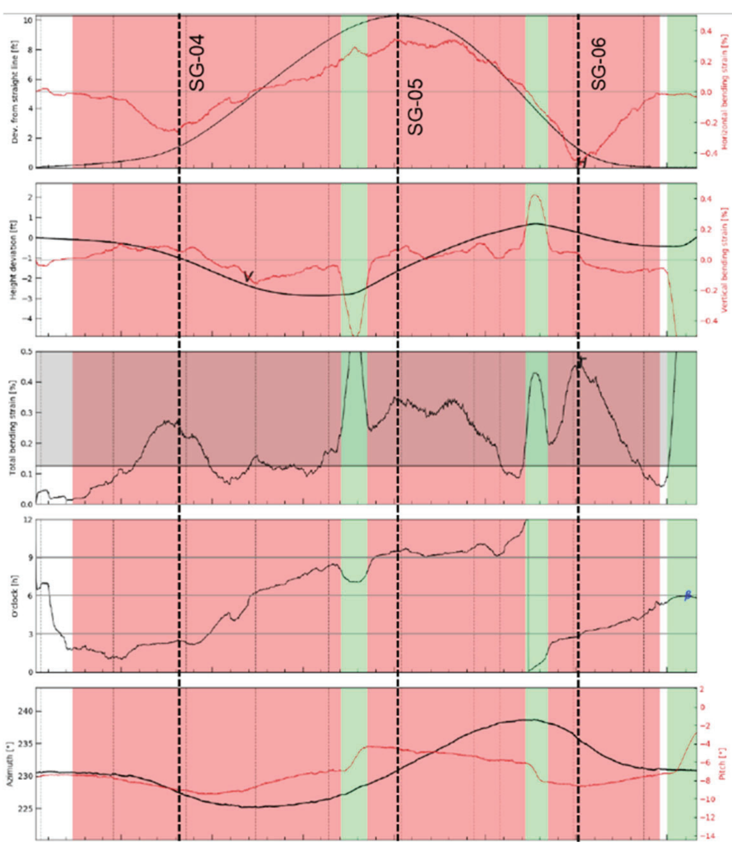

Figure 2: 2020 IMU Data (Before Stress-Relief Excavation)

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Instrumentation Measurements Before Stress-Relief Excavation

In 2022, strain gauge sets were installed on the pipelines to monitor strain changes caused by landslide activity. Three strain gauge sets (SG-04, SG-05, and SG-06) were installed on the southern pipeline, two sets (SG-02 and SG-03) on the middle pipeline, and one set (SG-01) on the northern pipeline (Figure 1). Each set consisted of three individual strain gauges positioned around the perimeter of the pipeline at the 3 o'clock, 9 o'clock, and 12 o'clock orientations. The 3 o'clock gauges were oriented upslope, while the 9 o'clock gauges faced downslope. The locations of the strain gauges on the southern pipeline were selected based on the strain data from the IMU bending strain plot Figure 2. SG-04 and SG-06 were installed at locations on the pipeline exhibiting negative strain, indicating a right turn toward the northwest (movement upslope). At these locations, the 3 o'clock position was under tension, and the 9 o'clock position was under compression. SG-05 was installed at a location with positive strain, indicating a left turn toward the southeast (movement downslope), where the 3 o'clock position was under compression, and the 9 o'clock position was under tension.

The strain gauge SG-04 was installed near the headscarp of the active landslide where tensile horizontal bending strain of approximately -2,500 microstrains was measured. Similarly, strain gauge SG-05 was installed near the middle of the active landslide where maximum compressive horizontal bending strain of approximately +3,500 microstrains was measured. Additionally, strain gauge SG-06 was installed near the toe of the active landslide where maximum tensile horizontal bending strain of approximately -5,000 microstrains was measured. Vertical strain at all three locations on the southern pipeline was relatively low (less than 250 microstrains) and showed signs of overbend in the downward direction. Since ILI was not conducted on the middle and northern lines; therefore, the location of maximum horizontal bending strain on these lines was not identified for strain gauge installation. On the middle pipeline, strain gauges (SG-02 and SG-03) were installed near the headscarp of the active landslide delineated boundary to monitor strain accumulation caused by downslope movement of the landslide. The strain gauge (SG-01) on the northern pipeline was installed at a location where the movement of the active landslide was expected to have a direct effect.

