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RECENT PRCI GUIDELINES FOR PIPELINES EXPOSED TO LANDSLIDE AND GROUND SUBSIDENCE HAZARDS

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ABSTRACT

This paper summarizes key considerations in guidelines published in early 2009 that were developed through a Pipeline Research Council International, Inc. (PRCI) supported by PRCI, the Pipeline Hazardous Materials and Safety Administration of the Department of Transportation, and the California Energy Commission. Past practices for pipelines, as well as almost all other construction projects, have focused on avoidance of areas that have a reasonable probability of experiencing geohazards (defined as large ground displacements that may arise from slope failure, slope creep, earthquake triggered slope movement, and subsidence). This approach has been generally successful when there are limited restrictions on selecting a pipeline alignment. Avoiding potential geohazards is becoming increasingly difficult because of the inability to obtain landowner agreements, the lack of space in common utility corridors, environmental restrictions, incompatibility with existing land use, and/or public opposition.

In route corridors where geohazards cannot be avoided, the potential risks associated with these hazards must be managed. Pipeline integrity management strategies to mitigate geohazards consist of: (1) design measures that improve the pipeline resistance to the geohazard, (2) measures that limit or control the severity of the geohazard, and (3) operational programs to monitor ground displacement or pipeline response and identify conditions that may warrant further engineering investigations or mitigation activities. Identifying the most appropriate mitigation strategy needs to be based upon specific hazard scenarios and operating circumstances.

The PRCI guidelines provide recommendations for the assessment of new and existing natural gas and liquid hydrocarbon pipelines subjected to potential ground displacements resulting from landslides and ground subsidence. One of the most significant benefits of the guidelines is the systematic approach developed for managing pipeline risks from landslide and ground subsidence hazards. It is hoped that this approach, presented in detailed flow charts, will lead to improvements in current practices by providing a common framework for pipeline operators, the local, state, and federal agencies that have regulatory oversight, and the general public to engage in discussions regarding potential risks from pipelines in areas of unstable ground and the most effective and practical means to reduce those risks to an acceptable level.

INTRODUCTION

Past design practices for pipelines, as well as almost all other construction projects, have focused on avoidance of areas that have a reasonable probability of experiencing geohazards (defined as large ground displacements that may arise from slope failure, slope creep, earthquake triggered slope movement, and subsidence). This approach has been generally successful when there are limited restrictions on selecting a pipeline route. Deficiencies in the hazard avoidance approach can generally be traced to lack of knowledge at the time the route was selected, changes in environmental conditions (e.g., heavy and prolonged rainfall, loss of vegetative cover) or subsequent development near the pipeline alignment that leads to conditions that increase the potential for geohazards.

Avoiding potential geohazards is becoming increasingly difficult because of the inability to obtain landowner agreements, the lack of space in common utility corridors, environmental restrictions, incompatibility with existing land use, and/or public opposition. In route corridors where geohazards cannot be avoided, the potential risks associated with these hazards must be managed. Pipeline integrity management strategies to mitigate geohazards consist of (1) understanding the geohazards, (2) design measures that improve the pipeline resistance to the geohazard, (3) measures that limit or control the severity of the geohazard, and (4) operational programs to monitor ground displacement or pipeline response and identify conditions that may warrant further engineering investigations or mitigation strategies. Identifying the most appropriate mitigation strategy needs to be based upon specific hazard scenarios and operating circumstances.

A 30-month PRCI project to develop guidelines for managing risks to natural gas and liquid hydrocarbon pipelines from landslide and ground subsidence hazards was initiated in mid-2006. The scope of the project included a review of existing methods for identifying landslide and ground subsidence hazards, a systematic process for estimating the risks of these hazards to pipelines and potential benefits of various mitigation strategies, research into pipeline-soil interaction, and improved methods of determining pipeline strain from in-line measurements.

The guidelines developed under the research project have produced several benefits. The most significant benefit is related to the systematic approach developed for managing pipeline risks from landslide and subsidence hazards. It is envisioned that this approach, presented in detailed flow charts, will lead to improvements in current practices by providing a common framework for pipeline operators, the local, state, and federal agencies that have regulatory oversight, and the general public to engage in discussions regarding risks from pipelines in areas of potential ground movement. This common framework is based upon an understanding of the uncertainty in predicting potential ground displacements, methods to reduce the severity of the hazard through site modifications, pipeline design and operational measures, and vigilance through routine monitoring.

Experimental research conducted in this project provided support for recommending new relationships for quantifying pipeline-soil interaction. Recommendations for analyzing pipeline response to ground displacements in the guidelines incorporate these new relationships as well as recent findings from other researchers. Improvements in analyzing pipeline response to ground displacement enhance the ability to determine the appropriate balance among mitigation through pipeline design, geotechnical improvements, and operational measures.

The project also developed an algorithm to deduce both bending and axial strains in pipelines from ground displacement using geometry measurements made by advanced in-line inspection tools. This represents an improvement over current methods that address only bending strain. The algorithm is appropriate for cases where loading caused by ground displacement is predominately transverse. As the algorithm is computationally straightforward, the axial strain algorithm can be easily programmed into existing in-line inspection vendor software.

The following discussion is focused on a summary of the key aspects of the PRCI guidelines for managing landslide and subsidence hazards, improvements in the methods for assessing pipeline response to permanent ground displacements, and improved methods of determining pipeline strains using in-line inspection tools.

