Performance Review of Slope Inclinometers in a Pipeline Geohazard Management Program

Heidi Manicke
Westrek Geotechnical Services, Squamish, British Columbia, Canada
Doug Dewar
Pembina Pipeline, Calgary, Alberta, Canada

ABSTRACT
Slope Inclinometer (SI) technology has evolved over the past 50 years with refinements to sensors, cables, data collection/interpretation and the advent of complementary in-place inclinometers (IPI) and ShapeArray™ (SA) technologies. Fundamentally, the basic technology of monitoring the deformation of a casing or device placed in a borehole has not changed since the advent of SIs. SIs are often the primary geotechnical tool for landslide characterization and monitoring.

Data from the review of 64 non-operable and 163 operating borehole inclinometer (BI) installations is presented along with observations from the implementation of a pipeline geohazard management program (GMP) within Western Canada. The contributions of SIs to the overall GMP are evaluated and guidance for the future use of SI/SA/IPI technologies in pipeline GMPs is provided.

RÉSUMÉ
La technologie des inclinomètres de pente (IP) a évolué au cours des 50 dernières années avec des améliorations aux capteurs, aux câbles, à l'acquisition/interprétation des données et à l'émergence des technologies complémentaires comme l'inclinomètres en place (IPI) ou le ShapeArrayTM (SA). Fondamentalement, la technologie de base pour la surveillance de déformation d'un tubage ou d'un dispositif placé dans un trou de forage n'a pas changé de manière significative depuis l'avènement de l'IP. Les IPs sont souvent le principal outil géotechnique pour la caractérisation et la surveillance des glissements de terrain.

Nous présentons les données de l'examen de 64 installations IP/IPI/SA inopérable et de 163 installations IP/SA opérationnelles ainsi que les observations de la mise en œuvre d'un programme de gestion des géorisques (PGG) des pipelines dans l'Ouest canadien. Les contributions des IPs aux PGG sont évaluées et des conseils pour l'utilisation future des technologies IP/SA/IPI dans les PGG des pipelines sont fournis.

1 INTRODUCTION

Borehole inclinometer (BI) technology (including Slope Inclinometers (SI), ShapeArrayTM (SA) and In-place Inclinometer (IPI)) is often used as the primary geotechnical method for characterization and/or monitoring of landslides interacting with pipelines having extremely slow to very slow (<50 mm/yr) velocities (Dewar 2017). However, BI installation has many challenges within pipeline rights of way, including high costs associated with remote/steep slope access, ground disturbance and ongoing monitoring/maintenance. Moreover, conventional GPS survey, LiDAR, InSAR and pipeline inline inspection deformation/strain tools have rapidly advanced since the turn of the millennium as summarized by Dewar (2017 and 2020), Wang et al. (2016) and Rizkalla and Reid (2019). It is often cost prohibitive and not feasible to stabilize landslides that pipelines cross; therefore, the preferred mitigative measure is often HDD or reroutes. Additionally, shorter-term pipeline mitigations include running surface pipeline segments, strain relief programs or improvements to slope surficial/subsurface drainage. Pipe slope stabilization mitigations are often less common than other linear infrastructure such as railways, powerlines and roadways.

Babcock et. al. (2020) used multiple ground and pipe monitoring techniques to assess pipeline fitness for service and determine future monitoring/mitigations in an investigation of 5 km of conventionally trenched pipeline crossing a large, deep-seated landslide complex with up to 5 generations of superimposed spreads, slides and flows. Information from BI monitoring did not contribute significantly to the final engineering recommendations. As a result of the work, a hypothesis is introduced that BI technologies may be overused for pipeline specific applications based on pipeline strain capacities, new monitoring pipeline technologies and prevalent pipeline mitigative options.

A dataset review of 227 BIs indicated that there are challenges associated with BI installation and monitoring that often result in poor quality data.

The paper is divided into two parts 1) data results and review and 2) general and pipeline specific commentary based on the authors' experiences and opinions.

2 NOMECLATURE/TERMINOLOGY/LIMITATIONS

Landslide terminology follows Cruden and Varnes (1997) and soil to pipeline interactions are described using Dewar (2019).