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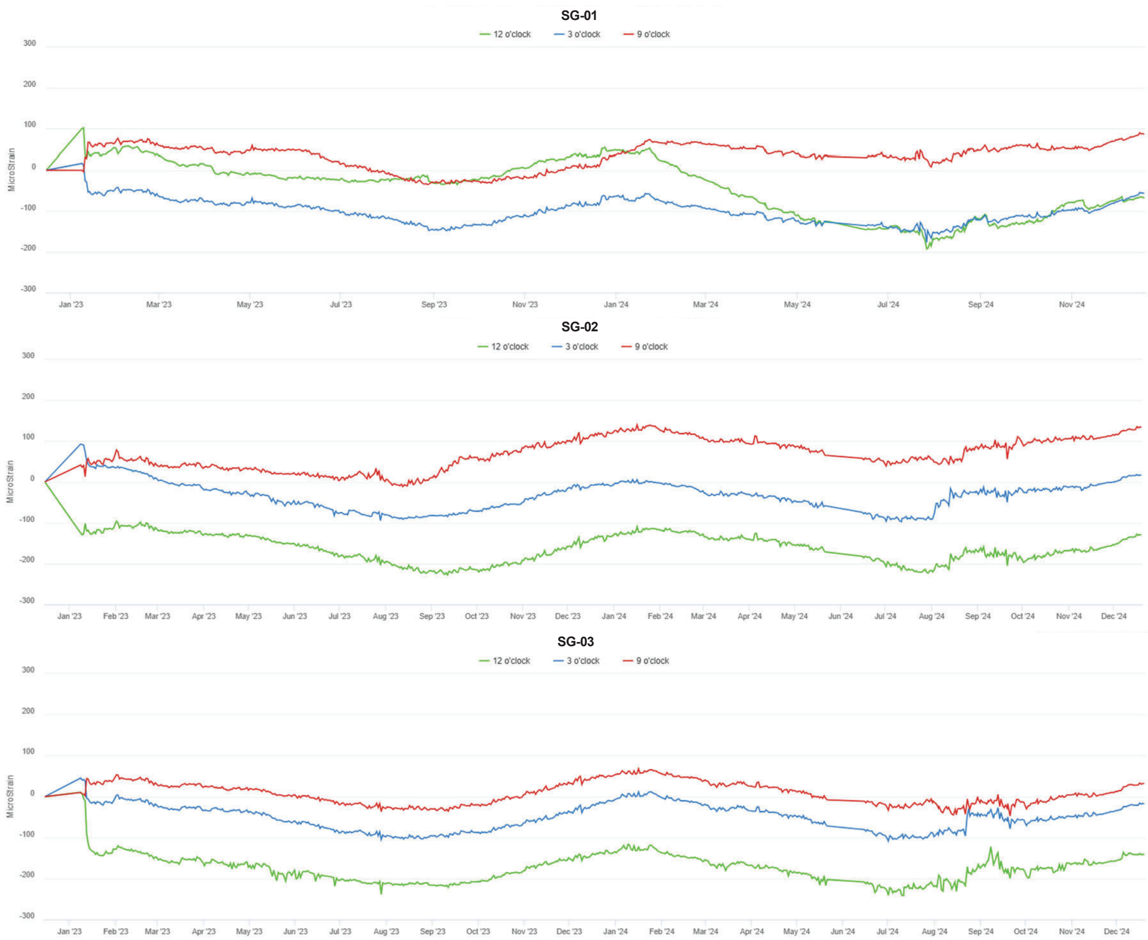

Figure 3: Strain Gauge Measurements on Southern Line Before Stress-Relief Excavation

Stress Relief Excavation

Due to the relatively high pre-existing bending strain on the pipeline, the operator opted to perform a stress-relief excavation on the southern pipeline, incorporating enhanced drainage as an additional mitigation measure for this section of the pipeline (refer to Figure 4). The excavation covered the pipeline segment within the landslide boundaries, extending an additional 80 feet upslope (to the northern side) beyond the left lateral flank of the active landslide. On the downslope (southern side), the excavation reached the toe of the landslide boundary. The total length of the stress-relief excavation was approximately 300 feet.

