

ESTIMATING THE INFLUENCE OF NATURAL HAZARDS ON PIPELINE RISK AND SYSTEM RELIABILITY

Michael Porter, M.Eng., P.Eng., LEG
Clint Logue, P.Eng., P.Geo., LEG
Dr. K. Wayne Savigny, P.Eng., P.Geo.
Fiona Esford, M.A.Sc., P.Eng., LEG
Dr. Iain Bruce, P.Eng., P.Geo.

BGC Engineering Inc.
500-1045 Howe Street
Vancouver, BC, Canada
Tel: (604) 684-5900 Fax: (604) 684-5909
www.bgcengineering.ca

ABSTRACT

Natural hazards (also known as ground movement or geohazards) can cause pipeline failures, with consequences ranging from injury/death, environmental impact, and property damage, to lengthy service disruption and a failure to achieve delivery targets. In North America and western Europe, pipeline failures resulting from natural hazards are typically rare (but costly) events. However, where difficult ground conditions have not been properly accounted for in pipeline design, construction, and operation, natural hazards may have an overriding influence on pipeline risk and reliability. These issues are discussed, and a framework for estimating the influence of natural hazards on pipeline risk and system reliability is introduced.

Keywords: Natural Hazards, Ground Movement, Geohazards, Reliability, Quantitative Risk Assessment

INTRODUCTION

Natural hazards (often referred to as ground movement or geohazards) are recognized by the pipeline industry as a potential cause of pipeline incidents. A cursory review of data from North America and western Europe suggests that natural hazards are not a major contributor to pipeline failures when compared to other causes such as third party impact, corrosion, and material defects. Upon closer inspection, however, the *risk* posed by natural hazards is proportionally quite significant.

Furthermore, where geologically active terrain is encountered and not properly recognized during pipeline design, construction, and operation, natural hazards may have an overriding influence on pipeline risk and system reliability. We provide some examples from Canada and South America that illustrate this point.

We review a number of available options for incorporating natural hazards into pipeline risk and integrity management programs. A framework that relies upon collection and review of pipeline and hazard attributes, as well as assessment of relevant historical incident data, to assign subjective probabilities of natural hazard occurrence and pipeline failure is introduced. The process is carried out using a phased approach to focus resources at the locations where pipeline failure is most likely to occur and where the risk of failure is greatest. Uncertainty associated with estimates of hazard likelihood and probability of pipeline failure decrease with each phase of study.

NOMENCLATURE

If we are to discuss techniques for understanding hazard exposure and estimating pipeline risk and reliability, we should use standard terminology. What follows is taken from the CAN/CSA-Q850 Risk Management Guideline for Decision-Makers [1], and a number of leading technical publications on risk assessment in engineering practice [2, 3, 4, 5].

Hazard refers to a condition with the potential to cause failure of the pipeline system or an undesirable effect on the system. A natural hazard is simply a hazard of hydrological, geological or tectonic origin.

The estimated annual probability of a hazard occurring is referred to as the Hazard Likelihood (H_p). Probability is a scale of measurement used to describe the likelihood of an event. It ranges from 0 (certain not to occur) to 1 (certain to occur). The probability of a hazard can be defined on the basis of a relative frequency of occurrence or as a subjective probability of occurrence.

Each occurrence of a natural hazard does not necessarily lead to an undesirable effect on a pipeline system. The potential for a failure depends on a number of factors, including the type and magnitude of the hazard, its proximity to the pipeline system, the pipeline's attributes and operational regime, and the presence of protective measures. Vulnerability (V) describes a measure of the susceptibility of a system to failure should a hazard occur. The scale on which vulnerability is measured extends from 0 to 1, inclusive, where a value of 1 indicates a certainty of failure.

We define the Probability of Pipeline Failure (p_f) as the product of Hazard Likelihood and System Vulnerability:

$$[\text{Eqn. 1}] \quad p_f = H_p * V.$$

Pipeline failure at a preliminary screening level is assumed to result in a leak or rupture and a temporary loss of ability to transport product.

Reliability (R) is simply a measure of the probability of no failure occurring, taken as:

$$[\text{Eqn. 2}] \quad R = 1 - p_f.$$

Pipeline failure may result in a wide range of impacts. This may include injury or death, loss of product, environmental impact, property damage, repair costs, inability to meet delivery contracts, loss of reputation, or the revocation of a license to operate. These collectively are referred to as the Consequence of Failure (C), and for simplicity are often expressed in monetary terms.

