GEOTECHNICAL RISK ASSESSMENT:
ESTIMATING SLOPE FAILURE PROBABILITY

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The TransCanada Pipelines Ltd. (TCPL) mainline system carries natural gas from the Alberta/Saskatchewan border to delivery points near the Quebec/Vermont border. The system contains pipelines that traverse approximately 4,000 kilometres (2,500 miles) of terrain and delivers about 2,900 Bcf of gas per year. As part of the integrity program this system has been subjected to a geotechnical hazard identification and assessment program over the last several years. The geotechnical hazard assessment process has identified hazardous sites and specific studies at these sites have been undertaken.

TCPL has recently begun a transition from performing Hazard Management to an overall Risk Management approach for pipeline integrity. As part of this process TCPL required that a geotechnical risk methodology be developed to analyze the risk posed to the pipeline due to landslides. Therefore a new landslide failure probability estimation process was developed to complete this program.

The failure probability estimation process developed considered one geotechnical hazard, a landslide of sufficient size that it would affect the pipeline. The estimation procedure used to assess the various sites was a “quantitative risk assessment procedure” (QRA). The QRA is a quantification of a Failure Modes and Effects Analysis (FMEA). The QRA process allows assessment and ranking of the likelihood of failure and/or the risks of various components within a system. The QRA methodology is a powerful screening tool that highlights areas of concern at any given site and allows comparison between sites. The landslide failure probability quantified during this process is then comparable to other risks to pipeline integrity.

The elemental failure modes for sliding were identified and ranked in the QRA based on the landforms and geological conditions in which the pipeline is located. Two failure modes: a simple slide and earthflow failures were identified and evaluated.

The life time failure probability was determined by assessing the potential causes of the slide. Each potential cause or sign that movement was occurring was identified and assigned a subjective probability that the individual cause would trigger a movement large enough to affect the pipeline. This was accomplished subjectively by an expert team assembled for this purpose.

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INTRODUCTION

The TransCanada Pipelines Ltd. (TCPL) mainline system carries natural gas from the Alberta/Saskatchewan border to delivery points near the Quebec/Vermont border. The system contains pipelines that traverse approximately 4,000 kilometres (2,500 miles) of terrain and delivers about 2,900 Bcf of gas per year. The location of the TCPL mainline system is shown in Figure 1. As part of the integrity program this system has been subjected to a geotechnical hazard identification and assessment program over the last several years. The geotechnical hazard assessment process has identified hazardous sites and specific studies at these sites have been undertaken.

The geotechnical hazard assessment process identified over 300 discrete geotechnical hazard sites in an initial phase of study. Following the initial hazard rating process, detailed rating was performed according to site specific attributes and 54 sites were rated as having a high geotechnical hazard. Detailed studies for 33 of these high hazards sites have been performed, including installation of geotechnical instrumentation and making predictions concerning slope movement based on stability calculations.

TCPL has recently begun to manage pipeline integrity through the use of risk management. The risk management approach attempts to compare all hazards to pipeline integrity based on a probability of failure basis. In order to compare the risks presented by geotechnical hazards, determination of the probability of failure is required. Estimation of the geotechnical risk required the development of a new method to estimate the probability of failure.

The overall geotechnical risk analysis methodology developed consists of a number of distinct steps; estimation of the probability of slope failure occurring, estimation of the probability of pipeline failure due to the slope failure and determination of the consequences of failure. This paper describes the method developed and used to estimate the probability of slope failure. The methodology used to determine pipeline failure due to slope movements has been described previously (Zhou et al. 2000).

DEVELOPMENT OF RISK ANALYSIS PROCEEDURE

The term risk can be generally defined as the combination of the likelihood (P_H) of a specified hazard H being realized, and the consequences of the event (harm and/or damage), (C_H). In many instances the combination takes the form of a multiplication, thus leading to the risk $R_H = P_H \times C_H$.

The hazard presented to a pipeline by slope movements is not directly related to the slope movement itself, but is related to the stress induced by the slope movement on the pipeline. The amount of stress transferred from the soil to the pipeline is a function of many factors, which include the pipe coating, the soil surrounding the pipeline, the length of pipeline affected by the movement, pipe curvature, the presence of weights or valves, and the rate of the pipeline movement. Previous papers have described the method (Zhou et al. 2000) which translates soil movements into pipe stress. When the magnitude and direction of the stresses applied to the pipeline due to slope movements are determined, they can be compared to the allowable stress in the pipeline.