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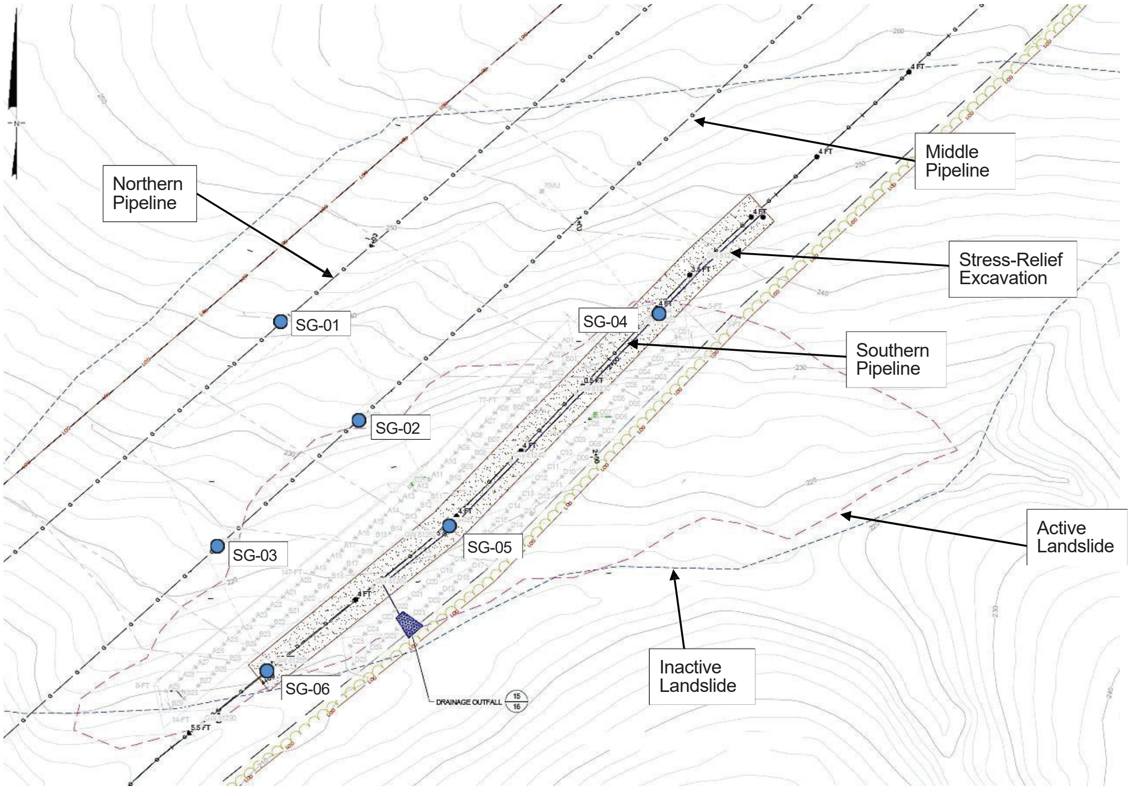

Figure 4: Landslide Boundaries, Extents of Stress-Relief Excavation and Subsurface Drainage Improvements

Pipeline rebound was measured as the pipe was being exposed and then twice daily during excavation using survey laths installed at 10-foot intervals along the exposed sections of the pipeline. However, this method has limitations, as the pipeline begins to deform as soon as the surrounding soil is removed. To mitigate this issue, survey laths were installed immediately after each 10-foot section of the pipeline was exposed. The installation procedure for survey laths, used to monitor rebound, is detailed in previous studies (Ahmadipur et al., 2022; Mckenzie-Johnson et al., 2020). Figure 5 illustrates the positioning of the survey laths and the displacement of the pipeline on the upslope direction relative to the survey lath on the downslope caused by pipeline upslope rebound. Similarly, displacements of the pipeline downslope were measured using the upslope laths.

To enhance safety during the stress-relief excavation, the operating pressure of the southern pipeline, where the excavation was conducted, was reduced. This reduction in pressure was implemented as a precautionary measure to minimize the risk of potential damage or failure of the pipeline while the surrounding soil was being removed. Additionally, hourly measurements were collected from strain gauges (SG-04, SG-05 and SG-06) installed on the southern pipeline to assess the stress change during the excavation.

The excavation was started at the middle of the stress-relief excavation area moving upslope during the first phase of excavation followed by downslope excavation from the middle towards the toe of the landslide during the second phase of excavation. This approach was adopted to minimize the duration of open excavation towards the toe during the stress-relief. To monitor this risk, hourly

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measurements from strain gauges installed on these pipelines were taken to detect any changes in strain that could indicate increased stress or deformation.