Risk is defined as the probability of failure multiplied by the consequence of failure, given by:

$$[\text{Eqn. 3}] \quad \text{Risk} = H_p * V * C.$$

A word of caution is required, however, as two scenarios may present the same risk value, but have different levels of acceptability. For example, an owner might be more comfortable with a 10% chance of incurring a \$1 million loss each year than with a 0.1% chance of losing \$100 million, despite the fact that the calculated risk is identical in both scenarios. The issues of risk perception and risk tolerance are important, but beyond the scope of this paper.

NATURAL HAZARDS AFFECTING PIPELINES

A variety of natural hazards can threaten the safe and efficient operation of pipelines. We can divide these hazards into three broad groups, Geotechnical, Hydrotechnical and Tectonic hazards.

Geotechnical hazards include processes such as landslides, debris flows, ground settlement and subsidence, and soil heave. Common triggers for these hazards include changes in groundwater conditions, erosion at the toe of slopes, thawing of permafrost, and freezing of frost-susceptible soils. Earthquakes can also trigger

geotechnical hazards, but tend to play a minor role in all but the largest magnitude events.

Hydrotechnical hazards are those directly associated with stream processes. They include scour, channel degradation, bank erosion, encroachment, channel avulsion and debris impact. The process of channel encroachment is identical to that of bank erosion, but involves a section of pipeline trending parallel (as opposed to across) a stream. Debris impact can occur where poorly designed aerial crossings have been constructed over streams capable of transporting large woody debris. Hydrotechnical hazards are largely triggered by flood events, and, in the case of small streams, by local precipitation. Disturbances to stream channels, including the affects of landslides, change in forest cover upstream, or the presence of poorly designed river control structures, can also increase hazard potential.

Tectonic hazards include processes associated with earthquakes and volcanism, including tsunamis, fault rupture, volcanic eruption, and soil liquefaction. These events occur rarely, but their impacts can be felt over a very large region causing damage to multiple pipelines and/or several sections of pipeline at the same time. As a result, the contribution of tectonic hazards to overall pipeline risk can be significant.

Expanded descriptions for the majority of these natural hazard types can be found in our earlier publications, notably: [6, 7, 8, and 9].

SIGNIFICANCE OF NATURAL HAZARDS

The relative significance of natural hazards is often underestimated by the pipeline industry and a brief review of published western European and U.S. incident data indicates why. The European Gas Pipeline Incident Data Group [10] reports that natural hazards only accounted for 7% of all pipeline incidents between 1970 and 2001 in Western Europe (Figure 1). External interference is cited as the leading cause (50%), followed by construction and material defects (17%), and corrosion (15%).

U.S. DOT natural gas transmission data for the period 1984 to 2001¹ [11] indicate external interference (37%), corrosion (23%), and construction defects (14%), are leading causes of pipeline incidents in the United States, with natural hazards only contributing to about 8.5% of incidents (Figure 2).

Data recently published by the National Energy Board for Canadian Regulated pipelines [12] indicates the leading cause of failure during the period 1991 to 2001 was corrosion (57%), followed by operator error (15%), with natural hazards contributing to about 12% of incidents (Figure 3).

¹ US DOT OPS data analysis for incidents on gas transmission lines greater than 2" diameter [11].

These failure frequency statistics do not tell the whole story. Pipeline incidents caused by natural hazards often result in larger leaks, greater property and environmental damage, and longer periods of service disruption than other hazard types. For example, natural hazards are the second leading cause of pipeline *rupture* (as opposed to holes and pinhole-cracks) in western Europe (Figure 1).

The average cost of a rupture is expected to be greater than for an incident resulting in a hole or small pinhole-crack, an assumption that is supported by U.S. DOT OPS incident data [11]. In the United States, property damage resulting from a typical pipeline failure caused by ground movement has an average cost in excess of \$430,000 U.S., over double that for other hazard types. As a result, earth movement-related gas pipeline failures have caused more property damage in the United States since 1984 than corrosion, and are only exceeded by costs associated with third party impact (Figure 2).

The relative significance of natural hazards is even more pronounced where pipelines are constructed in difficult terrain without full appreciation for natural hazard exposure. In South America, for example, the authors have been involved with several pipelines where natural hazards are clearly the leading cause of failure, with failure frequencies approaching 5 per 1,000 km.yr observed in extreme cases. Data for a typical pipeline indicate that natural hazards may be responsible for as many as 50% of the pipeline incidents in the South American Andes [13], leading to an average failure frequency exceeding 2.5 per 1,000 km.yr (Figure 4). This frequency is about 2 orders of magnitude greater than experienced in western Europe.