GROUND MOVEMENT HAZARD DEFINITION

Lateral spread, landslide and ground subsidence hazard identification relies primarily on subjective observations and review of relevant information by experienced geological or geotechnical specialists. The means to identify locations of future geohazards rely upon identifying (1) areas that have recently undergone large failures (e.g., slope movement, sink holes), (2) areas that are actively moving at slow but measurable rates, (3) areas that are very similar in terms of topography, geomorphology, hydrology, and soil properties to areas where evidence of past hazards is observed, (4) areas where changes in existing conditions (e.g., logging, deforestation, urban or industrial development) increase the risk of slope movement and/or (5) areas where activities leading to surface displacement are ongoing or planned (e.g., mining, ground water withdrawal, oil and gas production).

The guidelines developed under the PRCI project are founded upon a suite of guiding principles developed at an early stage of the project based upon the findings of the review of current practice and past research. Several of the more important principles are briefly mentioned below.

- There is generally no basis to assume that landslides that have exhibited small displacement rates (e.g., less than a few cm/yr) over a relatively short monitoring period (e.g., less than 10 years operating life) cannot exhibit episodic larger displacements (e.g., over 1 m in hours or days) over the typical life of a pipeline (50 to 100 years).
- Reliable landslide hazard definition is restricted to identifying the location, dimensions, soil properties, and depth of the slide plane. Estimating potential damaging displacements that might occur in a rapid failure condition (one to several meters over the period of hours to days) is beyond the current state of practice.
- Probabilistic estimates of landslide hazard will typically be limited to “order of magnitude” annual likelihoods (e.g., ranges of 0.1%, 1%, or 10% per year) based largely upon subjective judgment of experienced professional geologists or engineers.

- Given the location of a potential landslide hazard that could be a threat to pipeline integrity, there are only two options to address the related risk (1) take engineering steps to eliminate the hazard (e.g., grading, slope reinforcement, drainage) or (2) take operational steps to limit consequences of damage (e.g., periodic pipeline realignment to relieve stress, control potential loss of contents). Either option requires post-construction monitoring, although the type and frequency of monitoring are far less for option (1).
- Subsidence hazards that can practically be considered in pipeline design are related to subsurface removal of resources (e.g., water, oil, coal, etc.), drainage of saturated organic soils, and frost-heave and thaw settlement. Subsidence in karst terrains or hydrocompaction is often random and is generally difficult to identify and quantify. Approaches to address these random hazards are site and application specific and cannot be covered in detail in a general guideline document.
- Available models for estimating subsidence surface displacements associated with removal of resources at depth are only sufficient for assessing pipeline response if they provide estimates of both vertical and horizontal displacement patterns.

ASSESSING LANDSLIDE AND SUBSIDENCE HAZARDS TO PIPELINES

A fundamental question to be answered in performing an assessment of geohazard impacts on a new or existing pipeline is whether or not the desired level of performance has been achieved. The approaches in the guidelines assume that the performance requirements for the pipeline have been defined in a manner that permits some quantitative goals for the occurrence frequency for pipeline damage and consequences. The most important consequence of the rupture of a natural gas transmission pipeline is the potential for release and subsequent ignition of gas in areas where there is a potential for injury or significant property damage. Other consequences include service interruption and the cost of repair, cleanup, and restitution. Rupture of liquid hydrocarbon pipelines may have severe environmental consequences that are of equal or greater concern to the pipeline owner than potential safety issues and often govern the selection of performance requirements. However, in the majority of cases, current capabilities for assessing risk from landslide and subsidence hazards is not compatible with rigorous quantitative risk assessment practices often applied in other areas of engineering.

The guidelines do not establish acceptable levels of pipeline risk from which pipeline performance, expressed in terms of an acceptable annual probability of unacceptable response to geohazards, is defined. Decisions on performance requirements should be made on a case-by-case basis considering the governing risk measures (e.g., safety, environmental damage, operational disruption, economic loss, etc.) and local norms for risk tolerance. In most cases, it is considered reasonable to establish an upper-bound level of performance to be comparable to the performance requirements for non-pipeline projects, with similar consequences to the public (e.g., high-occupancy buildings, dams, bridges, LNG facilities).

Landslide Hazard Management

The general process for assessing multiple landslide hazards along a pipeline route and identifying appropriate mitigation measures is illustrated in the flow chart in Figure 1 and the process diagram provided in Figure 2.

Landslide hazard identification is assumed to begin with a qualitative assessment of available mapping and aerial photography to identify and rank areas of existing or potential slope instability. This is the typical first step for pipeline projects in areas where there has not been previous development. Various methods used for this initial landslide hazard assessment are identified in the guidelines. Landslides that are estimated to have mean recurrence intervals equivalent to the mean recurrence interval established by the pipeline performance requirements can be categorized as inactive. For example, a requirement that the annual probability of unacceptable pipeline performance be no greater than 0.0005 (1 in 2,000) would limit consideration of landslide hazards to those slopes with estimated mean recurrence intervals more frequent than 1 in 2,000 since this would accept a 100% chance of unacceptable pipeline performance. Considering that landslides that are currently stable require some triggering event, which is likely to be highly uncertain, and the limitation in establishing recurrence intervals for extremely rare slide movements, it is generally reasonable to consider landslides that are judged to have mean recurrence intervals of 10,000 years or greater (based upon an order of magnitude estimate) to be inactive, regardless of the pipeline performance requirements.