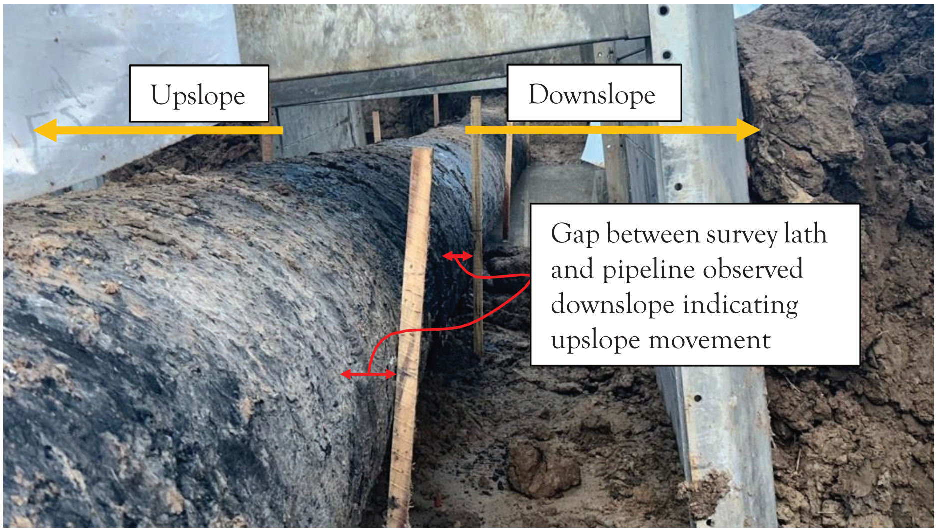

Figure 5: Pipe Deflection Measurements Using Survey Laths During Stress-Relief Excavation

Stress Relief Excavation Monitoring

Survey Lath Measurements

Figure 6 and Figure 7 present the horizontal and vertical pipeline rebounds measurements, respectively, collected using the survey laths. In Figure 6, positive rebound values indicate pipeline movement in the direction opposite to the landslide (i.e., toward the upslope) and negative rebound values indicate pipeline movement in the direction of the landslide (i.e., toward the downslope). Similarly, in Figure 7, positive rebound values indicate vertical movement of the pipeline upwards, and negative rebound values indicate vertical movement downwards. Since the soil support beneath the pipeline was not removed during the stress-relief excavation, negative vertical rebound values were not anticipated. The horizontal and vertical rebound data are depicted by dashed blue and brown lines, respectively, in Figure 6 and Figure 7.

In Figure 6 and Figure 7 , IMU bending strain data, shown by the solid magenta line, are included for comparison. The negative IMU bending strain values indicate pipeline movement opposite to the landslide (i.e., toward the upslope) and positive IMU bending strain values indicate pipeline movement in the direction of the landslide (i.e., toward the downslope). These IMU measurements were used to compare the horizontal and vertical rebound trends after excavation with its condition prior to construction. In Figure 6, the pipeline deviation from the straight line, depicted by the solid green line, represents the pipeline's deviation (in feet) from its original, straight alignment, measured since construction and prior to the stress-relief excavation. In Figure 6, the pipeline height deviation from the straight line, depicted by the solid green line, represents the pipeline's deviation (in feet) from its original alignment, measured since construction and prior to the stress-relief excavation.

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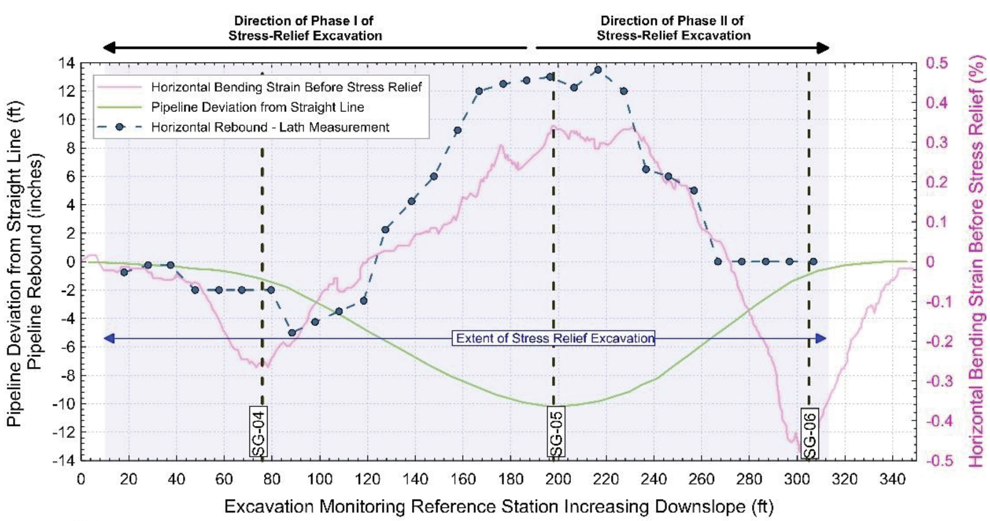
During the stress-relief excavation at the northern end of the pipeline, a maximum negative horizontal rebound (downslope movement) of approximately 5 inches was observed (Figure 6). Near the middle of the excavation, a maximum positive horizontal rebound (upslope movement) of approximately 14 inches was recorded (Figure 6). The maximum negative horizontal rebound (downslope movement) occurred in the upslope zone of the excavation around station 90 ft, close to the location of maximum negative horizontal bending strain (upslope movement) observed prior to stress-relief excavation. Similarly, the maximum positive horizontal rebound (14 inches) occurred in the middle zone of the excavation near station 200 ft, close to the location of maximum positive horizontal bending strain (downslope movement) observed prior to stress-relief excavation. These trends align with the expected pipeline behaviour during stress-relief excavation where the pipe was anticipated to rebound in the opposite direction of the pre-existing strain, thereby relieving the horizontal strain caused by landslide movement.