Closer to home, pipelines in British Columbia must also traverse difficult terrain. Analysis of British Columbian Oil and Gas Commission pipeline incident data for the period 1980 to 2003 [14] indicates that natural hazards are the second leading cause of transmission pipeline incidents, accounting for approximately 22% of failures (Figure 5).

The influence of natural hazards on pipeline risk and reliability is further emphasised by the fact that the statistics reported here are for a relatively short time period, typically 25 years or less. Thus, most pipelines in operation have not yet experienced their 1:100 year storm, 1:100 year flood event or 1:475 year earthquake.

Finally, natural hazards can contribute to the disbondment of old pipeline coatings, aggravate corrosion, and lead to stress corrosion cracking. The contribution of natural hazards is not always acknowledged and is likely under-reported in the failure statistics.

ESTIMATING RELIABILITY AND RISK Objectives and Available Approaches

In the fields of pipeline risk and integrity management, standard practice requires us to inventory hazardous conditions and allocate resources to sites posing

the greatest level of risk. This does not necessarily require that quantitative estimates of the probability of failure are obtained, rather that the relative probabilities and consequences of failure be weighed against each other in a systematic way when making management decisions. We briefly compare the objectives and available approaches for pipeline risk estimation, with a focus on quantitative methods. We illustrate how these can be incorporated in a program of natural hazard and risk management (NHRM).

CSA Z662-99 provides guidance on methods to estimate failure frequency and pipeline risk [15]. Approaches to estimating failure frequency include:

- analysis of historical operational and incident data;
- fault and event tree analysis;
- mathematical modelling; and,
- judgement of experienced and qualified engineering and operational personnel, based on known conditions.

With respect to risk estimation, Z662 outlines three possible approaches: Table 1 provides a modified description of these.

Table 1. Risk Estimation Methods

Method	Description
1. Risk Matrix	Qualitative estimates of frequency and consequence are expressed separately and combinations are presented in a two-dimensional risk matrix
2a. Semi-quantitative Risk Index	Factors that influence frequency and consequence are assigned values and mathematically combined, usually through summation
2b. Quantitative Risk Index	Factors that influence frequency and consequence are assigned values that, when combined through multiplication, give an estimate of failure probability and risk
3. Probabilistic Risk Analysis	Failure frequencies and consequences are estimated quantitatively and combined using probability theory

Qualitative (risk matrix) and semi-quantitative methods for incorporating natural hazards in an overall risk management program are well developed [5, 7, 8]. There are, however, numerous incentives for obtaining quantitative or probabilistic estimates of the likelihood and consequence of pipeline failure.

Pipeline operations are exposed to a number of hazards of which natural hazards are just one type. Expressing the probability and consequence of pipeline failure in a quantitative way facilitates comparison of natural hazard risks to other risks such as third party impact, corrosion, decreasing product demand, or increasing competition – in other words, an opportunity to compare apples with apples. Semi-quantitative risk indexing methods attempt to facilitate this comparison through the assignment of weighting factors to each of the

hazard index scores, but the process and results are not entirely satisfactory.

The likelihood of hazard occurrence and a pipeline's vulnerability to failure at a location of known hazard exposure can each vary by several orders of magnitude. For example, a pipeline may be situated below a slope with the potential for generating rapid rock slides that ranges from ~1.0 (almost certain to occur each year) to perhaps <0.01 (less than 1 chance in a hundred each year). If the pipeline is located on the ground surface, the conditional probability of failure, given that the slide occurs, may be on the order of 0.1 to 1.0. If the pipeline is deeply buried in a rock trench, the conditional probability of pipeline failure, given the occurrence of the same slide, could be less than 0.001. Thus, it is easy to imagine scenarios where natural hazards are identified, yet the likelihood of pipeline failure ranges over 4 or 5 orders of magnitude. It is difficult for qualitative or semi-quantitative methods to accurately depict this range of possible failure frequency.

Quantitative estimates of risk allow the evaluation of potential risk control measures through the use of risk cost-benefit analysis. By understanding the three factors that contribute to risk (hazard likelihood, system vulnerability and consequence of failure), each factor can be targeted as a means of reducing risk. These might include increased frequency of inspection, slope stabilization, pipe protection, or installation of warning or emergency response measures. Evaluating these options using quantitative methods improves our ability to make good decisions and allows us to illustrate the decision making process to others.

Insurance companies often assign premiums based on large pools of historical failure frequency and cost data. Some owners and operators would argue that their pipelines are built better or are being operated more safely than their competitors, and therefore deserve lower premiums. A quantitative risk assessment can provide convincing support for these arguments when justified, potentially resulting in a significant cost savings.