A^+ – SI casing groove orientation often aligned with direction of landslide movement

ADM – Area of Differential Movement (Dewar 2017)
BI – Borehole inclinometer, collectively incl. SI, IPI and SA
Blocked SI – any condition that does not allow an SI probe to pass through a zone of landslide slip surface interaction or allow for IPI/SA retrofit
Borehole Verticality – the inclination of the borehole from vertical
DoC – Depth of Cover, measured to the top of a pipeline
D_p – Diameter of pipeline
D_{ss} – Depth to slip surface
HDD – Horizontal Directional Drills
GMP – Geohazard Management Program
GNSS - Global Navigation Satellite System
ILI IMU – Inline Inspection Inertial Measurement Unit – technology used to calculate and monitor the shape of a pipeline during inline inspections
IPI – In Place Inclinometer
MEMS– Micro-electromechanical system accelerometers
SA – ShapeArray™
SMH– Survey Monitoring Hubs
Strain Capacity – Ultimate strain at which a pipeline will fail
Strain Demand Limit – factored strain capacity
RoW – Pipeline(s) rights of way typically 10 to 20 m wide
UCD –Upper Casing Deflection
Unk =Unknown

3 METHODOLOGY

3.1 Dataset

The dataset is limited to BI installations within the Western Canadian Sedimentary Basin, Rocky Mountains and Interior plateau of Alberta and British Columbia, Canada. The operational status of the BIs is outlined in Table 1 below.

Table 1: Operational status of BIs

Status	Count	Percent
Operational Real Time (SA)	25	11%
Defunct Real-Time (IPI)	2	1%
Operational SI- field read	103	45.5%
Operational Retrofit SI (with SA)	15	7%
Defunct	60	26.5%
Destroyed	3	1%
Unknown	19	8%
Total Sample	227	100%

The operational status was delimited based on:
Operational:

- Readable: BIs are manually read using a traversing inclinometer probe, or manually read SA or IPI with readout box.
- Real-Time: SA or IPI with no manual intervention required.

Non-Operational:

- Defunct: BIs have exceeded their serviceable life and are blocked by landslide deformations.
- Destroyed: damaged or destroyed by means other than landslide deformation (i.e. construction, third party interference, or meteorite strike).

Unknown: Status of these instruments is not known. This may be due to third party readings, or that the instrument is not actively monitored because the associated pipeline has been discontinued or abandoned.

3.2 Analysis Parameters

Data analysis included:

- Installation – casing diameter, stickup, overall shape, verticality and length
- Performance – status, UCD activity/orientation, casing compression, slip surface length, depth of movement, slip surface types, average rate of movement, total movement, movement characteristics, and drag down
- Qualitative review of data quality

Not all records could be considered complete because raw data sets were not always available and often there were gaps within the actual data recorded, particularly for installation data. Given that 227 SI records/datasets with 34 individual data fields per record were reviewed, only the key findings are presented in this paper.

4 DATA RESULTS AND REVIEW

4.1 UCD

Manually read SIs with known stickup were considered in the analysis of UCD. This was 184 of the 227 records reviewed. Table 2 summarizes the findings of a review of UCD data. UCD was observed in 11 of the 25 SAs reviewed, however, installation data on the depth of the uppermost sensorized segment in relation to ground surface was not readily available for many installs. Therefore, SAs were not included in the general UCD analysis statistics.

Table 2: UCD data review summary

Condition	Count	Percent	Percent of UCD
With UCD	128	70%	NA
Direction A+	85	46.3%	66%
Direction A-	15	8.3%	12%
Direction B+/-	28	15.4%	22%
Total Sample	184	100%	NA

The A^+ groove was not installed in line with the general direction of landslide movement in 20 (9%) of the sampled inclinometers. In 18 (90%) of these SI installs, the UCD generally aligned with the direction of landslide movement, not the A^+ direction.

Potential causes of UCD include:

1. Third-party Interference: third party damage of SI installations often with gas powered vehicles or

firearms. Most times this destroys the upper installation rather than resulting in an UCD.