Initial qualitative assessments should result in the identification of slides crossing or in close proximity to the pipeline alignment and a ranking of the landslides according to the estimated probability of unacceptable pipeline performance. Such estimates may include a wide variety of factors, but the most important are generally the annual likelihood of movement, the slide dimensions, the expected direction of slide movement relative to the pipeline alignment, an estimate of the likely impact of landslide movement on the pipeline, and the consequences of unacceptable pipeline performance. Initial assessments will typically be highly qualitative.

From the initial ranking, potential landslide locations will be identified for which more detailed assessment of landslide hazards will be carried out (e.g., field investigations, landslide hazard mapping, slope stability calculations). The purpose of the additional investigations is to confirm whether or not a credible landslide hazard exists, develop a better understanding of the key characteristics of credible landslide hazards, and conduct more detailed assessments of the pipeline response to the hazard. Information on the landslide dimensions (boundaries and depth), the expected direction of landslide movement relative to the pipeline alignment, and soil strength allow a preliminary assessment to be made of the level of vulnerability of a pipeline to slide movement. As illustrated in Figure 2, it is likely that the additional investigations will modify the risk ranking and change the number and priority of landside locations for which some mitigation will be necessary.

In some cases, defining a set of possible landslide displacement scenarios for which pipeline response can be evaluated can be very useful in the ranking process. By evaluating pipeline response to various displacement scenarios, a likelihood of pipeline failure can be estimated and used to assist in the relative risk ranking identified in Figure 2. It is important to note that specifying potential displacement scenarios is for the sole purpose of assisting in relative risk ranking. As noted in the discussion of the ground movement hazard definition, current practice is not capable of providing reliable estimates of landslide displacement.

Simplified hand calculation procedures can be used for a preliminary assessment if the pipeline alignment is straight as it crosses the area of ground displacement and for several hundred meters outside of the area of ground displacement, the depth of soil cover and soil strength properties are constant, and the direction of ground movement is either purely parallel or perpendicular to the pipeline alignment. However, it is recommended that the assessment of pipeline response always be performed using finite element analyses that explicitly account for non-linear pipeline-soil interaction using the methodology provided in the guidelines.

Pipeline design measures can be sufficient to reduce pipeline vulnerability provided the pipeline design demonstrates that the computed pipeline stresses or strains resulting from landslide displacement are acceptable for any magnitude of displacement. However, implementing a pipeline design that can withstand unlimited displacement is generally either not feasible because of limitations on available right-of-way through the zone of ground displacement or practical because of the necessary increase in pipe wall thickness or material grade. This does not mean that pipeline design measures are not a key component of an overall risk management strategy. Increasing the ground displacement that can be safely sustained by the pipeline directly affect decisions with respect to the selection of appropriate geotechnical mitigation measures, the frequency for monitoring ground displacement or pipeline response, and the need for other operational mitigation measures over the life of the pipeline.