Survey laths in the downslope area near the landslide toe, beyond station 260 ft, were installed during the final stages of the excavation. As a result, horizontal rebound measurements were not recorded at these locations.



Notes:

- Positive pipeline rebound measurements indicate upslope movement of the pipe.
- Positive pipeline deviation from straight line indicate downslope movement of the pipeline.
- Stationing starts from upslope increasing towards downslope direction.

Figure 6: Horizontal Rebound Measurements After Stress-Relief Excavation

During the stress-relief excavation, a maximum positive vertical rebound (upward movement) of approximately 5 inches was observed around station 130 ft close to the location of maximum negative vertical bending strain (downward movement) observed prior to stress-relief excavation (Figure 6). Positive vertical rebound (upward movement) was observed between station 80 ft and 260 ft where the negative vertical bending strain (downslope movement) was observed prior to stress-relief excavation. Since the soil support beneath the pipeline was not removed during the stress-relief excavation, negative vertical rebound (downward movement) was not observed between station 260 ft and 300 ft where small negative vertical bending strain (downslope movement) was observed prior to stress-relief excavation. These trends align with the expected pipeline behaviour during stress-relief excavation where the pipe was anticipated to rebound in the opposite direction of the pre-existing strain, thereby relieving the vertical strain caused by landslide movement.

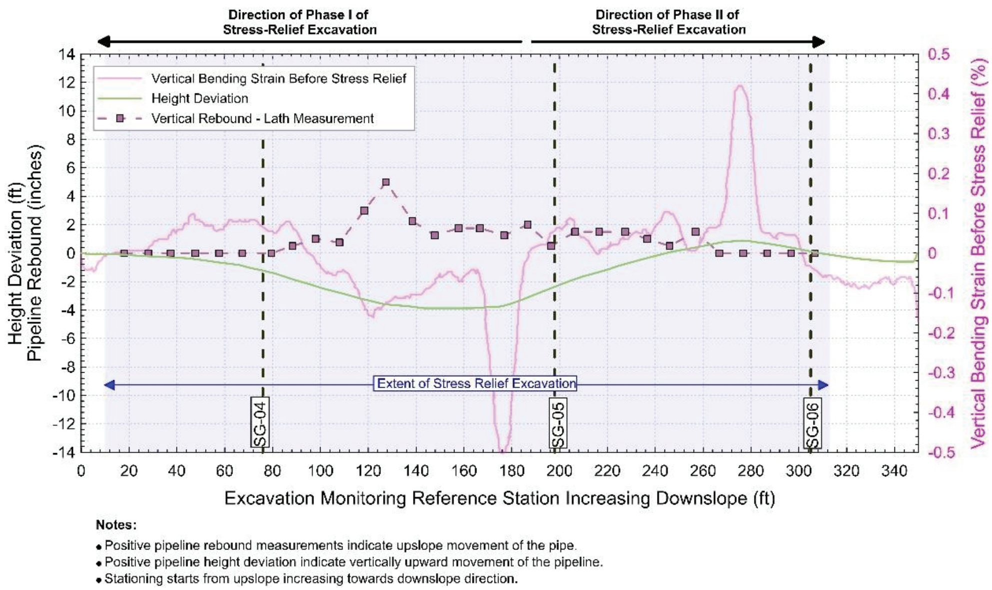


Figure 7: Vertical Rebound Measurements After Stress-Relief Excavation

Strain Gauge Measurements

During Phase I of the stress-relief excavation, the excavation started approximately 10 ft upslope of SG-05 at station 190 ft, progressing upslope towards SG-04. Excavation of approximately 50 ft was carried out upslope of SG-05, covering the area between stations 190 ft and 140 ft. However, the excavation was transitioned to excavate and expose the pipeline at SG-05 between station 190 ft and 210 ft, and the excavation continued further upslope from station 140 ft to 10 ft. During Phase II, the stress-relief excavation shifted downslope, starting at station 210 ft and progressing towards station 310 ft (Figure 6).