The methodology of converting movement into pipe stress does not present the full risk profile due to ground movements. For example if the methodology described above is used by itself, a site with no measured movement has no risk, even if the there is no measured movement because no monitoring capabilities are in place. Therefore a methodology of determining the probability of failure was developed at the high geotechnical hazard sites or both sites that have measured movement and sites where either movement has not been measured or no monitoring has yet been installed. The probability of a landslide occurring, P_L, determined in this process can be used to prioritize future detailed investigations.

The general procedure used to assess the failure probability was a quantitative risk assessment procedure (QRA), which was previously developed jointly by BGC Engineering Inc. and Oboni Associates (Abbot et al. 1998). The QRA is a quantification of a Failure Modes and Effects Analysis (FMEA). The QRA process allows assessment and ranking of the likelihood of failure and/or the risks of various components within a system. The QRA methodology is a powerful screening tool that highlights areas of concern at any given site and allows comparison between sites. The geotechnical risks quantified during this process are then comparable to other risks to pipeline integrity.

There are seven simple steps required to undertake a QRA; define the system, identify the hazards, identify hazards and elemental failure modes, combine elemental failure modes into compound failure modes, assess the probability of occurrence, estimate the consequences and present the results. The estimation of consequences was not performed as the consequences have been separately estimated for all types of hazards.

For the purpose of this process one geotechnical hazard was assessed, a landslide of sufficient size that could affect the pipeline. A landslide is defined as “the movement of a mass of rock, debris or earth down a slope” (TRB 1996). Two elemental failure modes were identified based on the landforms and geological conditions through which the pipeline travels; a slide and an earthflow. A slide is a downslope movement of a soil or rock mass occurring dominantly on surfaces of rupture or on relatively thin zones of intense shear strain. An earthflow is a spatially continuous movement in which surfaces of shear are short-lived, closely spaced and usually not preserved (TRB 1996).

Definition of the system was required for the two categories of landslides, slide and earthflow. For both the slide and the earthflow the boundary used was the widest limit that would contain an event that could directly or indirectly impact the pipeline. In practice this definition means that the area considered for a slide is limited to the crest to crest area of the valley and the area immediately around the ROW. For the earthflow failure this area is expanded, since the trigger location can be beyond the ROW and still affect the pipeline due to the retrogressive nature of the earthflow.

The probability of failure determination procedure consisted of two main components; hazard identification and failure probability estimate in terms of likelihood of occurrence. Failure probability was assigned subjectively by the expert team in accordance with the matrix in Figure 2. The first step was to determine the overall state of the system, in accordance with the expert opinion of the site. Then each individual factor listed in Figures 3 through 5 where assessed in terms of the likelihood that the factor would have an influence, and the magnitude of that influence. Each individual factor was assigned a subjective probability from Figure 2 based on the likelihood of influence (in accordance with the state of the system column) that was thought to exist at the site.

The development of the QRA methodology to determine failure probability at each river crossing consisted of the following main tasks:

- Develop a system to assess the level of knowledge for the site and the relative importance of the factors which define the knowledge of the site. This system is presented in Figure 3;
- Develop a system to assess the factors important to slide development and the relative importance of these factors. This system is presented in Figure 4; and,
- Develop a system to assess the factors important to earthflow development and the relative importance of these factors. This system in presented in Figure 5.

The risk estimation was performed by assessing the potential causes of either a slide or earthflow. Each potential cause or sign that movement was occurring was assigned a subjective probability, according to Table 2, that the individual cause would trigger a movement large enough to affect the pipeline. The expert team accomplished the estimation according to the following steps:

1. Description of the site conditions
2. Description of the performance of the site
3. Description of the performance of areas adjacent to the site

RISK ANALYSIS

General Information

In order to make an estimate of the accuracy of the failure probability, the level of knowledge about the site was assessed. Table 3 presents the seven categories of information that were assessed to determine the state of knowledge of the site. The relative importance of the seven categories is also included in Table 3. This assessment was performed by assigning a probability to each of the categories shown in Table 3 based on the level of knowledge in each category.