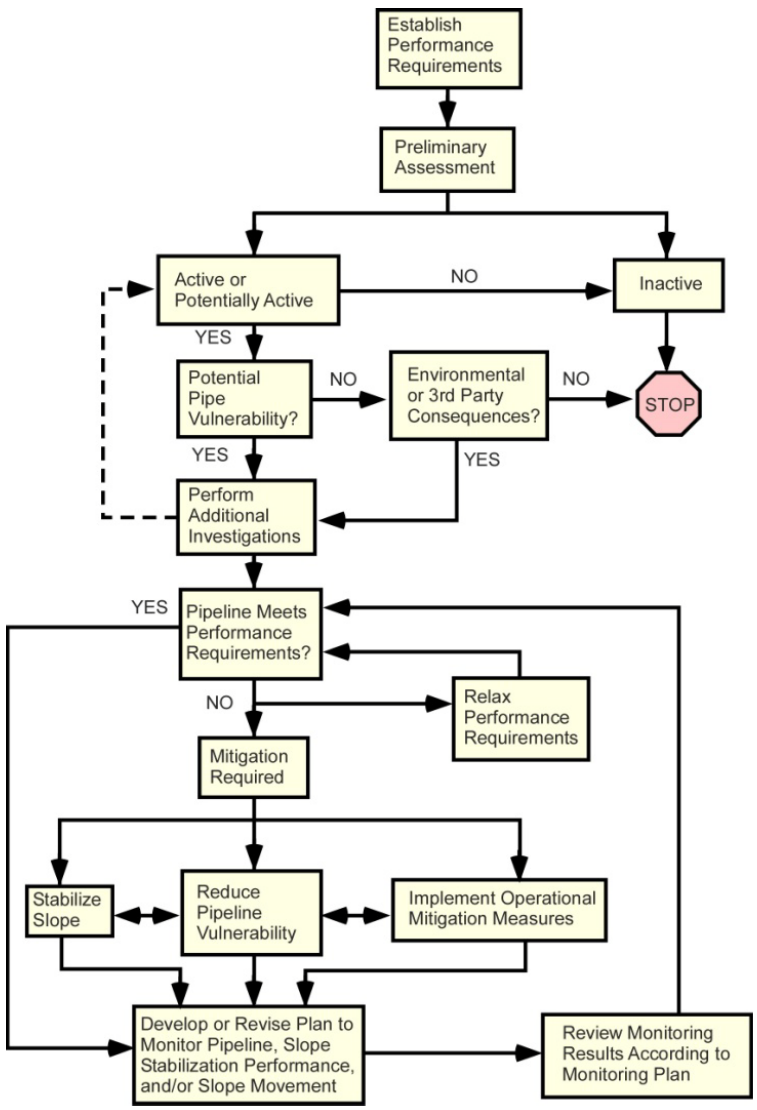

Figure 1. Flow Chart of Process for Management of Potential Landslide Hazards

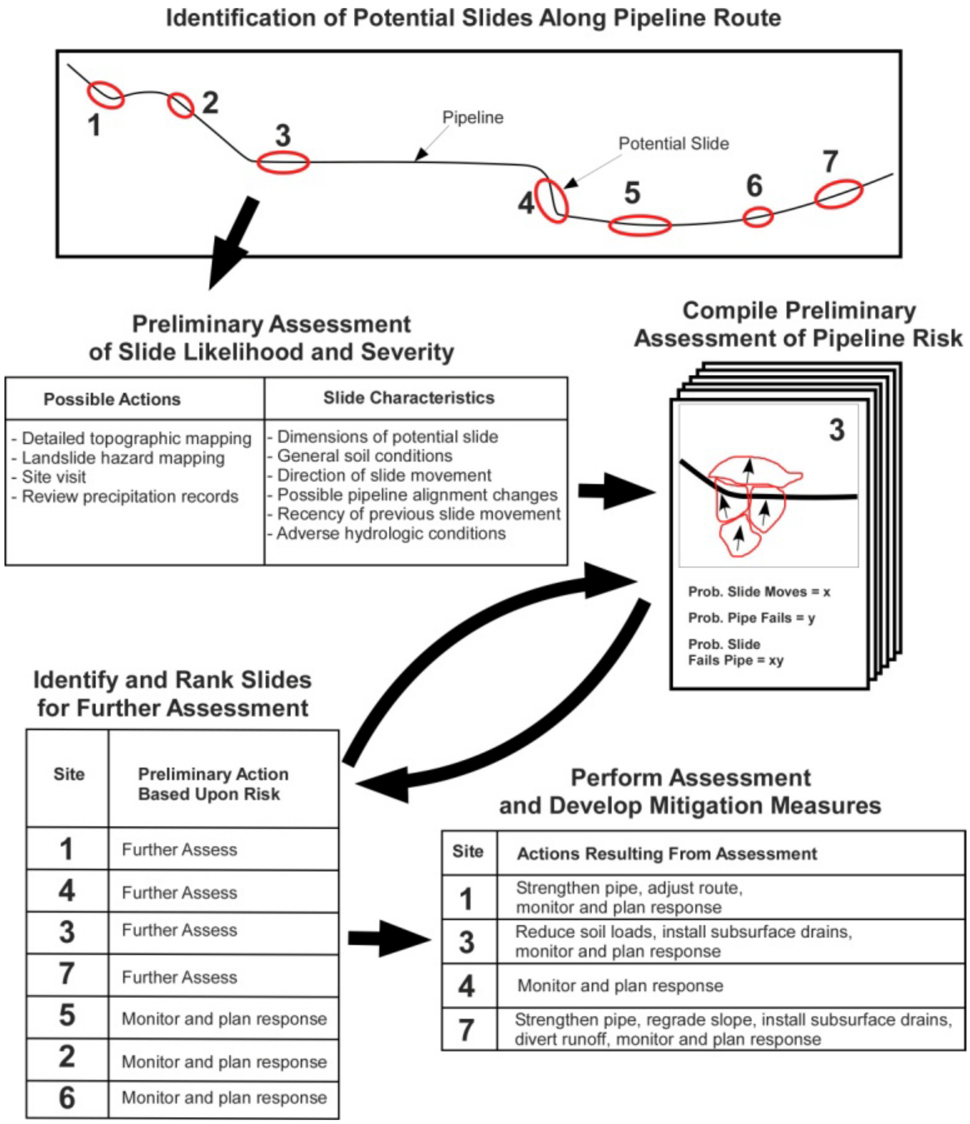

Figure 2. Process for Addressing Multiple Landslide Hazards Along a Pipeline Route

If the pipeline is assessed as not being vulnerable to the potential landslide hazard, an assessment of possible impacts of "third party" damage or environmental factors is necessary before the pipeline can be considered to meet the performance requirements. Third party damage generally refers to the consequences of actions undertaken by an individual or organization other than the pipeline operator or a contractor working on behalf of the pipeline operator. An example of third party damage relevant to the assessment of landslide risk would be an adjacent property owner stockpiling soil near the pipeline right-of-way that causes slope failure across the pipeline. Examples of environmental factors that could alter the assessment of existing slope stability include possible changes in adjacent land uses, deforestation from fire or insect infestation, and atypical weather patterns related to climate change.

If it is determined that the pipeline can be constructed such that it is not exposed to potential landslide displacements of significance, and there are no significant third party or environmental factors that would alter the current state of landslide hazard, then the pipeline meets the performance requirements no further investigation is required.

In cases where desired performance requirements cannot be met, there are several options. The most obvious is some relaxation of the performance requirement. Other alternatives rely on some combination of mitigation measures that can include slope stabilization, changes to pipeline design, operational measures, or a combination of all three. Slope stabilization will generally consist of combinations of (1) removing unstable soil material, (2) increasing internal soil strength through drainage, (3) reducing driving forces through grading, or (4) providing additional external resistance through buttressing, retaining walls, or tie-backs. Changes to reduce pipe vulnerability can include increasing pipe wall thickness or material grade and reducing soil loading through pipeline coatings or specialized backfill specifications. Operational measures will generally consist of (1) periodically alleviating pipe stresses through realignment or removal of backfill and/or (2) providing a means to minimize the consequences of pipe damage through containment and/or rapid shut-in of damaged pipe section.