The strain gauge SG-05 measured a gradual increase in compression at the 3 o'clock position and tension at the 9 o'clock position, indicating movement downslope during excavation between station 190 ft and 140 ft upslope of the strain gauge (Figure 8). According to the IMU bending strain measurements at SG-05 location, compression was observed at the 3 o'clock position and tension at the 9 o'clock position, i.e. pipeline moved downslope due to landslide activity (Figure 6). However, the strain changes recorded during stress-relief excavation did not align with the expected behaviour, where the pipeline would rebound upslope at SG-05 location during the stress relief. It was assumed that this discrepancy occurred because the pipeline at SG-05's location remained anchored while the upslope pipeline rebounded, creating additional strain at the gauge location. Supporting this assumption, once the pipeline at SG-05 was excavated, strain measurements showed a sudden shift: the 3 o'clock position transitioned to tension, and the 9 o'clock position transitioned to compression indicating that the pipeline rebounded downslope consistent with the expected direction of strain movement during stress-relief (Figure 8).

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Both strain gauges, SG-04 in the upslope area and SG-06 in the downslope area of the stress relief, showed minimal strain changes during the stress-relief excavation before the pipeline at these locations was excavated.

Based on the IMU bending strain measurements at the SG-04 and SG-06 locations, tension was observed at the 3 o'clock position and compression at the 9 o'clock position, indicating upslope movement of the pipeline caused by landslide activity (Figure 6). When the pipeline at SG-04 and SG-06 were excavated, the strain gauge recorded increased compression at the 3 o'clock position and increased tension at the 9 o'clock position, indicating a downslope rebound of the pipeline. This observation aligns with the expected rebound direction based on the IMU bending strain measurements before the stress relief.

As the excavation progressed upslope of SG-04 up to station 60 ft, the strain gauge at the 3 o'clock position showed a continued increase in compression, while the strain gauge at the 9 o'clock position recorded a continued increase in tension, indicating further pipeline rebound. However, when excavation advanced from station 60 ft to station 18 ft, no additional rebound effects were observed. Therefore, the stress relief excavation was stopped at station 18 ft on the upslope area. Excavation downslope of SG-06 beyond station 310 ft was not conducted due to the presence of a surface flow channel, which would have required obtaining an environmental permit.

Backfilling was performed after stress-relief excavation using a non-cohesive deformable fill to minimize stress concentration during potential future movement. No changes in strain were recorded by strain gauges during the backfill.