One additional factor was used to determine the accuracy of the state of knowledge. If none of the expert panel members had visited the site, the resulting accuracy of the failure probability estimation was considered to be half that of sites where the site had been visited by at least one of the expert panel.

The value determined from the general information was used to define the accuracy of the probability of sliding. This was accomplished by assuming that the most accurate assessment possible, a probability of 1 for general information, would correspond to the sliding probability being within 10% (15% if the site was not visited) of an order of magnitude of the estimated value. The least accurate assessment possible, a probability of 10^{-5}, was assumed to correspond to the probability of sliding being within one (one and a half of an order of magnitude if the site was not visited) order of magnitude of the estimated value. A linear interpolation was used between these two extremes.

Sliding

For the assessment of the sliding failure the state of the system was established separately for each site by considering the following: soil/rock type, slope height, slope angle, presence of mitigation works, size of the water course and location of the site in the meander loop (outside bend being critical). These factors defined the column to be used in Table 2 when assessing the factors that could cause a slide.

The assessment of the probability of a slide occurring was assessed by considering the factors: toe erosion, scour, bank failures, external water source to slope, seepage exiting on the face of the slope, piezometric conditions, earthquake, loading at the crest, tension cracks, compression ridges, headscarp and damage to vegetation. These factors used to assess the probability of a slide, consist of three general categories: factors that could trigger a slide, factors leading to a general lowering of the factor of safety and factors which indicate that movements have occurred or are currently occurring.

As mentioned previously, the probability of sliding considers only landslides of sufficient size that they would affect the pipeline. Smaller slough failures were therefore not considered in this assessment, although these slough failures likely have a higher probability of failure than the larger failures. The effects of the smaller slough type failures were included, by determining the probability that a smaller failure may lead to a larger failure. The weighting factors on Figure 4 indicate the relative importance of the factors on the likelihood of a slide failure.

A subjective probability was assigned to each of the categories according to whether the factor would lead to a slide failure on a particular site. This assessment included determining the state of the system for the site and then assigning to each factor the subjective probability as outlined in Figure 2.

The probability of failure at each site was determined during the QRA is presented in Figures 6. The error bars included on the plot were determined from the general information.

EarthFlow

An initial screening exercise based on the general soil type and slope instability history identified that 11 of the 56 sites had the potential to develop a retrogressive earthflow.

Given that earthflow failures are initiated by an initial slide failure, the probability of an earthflow developing was assessed in two parts. The first was an assessment of the probability that retrogression could develop at the site. The second part combined the results of the probability of an initial slide and the probability of retrogression to determine the probability of an earthflow developing at the site. The subjective probability was assigned to each of the following factors to determine the probability of retrogression developing:

- Presence of previous earthflows
- Sensitivity
- Remolded shear strength
- Energy
- Outlet to flowing soil

The weighting factors on Figure 5 indicate the relative importance of the factors on the likelihood of an earthflow failure developing.

The probability of an earthflow developing was determined for 11 sites. The results are presented in Figure 7.

Conclusions

This paper has presented a methodology of quantitatively estimating the probability of a landslide occurring at a particular site. The modified QRA method includes a method to estimate the accuracy of the subjective determined failure probability.