A key recommendation in the PRCI guidelines is that periodic monitoring is required if a potential pipeline vulnerability exists. The specific types of data to be collected and the monitoring frequency are highly dependent upon the type of mitigation measures and the relative potential for adverse landslide conditions. The development and periodic review of a detailed monitoring plan are essential components of the overall mitigation process. Monitoring data are fed into the overall monitoring plan. The data may result in changes to the monitoring frequency or operating parameters. The data need to be used to continually assess if the pipeline still meets the performance requirements. If not, this may trigger when strain relief is required, further field investigations are necessary, or other mitigation options need to be considered and implemented. Thus, a continuous loop is put in place for monitoring, updating, and re-evaluation.

Subsidence Hazard Management

While the process for addressing subsidence hazards in pipeline design generally follows the same framework as previously discussed for landslide hazards (see Figure 3), there are some key differences related to the nature of subsidence hazards.

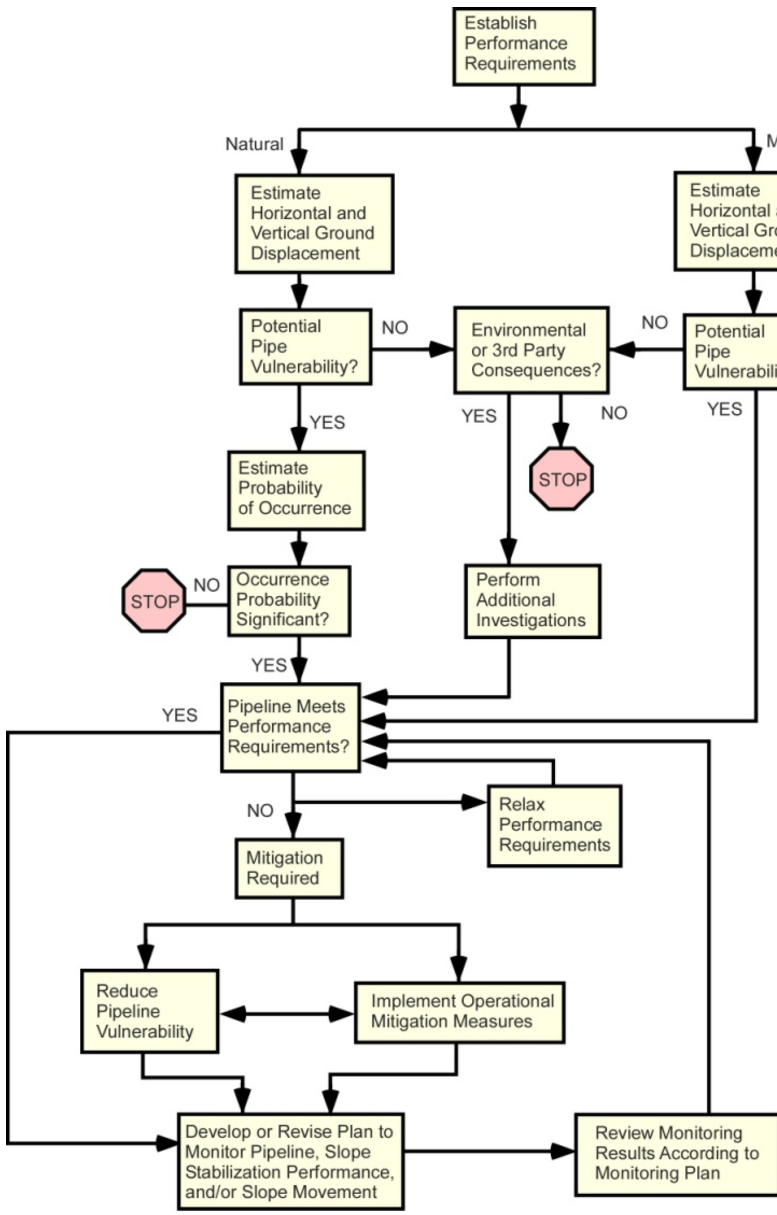

Figure 3. Flow Chart of Process for Management of Potential Subsidence Hazards

Subsidence arising from natural causes (e.g., hydro-compaction, sinkhole) is largely a random hazard with the likelihood and severity primarily based upon observations of historical patterns. For natural subsidence hazards, it may be possible to demonstrate adequate pipeline performance based upon a statistical assessment of the probability of occurrence of a subsidence event, such as illustrated in Figure 4, of sufficient magnitude to lead to unacceptable pipeline response (e.g., sinkhole size larger than what can be spanned by the pipeline). In reality, situations suitable for statistical quantification of natural subsidence hazards are rare. In general, the only practical approach to defining a natural subsidence hazard will rely on judgment and historical knowledge of past occurrences of subsidence.

Subsidence from mining differs from natural subsidence in two key respects. First, the location and time of occurrence of mining subsidence are largely known because of past and ongoing, or planned mining activities. For subsidence related to planned long-wall coal mining activity, there will typically be some uncertainty regarding the direction in which mining will progress. Second, the amount of mining subsidence can be estimated with a reasonable level of reliability based upon historical observations or analytical models.

Key parameters for defining natural and mining subsidence hazards include the length of pipeline impacted, the alignment of the pipeline through the subsidence zone, and the expected vertical and horizontal ground displacement relative to the pipeline alignment.