2. Bioturbation: large wildlife and/or livestock may rub against BI casing protectors.
3. Frost heave/soil swelling/settlement of protective casing and soil/grout/concrete backfill.
4. Near Surface Grouting Issues: grout settlement requiring near surface grouting/casing protector install once rig and proper grouting equipment has been demobilized. Upper hole may be finished with grout, sand, cuttings and/or bentonite after final grouting.
5. Reading interactions: Cyclic loading or pulling on casing, particularly with older non-MEMS probes and cables. For example, older 150 m (500 ft.) analog cables and probes can have a weight of up to 30 kg. When pulled horizontally up and over a wheel fixed to the top of the casing, a significant moment is created at the top of the casing.
6. Landslide: near surface soil creep, earth flows and slides within a deeper landslide may push the casing over.

Items 1 through 4 above should not favor a preferred orientation. Item 5 may have a preferred A^+ orientation for older installations with heavier equipment and Item 6 should have a preferred A^+ if the BI groves are aligned with the direction of movement. Given that 66% of the data set has a preferred A^+ and uses modern MEMS type probes and cables that should be pulled straight up, the practice of ignoring UCD should be done with great caution. Conversely, consultants should not automatically present UCD on velocity plots when it may not actually be ground movement.

Table 3 shows the results of the review of UCD versus casing stickup.

Table 3: UCD versus casing stickup

Stickup	Height	#	UCD	%
Flush/near ground	<0.25 m	4	2	50%
Low	0.25 to <0.6 m	17	10	59%
Regular	0.6 to <1.0 m	135	102	76%
Excessive	≥1.0 m	17	14	82%
Sample Total		173	128	74%

The greater the stickup, the greater the lever arm and the more susceptible the instrument is to UCD.

4.2 Slip Surface

Figure 1 provides examples of slip surface types and Table 4 provides a breakdown of slip surface types within the dataset. Note that UCDs are not included in the determination of slip surface type. It should be cautioned that there is a great deal of variability in potential slip surface types, but for the purposes of this study, simplifications and broad grouping was required to keep the data manageable. Multiple refers to having multiple simple slip surfaces and composite refers to having simple slip surfaces along with either compression or earthflow features. When a slip surface was defined as unknown, the data was too noisy to provide a reasonable interpretation.

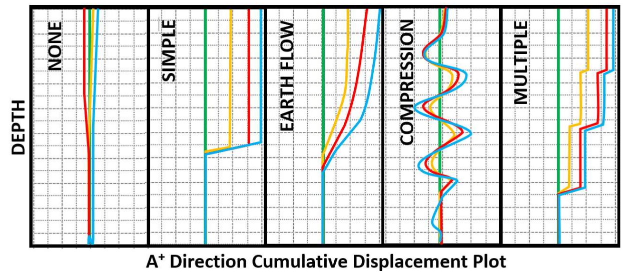

Figure 1: Representative slip surfaces

Table 4: Slip surface types

Slip Surface Type	Sample	Percent
None	31	14%
Simple	79	35%
Earth flow	60	26%
Compression	1	0.5%
Multiple	31	14%
Composite	8	3.5%
Unknown	17	7%
Total Sample	227	100%

The maximum and average displacement were also analyzed, however, maximum underestimates the true displacement, as it is based on the final SI reading, which occurred before the instrument could no longer be read. Larger diameter 85 mm casings appear to have 33% more capacity for movement prior to becoming blocked, as seen in Table 5. This may be significant when using SIs for slope monitoring but may not be significant when using BI technology to characterize landslides. Given the potential additional costs of mobilizing drilling equipment that can create a hole large enough to accommodate 85 mm casing, the potential advantages of going with the larger casing may be minimal, particularly when the goal of the drilling program is to characterize rather than to monitor a landslide.

Table 5: Average displacement recorded at last SI reading

Casing Diameter	Average	Max.	Min.
70 mm	63 mm	245 mm	5 mm
85 mm	81 mm	260 mm	5 mm

Figure 2 is a graph of cumulative movement for blocked defunct SIs plotted to separate 70 mm and 85 mm casings. It shows that 85 mm casings can experience more deformation prior to the SI becoming blocked for a given slip surface length. It also demonstrates the extreme scatter in the data. Linear relationships are shown within the figure but are questionable at best. The authors additionally plotted the data versus a strain index (displacement/slip surface zone length), but no meaningful relationships were found.