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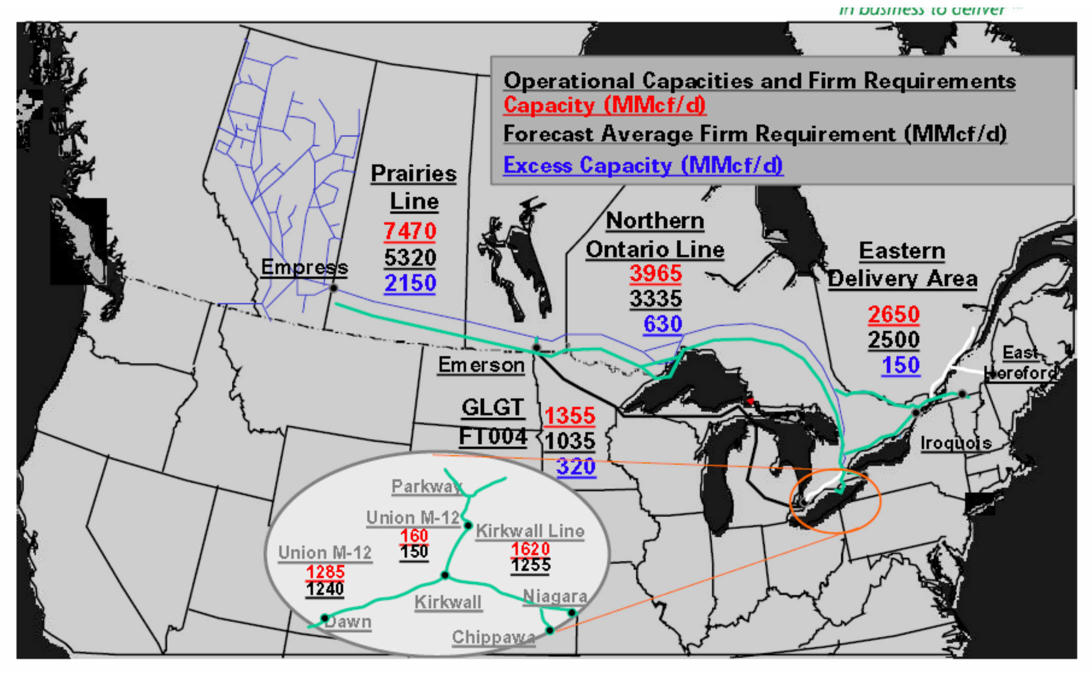

Figure 1: TCPL Mainline System

		State of the System		
Likelihood of Parameter Having an Influence		Good	Moderate	Poor
		G	M	P
Very High Likelihood of Influence	VH	10^{-1}	5×10^{-1}	1.0
High Likelihood of Influence	H	10^{-2}	5×10^{-2}	10^{-1}
Moderate Likelihood of Influence	M	10^{-3}	5×10^{-3}	10^{-2}
Low Likelihood of Influence	L	10^{-4}	5×10^{-4}	10^{-3}
Negligible Likelihood of Influence	N	10^{-5}	5×10^{-5}	10^{-4}

Figure 2: Subjective probability assessment table

General Information

		Weighting	Subjective Probability	Summation
Natural Hazard Maps	Area is covered and Map is Checked	0.05		0.00E+00
Geological Maps	Area is covered and Map is Checked	0.05		0.00E+00
Aerial Photos	Area is covered and Photos Checked	0.1		0.00E+00
Preceeding Regional Study	Quanity and Proximity of the Study	0.1		0.00E+00
Preceeding Specific Study	Quality of the Study	0.45		0.00E+00
Monitoring Equipment Present	Type and Quantity of Instrumentation	0.05		0.00E+00
Present Monitoring Activities	Frequency of Measurement	0.2		0.00E+00
	Total	**1**		0.00E+00

Figure 3: General Information Assessment Form

		Weighting	Subjective Probabilty	Summation
Slides	Toe Erosion	0.25		0.00E+00
	Scour	0.05		0.00E+00
	Bank failures	0.05		0.00E+00
	External Water source to slope	0.05		0.00E+00
	Seepage exiting on face of slope	0.05		0.00E+00
	Piezometric Conditions	0.1		0.00E+00
	Earthquake	0.1		0.00E+00
	Loading at the Crest	0.1		0.00E+00
	Tension Cracks	0.1		0.00E+00
	Compression Ridges	0.05		0.00E+00
	Headscarp	0.05		0.00E+00
	Damage to vegetation	0.05		0.00E+00
	Total	**1**		
			Total	
			Pf	0.00E+00

Figure 4: Slide Assessment Form

Soil Slope

		Weighting	Subjective Probability	Summation	
Retrogression	Presence of Previous Earth Flow	0.2		0.00E+00	
	Sensitivity	0.2		0.00E+00	
	Remolded Shear Strength	0.25		0.00E+00	
	Energy Term	0.25		0.00E+00	
	Outlet to flowing soil	0.1		0.00E+00	
	Max Total	**1**			
			Total	0.00E+00	
			Pf		retrogression
	Pf(landslide)*Pf(retrogression)	=	**Pf**		retrogressive landslide