As with landslide hazards, pipeline vulnerability is assessed to determine whether or not the subsidence hazard poses a credible threat to pipeline integrity. The assessment of pipeline response to subsidence hazards is performed for a specific range of displacements for surface subsidence related to removal of subsurface resource, or a specific hazard depth and diameter for sinkholes.

Options to reduce pipeline vulnerability from subsidence hazards are largely limited to modifying the pipeline design or implementing operational measures to limit the likelihood of unacceptable pipeline performance. While there are some examples of geotechnical mitigation measures, such as filling in voids from past mining activities or modifying potentially collapsible soils, the applications have been primarily focused on limited sites for construction of surface facilities and are rarely practical to implement along a long pipeline alignment. Regular monitoring will typically be necessary to verify mining subsidence patterns are occurring as predicted. In areas where there is evidence that natural subsidence features are possible but are not expressed along the pipeline alignment, monitoring is necessary to identify onset of natural subsidence events that might adversely affect the pipeline.

ASSESSING PIPELINE RESPONSE TO GROUND DISPLACEMENTS

The recommended approach for performing an analysis of pipeline response to permanent ground displacement requires representing the condition of continuous pipeline embedment by discrete axial, vertical, and horizontal soil springs as illustrated in Figure 5. Movement of the surrounding soil with respect to the buried pipeline may force the pipeline to move with the soil or result in differential movement between the pipe and the soil. A key characteristic of soil loading is that it increases only to the point at which gross failure of the soil occurs. Capturing this characteristic requires a non-linear representation of the soil springs.

Figure 4. Cover-collapse Sinkhole in Mantled Carbonate Karst near Ocala, Florida (Photo by Tom Scott)

A comprehensive review of relationships developed to represent pipeline-soil interaction is contained in a 2003 report prepared by C-CORE [1]. The expressions for maximum soil spring force are based upon laboratory and field experimental investigations on pipeline response, as well as general geotechnical approaches for related structures such as piles, embedded anchor plates, and strip footings. Several of the equations have been derived to fit published curves to facilitate use in spreadsheets or other computer-based applications. The recommendations for defining soil springs for analysis of pipeline response in the landslide and subsidence guideline document include several modifications to the recommendations in the PRCI seismic guidelines published in 2004 [2] that are worth noting:

- Recent experimental investigations [3, 4] have confirmed that there is no increased lateral soil resistance in moist sand [5]. Lateral soil spring definitions are based upon dry sand as recommended in [4].
- Lateral soil resistance for drained and undrained loading in clays is based upon recommendations developed by C-CORE [1, 6].

- Recommendations for alternate axial soil resistance relationships are provided for sand considering conditions in which the sand may be dilative.
- Recommendations are provided for accounting for various trench effects based upon work by C-CORE [1] and Honegger et al. [3].

The soil spring definitions recommended for analysis are intended to be applied independently in a pipeline-soil analytical model. This assumption is a simplification of the highly complex interaction that occurs at the pipeline-soil interface.

It has long been recognized that there is some interdependence among the soil restraint acting on the pipeline. ASCE [7] discussed the issue of axial-lateral soil spring interaction in the description of the analytical approach of Kennedy et al. [8]. Past experience has demonstrated that the impact of higher axial soil loading on the pipe over the typically short length of pipeline experiencing relative lateral pipeline-soil displacements (typically less than 50 m) has negligible effect on the computed pipeline strains. The reason for this is that in situations where the axial soil load is an mportant contributor to pipeline strain, the maximum axial soil load will typically exist over hundreds of meters of pipeline, minimizing the impact of a local region with higher axial restraint.

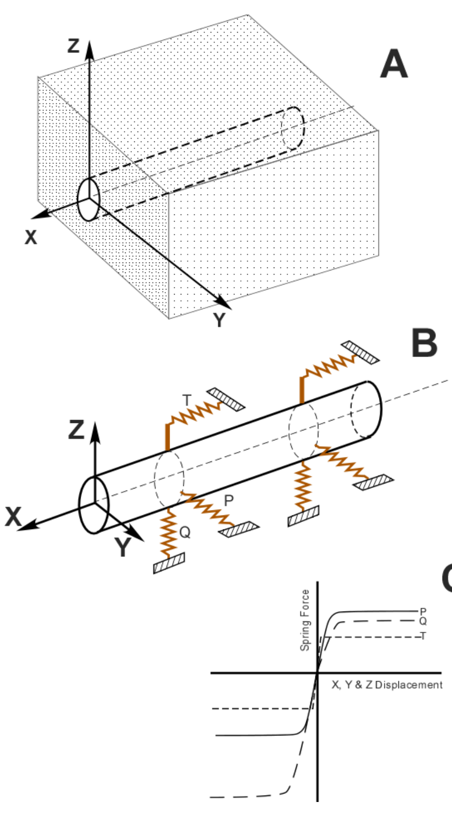

Figure 5. Spring Analog for Analyzing Pipeline-Soil Interaction

Analytical and centrifuge investigations performed as part of the PRCI project [6] reexamined the interaction of axial and horizontal soil forces. The C-CORE findings confirmed an increase in the same range as Kennedy et al. [8] for the axial soil load that could be transferred to a pipeline in sand in combination with horizontal pipe displacement through the soil. More importantly, the interaction envelope recommended by C-CORE and illustrated in Figure 6 requires that the horizontal soil spring force be reduced as a higher axial soil force is mobilized. Such reductions in horizontal soil spring force, even if they occur over a limited length of pipeline (e.g., 50 m), can significantly reduce pipeline bending strains.