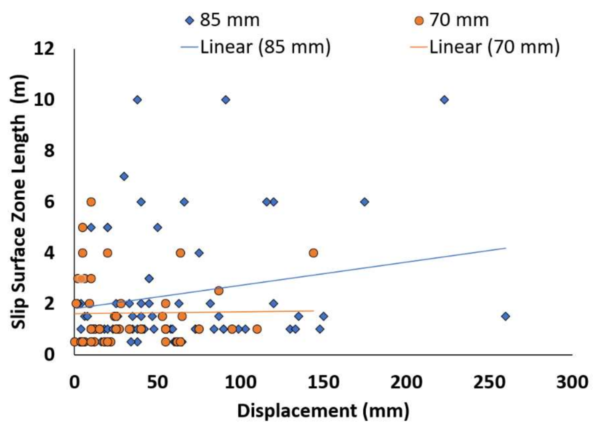

Figure 2: Blocked defunct SI cumulative displacements versus slip surface zone length

4.3 Premature SI Failures

Premature SI failure may be due to installation issues and/or greater than expected landslide movements/accelerations. The installation issues may include poor backfill in the case of a BI installed following a strain relief, a casing joint intersecting a shear zone in a very active landslide or casing groove alignment issues where the casing grooves do not align following installation.

SI installations that were blocked prior to the second reading were 5 out of the 227. No SA nor IPI in the sample set had a premature failure.

Table 6: Premature BI failure data

Condition	Count	Percent
No	196	86.5%
Potential	10	4.5%
Yes	5	2 %
Unknown	16	7%
Total Sample	227	100%

4.4 Drag Down

There were 2 occurrences observed in the dataset, although there may be others that were not evident or measured, as recurrent measurements of stickup were not common. One defunct blocked 70 mm casing SI was observed to have “drag down” because of a near surface slip surface and soft overlying soils. The other occurrence was an operable 70 mm casing. The drag downs were approximately 370 mm in both cases.

4.5 Data Quality

BI data quality was subjectively determined using the following criteria:

- Good: Quality data is obtained from the instrument, with minimal noise. Ground movement or lack thereof is evident and obvious.
- Marginal: Landslide interactions are evident through noise. Data corrections are often required.
- Poor: SI data provides nebulous outputs due to poor installation or being blocked following the initial reading (SA retrofit not possible).

SI data quality is related to many factors. Many of the cumulative errors that plague SI data are related to the probe, such as bias or rotation and to reading repeatability/human factors. These errors can often be corrected during data reduction or be reduced through good, repeatable reading practices.

Errors related to the quality of the SI installation include casing spiral and depth position error (which may also stem from large displacements on a slip surface). SIs suspected of casing spiral may be surveyed using a spiral probe and the dataset corrected with most available software. However, depth position errors are difficult to correct, even when the vertical displacement is known (Slope Indicator, 2022) and these are often, but not exclusively, related to the shape of the casing or landslide deformation.

Tables 7 and 8 present data quality versus install type and shape, respectively.

Table 7: Data quality analysis

Quality	All Data*	SI 70mm	SI 85mm	SI Unknown	SA
Good	158 (70%)	53 (75%)	76 (66%)	6 (43%)	23 (92%)
Marginal	47 (21%)	12 (17%)	31 (27%)	2 (14%)	2*** (8%)
Poor	6 (3%)	2 (3%)	3 (2.5%)	1 (7%)	0
Unknown**	14 (6%)	4 (6%)	5 (4.5%)	5 (36%)	0
Sample Total	225	71	115	14	25

* No IPIs within data set
** Data not available for all installations
***Suspect SA retrofit does not meet manufacturers specifications for casing compression resulting in erroneous data