Figure 5: Earthflow Assessment Form

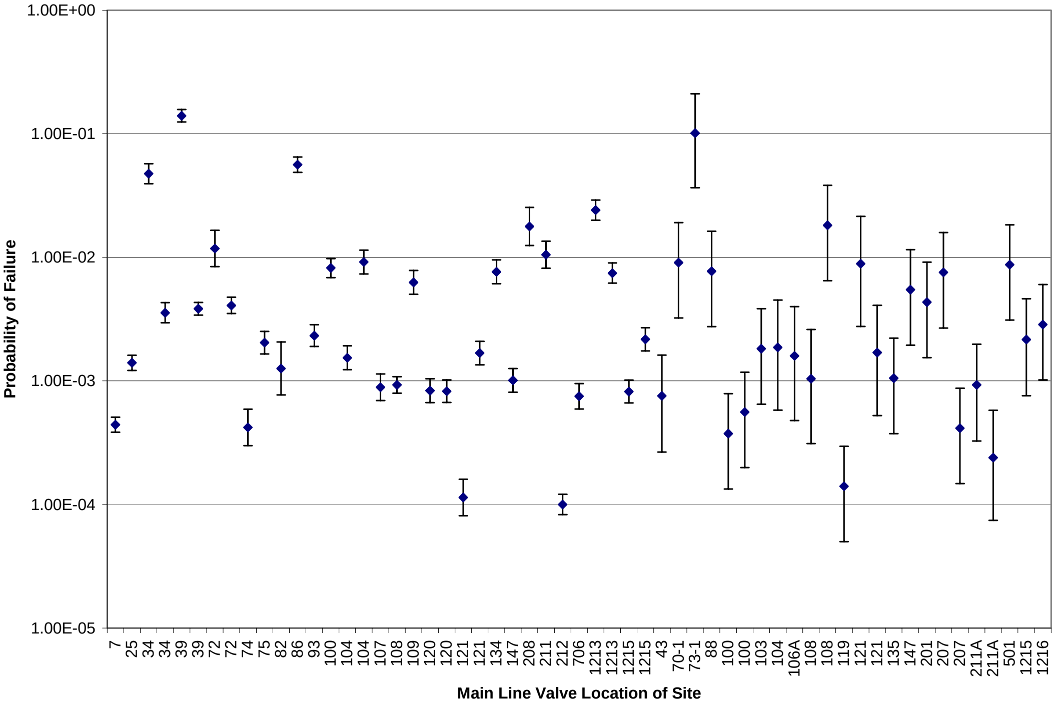

Figure 6: Results of Slope Failure Probability Assessment

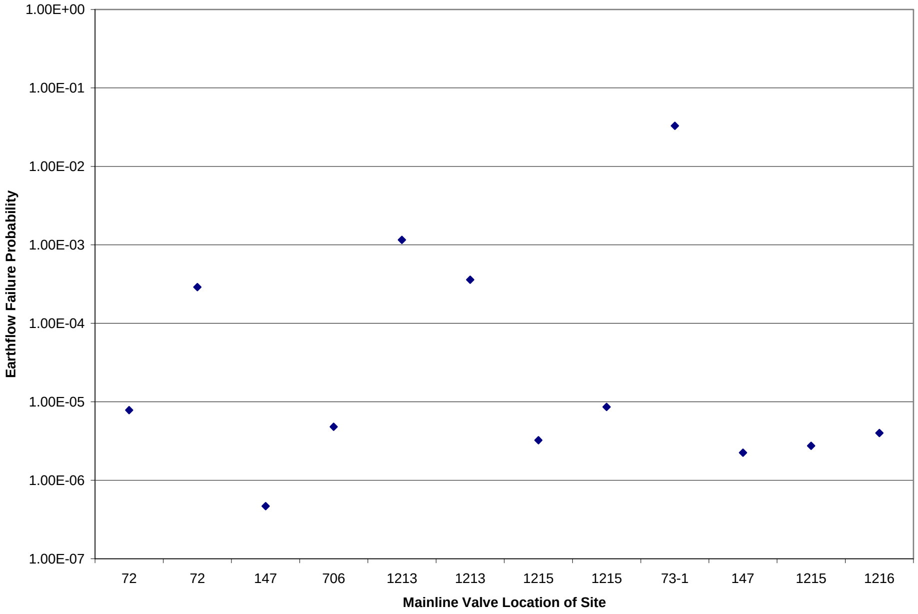

Figure 7: Results of Earthflow Failure Probability Assessment