The interaction curve developed by C-CORE exhibited differences with other research performed on axial-lateral interaction in sand that could not be readily explained during the course of the project. For this reason, the C-CORE sand interaction relationships are contained in the guidelines, but it is recommended that decisions on whether or not to incorporate interaction effects into an assessment of pipeline response be made on a case-by-case basis, considering the acceptability of the level of conservatism associated with not accounting for interaction.

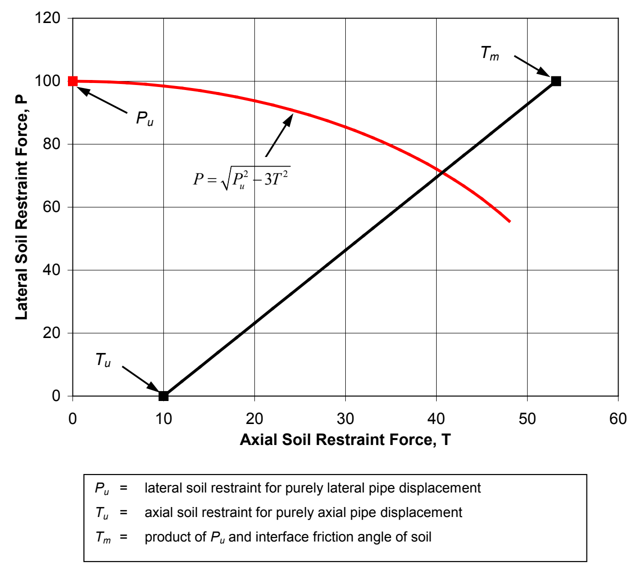

Figure 6. Example of Axial-Lateral Interaction Envelope Recommended by C-CORE

While there have been several notable advances in analyzing pipeline-soil interaction using three-dimensional continuum models, the recommendations in the guidelines are based upon modeling the soil as discrete springs acting on a pipe element. Several significant obstacles, many of which are shared by simple soil spring analogs, need to be resolved before continuum analysis methods can be considered superior to pipe element and soil spring representations. Even then, the level of improvement using continuum models must be sufficient to offset the substantial increase in effort to obtain a solution before continuum models can be recommended for routine engineering applications.

PIPELINE STRAINS FROM IN-LINE INSPECTION

Specialized in-line inspection (ILI) tools used to map the centerline of a pipeline are often referred to as geometry pigs.

Geometry pigs are capable of measuring pipe centerline orientation (pitch and azimuth) and odometer distance. From these measurements it is possible to determine coordinates that define the plan and profile of a pipeline. Flexural strains can then be deduced from the curvatures determined from the pipeline coordinates. As part of the PRCI project, efforts were directed toward developing an algorithm for deducing the centerline longitudinal or axial strain from geometry pig measurements of a laterally displaced pipeline. The approach in Hart et al. [9] is based upon changes in the pipeline geometry and in particular, changes in the pipeline curvature. The algorithm is limited to lateral displacements of the pipeline that result in a predominantly transverse loading; i.e., the induced transverse component of the loading is much greater than its axial component.

In long, straight sections of real pipelines remote from field and fabricated bends, the actual profile of the pipeline will not be perfectly straight. There are inevitable variations in the trench profile that will result in modest amounts of elastic "roping" curvature over distances of one to several pipe joint lengths. In addition to these "global" deviations from a perfectly straight pipeline profile, a geometry pig survey will undoubtedly highlight repeatable, low amplitude, short length noise features along the pipe profile (e.g., due to expander marks, longitudinal weld seams, weld beads, minor offsets and misalignments at girth welds, etc.). Although all of these features of the "as-built" pipeline geometry can show up as curvature in the data from a geometry pig survey, none of these features are associated with pipeline curvature due to imposed ground displacements. Therefore, the ideal framework for applying the approach of Hart et al. [9] is one in which there is a baseline geometry pig survey of the pipeline soon after construction. The lack of a baseline survey can be an impediment to the accuracy of strains deduced from curvature measurements. However, the loss of accuracy is generally no greater than any other approach, including various external gages and instruments and analytical modeling that rely upon assumptions regarding the as-built pipeline geometry. Moreover, the as-built strains are typically much smaller than the plastically-induced strains from ground movement and, in most instances, can reasonably be neglected in a structural integrity assessment.

The value of the technique developed in the PRCI project is demonstrated in Figure 7 in which some representative results from finite element simulations are compared with the strain estimate using the algorithm of Hart et al. [9]. The comparison covers large variations of displaced pipeline parameters, pipeline orientations relative to ground displacement, and types of ground displacements (e.g., landslide, subsidence, fault creep). It is clear from Figure 7 that the algorithm is generally capable of deducing the total pipeline longitudinal strain from geometry pig measurements within ±10% to ±20%.

A key factor in determining total longitudinal strain from geometry pig data is the gage length over which numerical differentiation of the pipeline orientation is performed. Specifically, selecting too large of a gage length will result in the curvature and, hence, the longitudinal strain being underestimated. Therefore, care must be exercised when selecting an appropriate gage length. An improved estimate for the curvature can be attained from curvatures computed for two different gage lengths and this estimate was used in the comparison in Figure 7.