Table 8: Data quality versus BI shape

Shape	Total	Good	Marginal	Poor	Unknown
Straight	57	48 (84%)	6 (10%)	1 (2%)	2 (4%)
Curved	37	29 (78%)	7 (19%)	1 (3%)	0
Sinusoidal	50	26 (52%)	20 (40%)	3 (6%)	1 (2%)
Kinked	8	6 (75%)	2 (25%)	0	0
Unknown*	48	26 (54%)	10 (21%)	1 (2%)	11 (23%)
Sample Total	200	135	45	6	14

*BI shape/absolute position plots not available

Correlations of poor-quality data to the number of probe inclination reversals appear to be evident in the data, with SIs sinusoidal shape providing significantly lower quality data compared to other shapes. This is unsurprising considering the susceptibility to depth-position error and the difficulty correcting this error. The quality of the data in sinusoidal installations is often improved by SA install or retrofit, where the errors associated with a traversing probe are eliminated and along with it, the depth-position error.

4.6 BI Verticality and Spiral

Borehole verticality data was available on 150 of the sampled SIs. 33 (22%) were found to have a borehole verticality greater than 3°. Suggested verticality is often 1° to 2° from vertical (Slope Indicator, 2022), as the MEMS sensors measure inclination from vertical and become less accurate/more prone to error as the sensor orientation becomes more inclined.

The average verticality was 2.25° and maximum recorded verticality was 21° on a 152 m borehole installed using a water well drill rig, supervised by the older author. Table 9 shows a breakdown of the quality of data associated with SIs verticality.

Table 9: Data quality and BI verticality

BI Verticality	Total	Good	Marginal	Poor	Unknown
>3°	33	26 (79%)	6 (18%)	1 (3%)	0
≤3°	117	83 (71%)	28 (24%)	3 (2.5%)	3 (2.5%)*

* Only baseline readings were available for 3 SIs, so the quality of the data is unknown

The data from this sample suggests that verticality is less important than installation shape, as discussed in the previous section, to overall data quality and appears not to significantly impact data quality.

Spiral surveys were performed in 2018 on 15 of the SIs in the sample set, which ranged from 50 to 139 m depth. Industry standards for most casing manufacturers are a maximum of 0.3° of spiral per 3 m length of casing. However, 10 (67%) of the 15 SIs with spiral surveys had greater than 0.3° of twist per 3 m length. These “twisted” SIs had “Marginal” quality data 90% (9 out of 10) of the time.

However, this subset of data is also biased, as the installations were chosen for spiral surveys as they are greater than 50 m deep. Deeper installations generally have more installation issues, so it is possible that this higher likelihood of “Marginal” data is biased. Spiral survey of shorter SIs would provide further insight.

5 GENERAL DISCUSSION

5.1 General Commentary

Young, inexperienced field engineers taking direction from more senior office engineers and inexperienced/complacent drillers likely contribute significantly towards observed installation issues. It is suspected that there would be a very high correlation between the experience of the field engineer and the driller and the quality of the installation. Often, there is a bias to underreport issues or occurrences in the field that may impact the quality of the installation. Drilling records and field reports are often incomplete or edited/sanitized during any review process to reduce potential liability. Borehole logs may have gone through several edits prior to being released to the client. This may further complicate trying to explain data anomalies in marginal or poor-quality data. Additionally, BIs are generally not installed in ideal conditions, either from a logistical or geotechnical point of view.

The data review in Section 4 strongly suggests that more attention should be given to the quality of the installation to reduce the potential for poor quality data. This likely can be achieved through better training and more rigorous procedures for SI installation, especially associated with finishing off installs near the ground surface and keeping the casing straight down the borehole. For example, there is no known standard and/or research to indicate what is the best type of surface casing protector or what is the best method to counteract buoyancy during install and grouting.

Every effort should be made to reduce the potential for a poor installation, as BI installs are “money down the hole.” Most install costs are expended prior to any verification of installation condition. A complete reinstallation or possible retrofit are often the only remedy for poor installs or blocked SIs.