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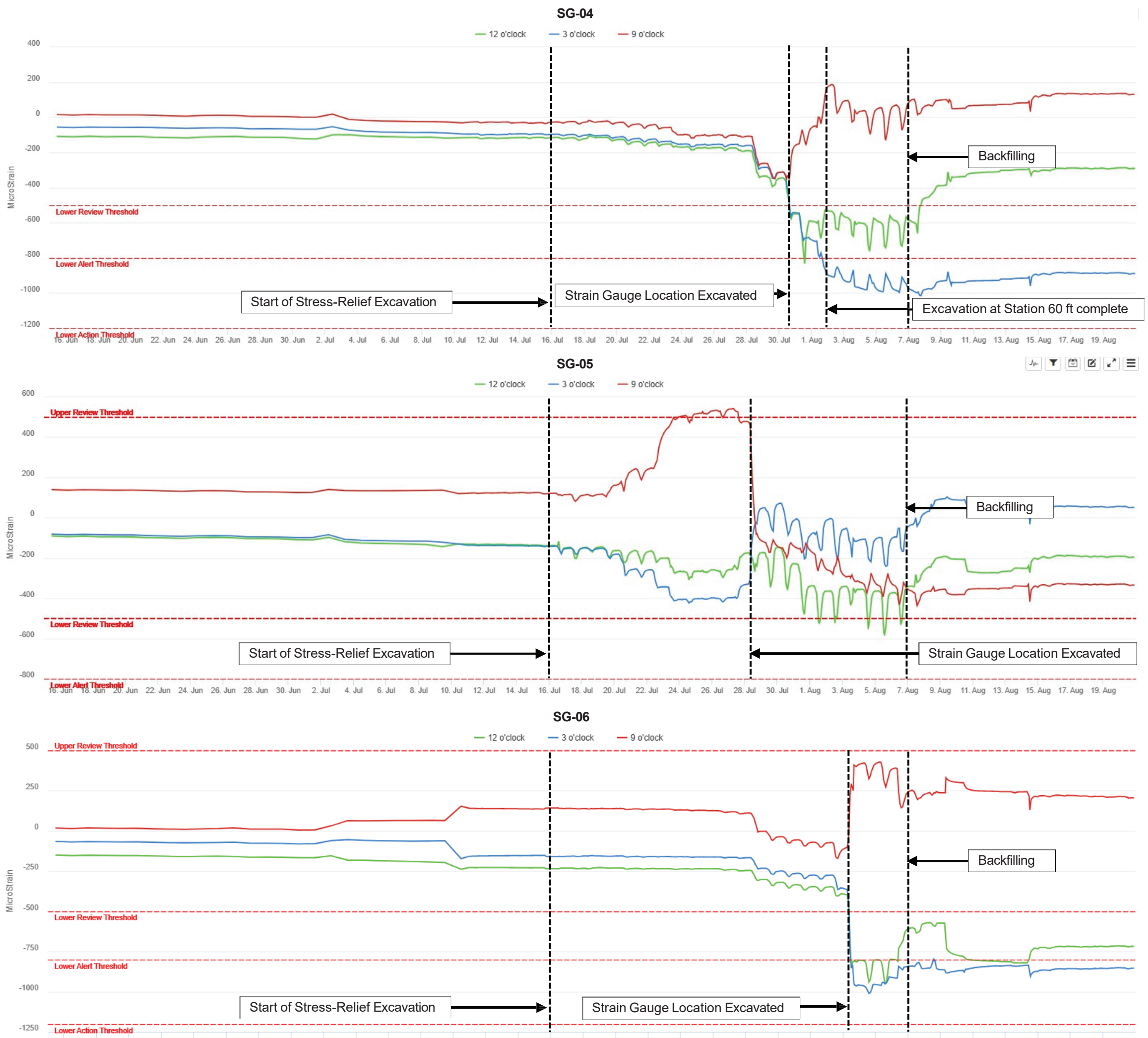

Figure 8: Strain Gauge Measurements During Stress-Relief Excavation

Strain gauges SG-01 on the northern pipeline, along with SG-02 and SG-03 on the middle pipeline, were monitored during the stress-relief excavation. These strain gauges exhibited minimal changes in strain throughout the excavation (Figure 9). Therefore, the pipelines upslope of stress-relief excavation was considered to have minimal effect due to stress relief.