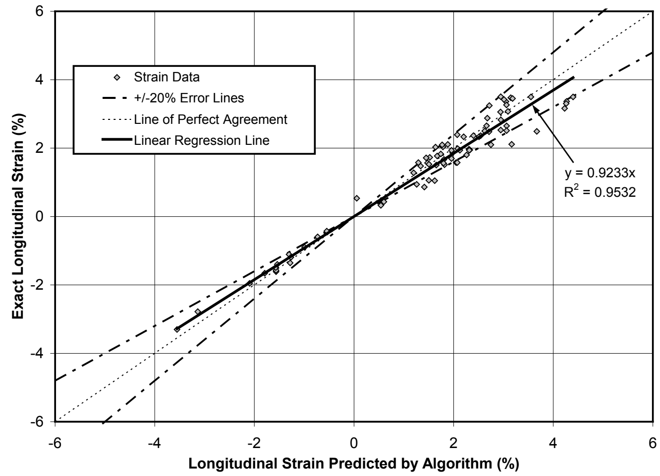

Figure 7. Comparison of Simulated Algorithm Strains and Actual Strains

Establishing a reliable estimate for the curvature is further complicated by noise in the geometry pig data signals resulting from pipeline irregularities, girth welds, etc. When a baseline survey of the "as built" pipeline exists, it can be used essentially to subtract the measurement noise traceable to pipeline irregularities from the measured signal. In the absence of a baseline survey, various means for filtering the geometry pig data are available. For example, it may be appropriate to filter the noise in the pitch and azimuth profiles utilizing a low-pass filter. An alternative approach that is often used to smooth out the data is to select a gage length when deducing the curvature that is several multiples of the pipe diameter (longer than the characteristic length of the noise features). This is a feasible approach provided that the selected gage length does not degrade the accuracy of the curvature measurement (i.e., the gage length must be sufficiently small compared to the characteristic length of the highly strained region of the pipeline, but large compared to the characteristic length of the noise).

FUTURE NEEDS

During project review meetings with PRCI, several needs have been identified for improving the guidelines document in the future.

A significant area of interest not addressed in the guidelines is the threat from earthquake-triggered slope movements. This topic area was specifically not included in the scope of the original guidelines in order to prevent seismic issues, which have the benefit of having a relatively well-understood triggering mechanism, from dominating the content of the document.

The geohazards guidelines document has purposely avoided discussions and recommendations revolving around what measures should be used to define performance and what levels of performance should be acceptable. The approach in the guidelines is to assume that the user has already determined how performance is measured and what level of performance is acceptable. While this is likely the case for users that must deal with geohazards on a more or less routine basis, other users could have difficulty making these decisions. One reason for not delving into the issue of performance requirements is the fluidity of recommendations within the industry, particularly with respect to events that might never occur during the design life of a pipeline (i.e., average occurrences of once in several hundred years). Specifically, there are issues that need to be resolved regarding whether or not performance goals for normal operation are equally applicable to hazards typically categorized as “force majeure.”

One approach to assist users in making performance decisions is to provide them with examples of performance metrics and acceptable performance from past projects undertaken by others. Another approach is to develop a weighted parameter process, accounting for factors related to safety, reliability, economics, and public perception of risk, which leads to a “score” associated to a performance requirement. This weighted parameter process could be similar to the approach used in American Lifelines Alliance guidelines for assessing the performance of oil and natural gas pipeline systems for natural hazards human threats events [10] for defining the level of effort appropriate for resolving questions related to oil and gas pipeline risk.

As noted in the paper, there remain some questions regarding the applicability of soil restraint definitions for the interaction between relative axial and horizontal ground displacements. Part of this uncertainty is related to differences in characterization of axial-lateral pipe-soil interaction between C-CORE data and data by others. These differences need to be investigated and resolved. Support for the interaction relationships developed by C-CORE may also be available if pipe-soil interaction tests performed as part of a proprietary research project could be made available for review.

ACKNOWLEGEMENTS

The PRCI project was undertaken by three contractors, D.G. Honegger Consulting, C-CORE, and SSD, Inc. and the contributions of several organizations and individuals are gratefully acknowledged. An ad hoc steering group for the guidelines project was established by PRCI and chaired by Mr. Richard Gailing. This steering group provided technical review and PRCI approval of the final report. Dr. James Merritt, the PHMSA Organization Program Coordinator for the project, participated in the initial project meetings and provided suggestions that assisted in defining level of detail and areas of emphasis for the guidelines. Dr. Rex L. Baum, Dr. Devin L. Galloway, and Dr. Edwin L. Harp at the U.S Geological Survey (USGS) provided much of the material related to the state-of-practice on landslide and subsidence hazard identification under a cooperative research and development agreement. Their summary is published as USGS Open File Report 2008-1164. Individuals assisting in the preparation of the guideline with expertise in geotechnical engineering, landslide hazard evaluation and risk assessment, pipeline geohazards risk assessment, and techniques and methods for general monitoring of pipeline alignments and location-specific landslide monitoring included Mr. Raymond Boivin of Plateau Engineering Ltd., Mr. Richard Butler of Golder Associates Ltd., and Mr. Moness Rizkalla of Visitless Integrity Assessment Ltd. An ad hoc steering group for this project was established by PRCI to provide technical review and PRCI approval of the final report. In addition, valuable review of the guidelines document was provided by Dr. Jeffrey R. Keaton of MACTEC Engineering and Consulting, Inc. and Mr. Mark E. Schmoll of URS Corporation.

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