Installation data reported for BIs is incomplete in many instances, particularly for older installations where company records have been lost or are inadequate. Often only cumulative plots are provided, which don’t provide adequate information for interpretation, especially when the data quality is marginal or poor. Shape/absolute position plots are essential for understanding and interpreting BI data, as they provide further insight into the dataset, notably when it is of marginal or poor quality.

5.2 Landslide Characterization

BIs are used to determine if there is landslide activity and the depths of any slip surfaces. Often SIs can be retrofitted with an IPI or SA prior to becoming blocked to extend the life of the SI. If an SI is blocked, a new installation would be required to continue monitoring, which is likely logistically more difficult and more expensive than retrofitting an existing instrument. Table 10 provides guidelines to reduce the need for premature reinstallation.

Data from the results in Figure 2 and Table 6 support these results when there are no economic/access constraints that would limit borehole diameter. For example, 85 mm casing would be hard to install in helicopter access only drill sites. This should be combined with the consideration that only 2 to 5% of SIs are prematurely blocked as noted in Table 6. While this number may seem small, an individual client/project that ends up having blocked SI without providing any movement data may become a significant issue, particularly to private clients.

Table 10. Recommended BI installs

Expected Average Landslide Velocity	Casing size and type of SI
Extremely Slow <16 mm/yr	70 or 85 mm casings for SI installs, SA not required
Very Slow 16 to 50 mm/yr	85 mm for all SI installs, but SA are preferred
Very Slow >50 mm/yr	SI Installs not recommended, SA should be installed

5.3 Landslide Monitoring

Engineers may focus on the accuracy of the survey when it may not be a significant issue, particularly in the pipeline content, as discussed in Section 6. Additionally, BIs tend to be very accurate within a certain range, which would increase from 70 mm SIs, 85 mm SIs, IPIs then 500 mm segment SAs and, finally, the recently developed 250 mm segment SAs. Near the end of the range, any BI technology would become less accurate/defunct as either:

- An SI casing pulls apart, shears, ovalizes or bends, becoming blocked. Note that there may be an opportunity to install an SA. In severe cases, the SI casing may be pulled into the ground.
- An IPI or SA segment or segments breaks or bends, and the internal instrument reports an angle less than the actual inclination of the borehole.

Conversely, Surveys and LiDAR have an unlimited travel. Conventional and GPS surveys always tend to become more apparent once a minimum of 25 to 50 mm of movement is measured based on the authors' experience. As always, BIs typically only require minimal movements (approximately 2 to 5 mm) to confirm landslide activity.

Survey monuments tend to get damaged at the same rate as SI stickups and obviously have a lower repair/replacement cost.

5.4 Slope Stabilization

BIs are an essential part of any geotechnical investigation to characterize and subsequently monitor any slope stabilization performance. As previously established, subsequent BI measurements will be far more accurate and precise than survey measurements. When the assessment criteria changes from assessing a critical amount of movement that could potentially pose a threat to a pipeline to assessing the performance of a slope stabilization, BI monitoring is required to give an early warning of any performance issues. Refer to Section 5.3 for a discussion of detection limits.

6 PIPELINE CONSIDERATIONS

6.1 General Logistical Considerations

There are many well-known logistical challenges for BI installation and monitoring associated with budgetary concerns, site access, steep slope work and drilling logistics/break downs. Additional pipeline related concerns include:

- Landowner/permitting issues as pipelines are in RoWs, rather than on land owned by the client. Additionally, First Nations consultation is often required.
- Working in proximity to active pipelines may limit or restrict drilling activities. This includes any pipeline crossings required for site access.
- Ground disturbance standards typically require the exposure of active pipelines prior to work and do not permit drilling within 5 m of the outside edge of a pipeline. Pipelines must be hand or hydrovac exposed rather than using a surface locator under most operator's ground disturbance standards. For pipelines with deep cover this may be a project showstopper.

6.2 Pipeline Position

Most pipelines interacting or potentially interacting with landslides are installed conventionally in trenches with DoCs ranging from 0.6 to 1.5 m. As the depth of the slip surface becomes deeper, surface measurements either from SMHs and/or LiDAR/InSAR, generally become more relevant in defining potential interactions, as demonstrated in Figure 3 below.