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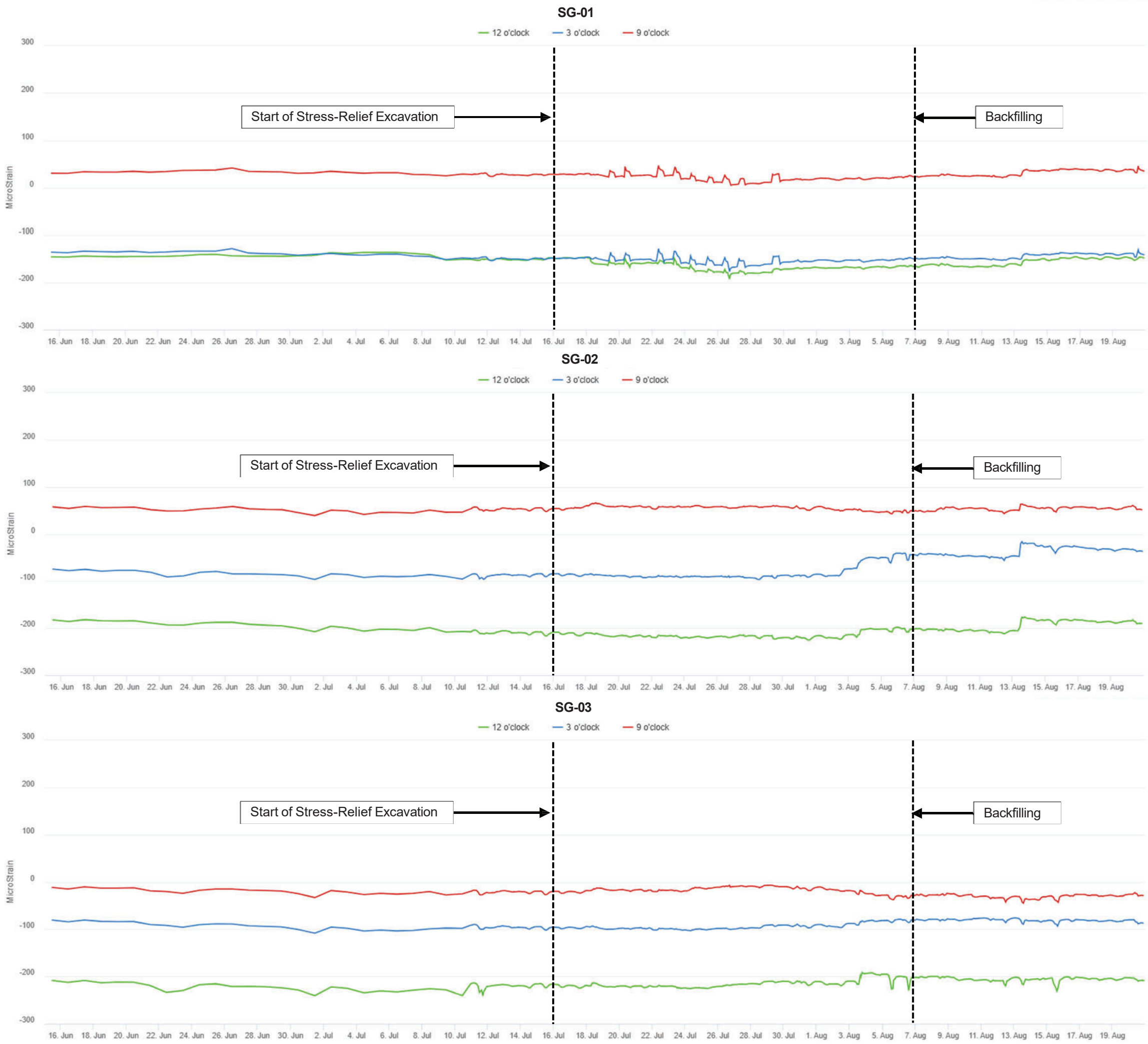

Figure 9: Strain Gauge Measurements on Upslope Pipelines During Stress-Relief Excavation

Post- Stress-Relief Activities

Stress-relief excavation was completed in approximately 3 weeks. Once the excavation was completed, a non-cohesive deformable fill was installed to redistribute stresses during future movement by allowing slight deformation and reduce stress concentrations and improve drainage within the stress relief. Additionally, a subsurface enhanced drainage system was installed within the stress relief excavation.

Summary

Stress-relief excavation is an effective mitigation measure to reduce strain demand on pipelines impacted by landslides. This study presents a quantitative evaluation of stress-relief excavation effectiveness through a detailed case study by including actual data such as pipeline deflection and rebound measurements, IMU bending strain changes before excavation, and instrument readings from strain gauges and inclinometers. Key findings and observations from this case studies are summarized below:

- Although stress-relief excavation is typically considered a short-term mitigation measure, proper design and execution—when combined with complementary measures like drainage improvements and deformable backfill—can reduce and control pipeline strain demand for several years.
- Maximum bending strains on a pipeline affected by landslides do not always occur at the point of maximum out-of-straightness. They can also develop at reaction points along the deformed pipeline.
- The scope of stress-relief excavations must be carefully determined, considering both landslide boundaries and the extent of IMU-detected bending strains.
- Pipeline rebound of approximately 1-feet horizontally and 5-inches vertically was observed during stress-relief excavation.
- Strain gauges provide valuable insights into strain changes before, during, and after stress-relief excavation. For optimal results, gauges should be installed at locations with the highest strain demands or where strain changes are most likely. These locations can often be identified using IMU bending strain data.
- A good correlation was observed between survey lath measurements and strain gauge data, confirming the reliability of both methods.
- IMU data may overestimate pipeline out-of-straightness. Pipeline rebounds during stress-relief excavation should ideally be monitored using survey laths to ensure accuracy.
- Stress-relief excavation is a temporary geohazard management measure. Ongoing monitoring of pipeline strain demand and continued ground movement after excavation is essential to ensure pipeline integrity over time.

These findings emphasize the importance of a systematic approach to stress-relief excavation and monitoring, ensuring the long-term safety and functionality of pipelines affected by landslides.

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