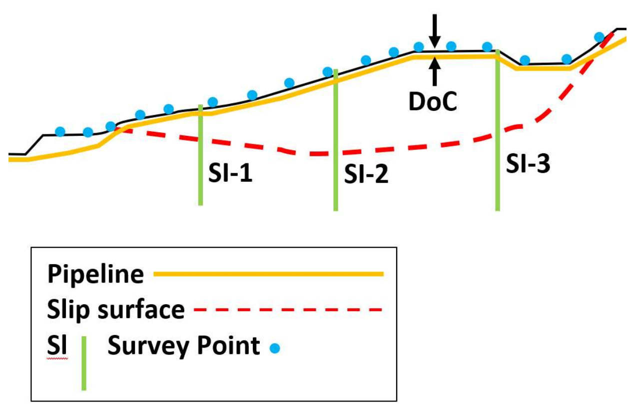

Figure 3: Depth of cover versus slip surface depth in conventionally trenched pipelines.

Furthermore, BI data provides a few sparse points of information on a slope, whereas SMHs can provide numerous points of data or area-based methods such as LiDAR typically scan most of the RoW and surrounding slopes. For movements parallel to the pipeline alignment, most failures tend to occur at the toe of a landslide where interactions are exacerbated by pipeline bends or at the main scarp where tension may pull a pipeline apart. For movements perpendicular to the pipeline, failures generally occur at areas of maximum strain or near the boundaries of the movement where pipelines are in tension. When determining areas of concern within a pipeline and relating to pipeline monitoring data, including ILI IMU assessments (Dewar 2020), it is essential to delimit areas where the pipeline crosses ADMs within a landslide. BI data is generally not as useful as surface data and ILI IMU for delimiting ADMs.

Conventional and GNSS survey technology has become a reliable source of slope monitoring data for pipeline applications (Wang et. al. 2016). Additionally, surface displacements can be tracked near real time as reliably as SA slip surface displacements. Bracic and McMahon (2020) have demonstrated the viability of near real time GNSS survey monitoring in pipeline applications.

6.3 Ground Displacement and Pipeline Strain Capacity

Based on the authors' experience there is a significant discrepancy between the ground displacements a single SI/SA can measure, and the total landslide displacement required for a soil/pipeline interaction to exceed a pipeline's strain demand limit. Dinovitzer et al. (2014) reports up to 3 m of cumulative slope movement parallel to 4 conventionally buried pipelines without a loss of containment. The authors' experience on numerous interacting perpendicular to pipeline landslides demonstrates that over 1.5 m of ground movement can be accommodated without a loss of containment. It should be cautioned that in most soil to pipeline interaction scenarios (Dewar 2019), landslide displacements do not directly equate to pipeline strain. Oswell (2021) provides a more detailed explanation and simplified methods of calculating strains induced by ground movements. Figure 4 details the detection limits, maximum displacements, and landslide ground movement.

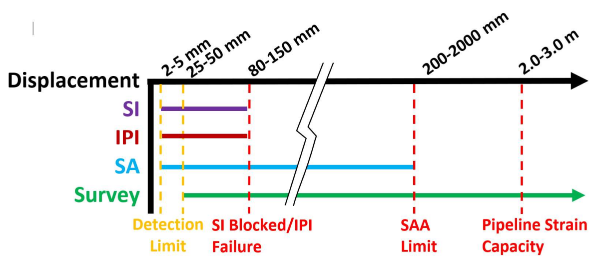

Figure 4: Detection limits and functional range for BI and surface surveys versus pipeline strain capacity considering a 2 m zone of shear

If it is assumed that a 70 mm SI would fail somewhere between 60 and 80 mm of displacement, a minimum of 18 SIs would be required to monitor a landslide to pipeline failure. Less installs would likely be required, as there would be a time gap between an SI becoming blocked and replacement. An unknown amount of displacement would occur during any gaps, which may be problematic, especially when using soil to pipeline interaction models with a defined strain demand limit based on ground movement. While the best effort can be made to replace an instrument before it becomes defunct, accelerations in movement and other logical challenges may occur. Installing adjacent SMH is recommended for all BI installations to avoid data gaps.

6.4 Pre and Post HDD Assessments

BIs are often installed during HDD feasibility assessments to determine if there are any indications of ground movement. The main limitation of using this method of investigation is that there may be multiple slip surfaces and the higher elevation slip surface may block the BI prior to any information being collected on the lower slip surface(s). Additionally, any monitoring period tends to be relatively short when compared to the overall operating life of any pipeline. Geotechnical engineers may rely more heavily on interpretations of overall landslide morphology and general regional experiences to determine the deepest credible slip surface (Figure 5), which will be then used to help determine the no drill zone for the HDD. Additionally, looking back using InSAR may be helpful in determining landslide activity for pipelines drilled through landslides.

Many historic and some more recent pipelines include HDDs that have had no geotechnical input and are focused on either crossing a watercourse and/or avoiding work on steep slopes with no consideration for landslide interactions. Many pipelines have been drilled either clearly through a landslide body, potentially intersecting a probable slip surface and/or nebulously being located within or close to a deepest credible landslide extent, as depicted in Figure 5.

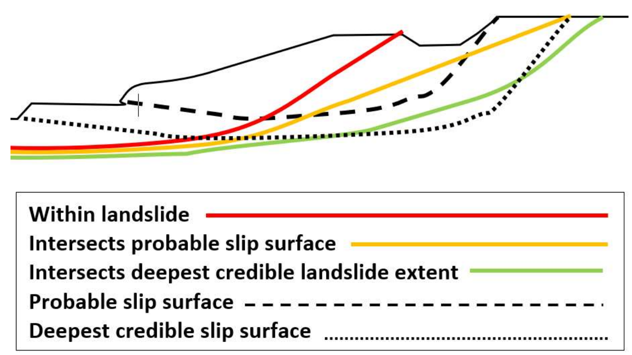

Figure 5: Typical HDD landslide interaction scenarios

BIs within or adjacent to a RoW are typically not an acceptable method of assessing potential interactions, as the relative position of the borehole to the deep pipeline cannot be acceptably verified. While it's highly improbable an offset borehole would intersect a pipeline, the potential consequences are severe enough that any ground disturbance activity would have to have a significant offset from the pipeline outside of any existing RoW. Section 4.6 reports a maximum borehole verticality of 21° which, if applied to a drilling program, would require significant SI setbacks for deep HDD installs.

7 CONCLUSIONS

The following conclusions are given:

- UCD should not be immediately ignored when interpreting SI data.
- The lifespan of an SI varies significantly and depends on a variety of factors, including casing diameter, installation and the zone of deformation. Generally, 85 mm casing has 33% more lifespan than 70 mm casing.
- SI data is influenced by the quality of the install, including casing shape and inclination. When installing BIs, the data strongly suggests that more attention be paid to the quality of the installation.
- BI technology use should move from a primary to a complimentary role in favor of survey, LiDAR, InSAR and ILI IMU technologies for conventionally buried pipelines, as most of the interactions occurring near the ground surface are at landslide boundaries or other ADMs rather than at depth.
- BIs should be used and installed as per accepted industry practices for pipeline slope stabilization mitigations.

8 FURTHER RESEARCH

Current data collection does not really provide enough information to assess the causes of UCDs. Additional data can be collected to measure and monitor casing protector tilt and drag down. Data from adjacent 6 m deep SI casings finished flush to the ground surface and SMH adjacent to new BI installs could provide useful information to determine the nature of UCDs. Additionally, the stick up protector tilt and tilt direction can be measured while reading BIs. UCD and SA relationships require further study as the current data set is not adequate in defining the exact position of the uppermost SA active segment in relation to the ground surface.

Consider doing further work to develop better methods to better characterize and measure casing drag down.

Dewar (2022, Slide 54) recommended that ILI IMU type methodologies, as defined by Hart et al. (2019), be used to define the shape of SI casings that slip surfaces rather than summing angles across slip surfaces to better understand and classify interactions between BI casings in the ground. Additional insight into blocked casings could be provided by caliper tools.

9 ACKNOWLEDGEMENTS

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