Finally, there is a push by industry (at least in Canada and parts of Europe) to adopt target reliability levels for onshore pipelines [16, 17]. In other words, it has been suggested that pipelines be designed so as to not exceed a certain probability of failure, with the acceptable failure rate governed by the potential consequence of product release at a given location. Working towards a target reliability requires that quantitative estimates of the probability of pipeline failure are obtained.

In summary, provided unnecessary complexity can be avoided, quantitative or probabilistic methods appear well suited to meet the objectives of pipeline NHRM.

Quantitative Methods

There are several quantitative methods to estimate the frequency of pipeline failure, consequence of failure, and

risk. The selection of the most appropriate methods is both hazard and scale dependent.

Consider the manufacture of a component, like a pump. Such components are made to be identical by their manufacturing process, and their probability of failure is determined from their failure frequency in repeated trials consisting of in-service performance or destructive testing. This is referred to as the relative frequency or statistical approach to probability determination [18].

Sometimes estimation of the probability of natural hazard occurrence is also amenable to a statistical approach. Highways and railways in southwestern British Columbia have been collecting rock fall magnitude-frequency data for several decades over many kilometres of roadway and many miles of track [19]. Because rock falls occur relatively frequently and the historical database extends over several decades, it is possible to use this data to estimate the annual probability of rock fall of a given magnitude, over broad sections of the facilities.

The estimation of the probability of pipeline failure at a specific site, as might be required for prioritising maintenance efforts or optimising a route location, for example, usually requires a different approach. Clearly, taking the probability of failure over an entire facility (using means such as historical incident data) and multiplying this by the proportion of the facility length that the specific site occupies does not give satisfactory results. Conditions at the site may be inherently more or less hazardous than the average condition over the entire facility length.

Furthermore, the statistical approach is not readily amenable to assigning probabilities of hazard occurrence along new or proposed facilities, along facilities where no records of hazard occurrence have been maintained, or where frequency is difficult to estimate based on poorly preserved evidence at the site. Herein lies the power of the subjective, degree of belief approach, defined by Vick [18] as a means of assigning, "...the probability of an uncertain event [through a] quantified measure of one's belief or confidence in the outcome, according to their state of knowledge at the time it is assessed."

The process allows experts to make use of statistical data (be it from local, regional, or other locations) as well as an evaluation of the unique characteristics of a given segment or site along a pipeline (such as soil, slope and groundwater conditions, observations of erosion, pipe burial depth, location relative to a potential hazard, and other pipeline and operational attributes) to assign a subjective probability of hazard occurrence and system vulnerability. As the expert's knowledge of site conditions improves, so does the precision of the probability estimates. The interested reader is referred to recent work by Muhlbauer [5] and Vick [18] for further elaboration.

At the most detailed level, expert judgement may be applied to the input parameters required for complex

reliability analyses. For example, when considering a slope stability and soil-pipeline interaction problem, probability distributions can be assigned to soil strength and groundwater conditions to estimate the probability of slope failure. Knowledge of the slope failure mechanism and/or slope monitoring data can be used to estimate the rate and magnitude of slope displacement and the resulting loads on the pipeline. A probability distribution to describe the capacity of the pipeline to withstand these loads can be compared with the predicted loads, leading to a detailed estimate of the probability of pipeline failure. Clearly, this level of effort is best reserved for specific sites where hazardous conditions are known to exist.

Phased Approach to Risk Management

Hazard identification and risk estimation are important first steps in the implementation of a risk management program. Where natural hazards have been identified as contributing to pipeline risk, NHRM should aim to:

- address the full range of natural hazards that a pipeline is exposed to;
- identify where these hazards are most likely to occur;
- provide an estimate of the probability of hazard occurrence, and the probability of pipeline failure;
- permit an evaluation of the influence of hazard exposure on pipeline risk and system reliability;
- facilitate comparison of risks from natural hazards with those related to other causes; and,
- highlight means of reducing risk and improving reliability in a defensible and cost-effective manner.

To meet these objectives we promote a 5-phase approach to natural hazard and risk management:

- Phase I – Preliminary analysis and screening;
- Phase II – Hazard inventory and preliminary risk estimation;
- Phase III – Detailed investigation;
- Phase IV – Risk evaluation, cost-benefit analysis; and,
- Phase V – Action, monitoring and re-evaluation.

The first 3 phases are dedicated to hazard identification and estimation of hazard likelihood, system vulnerability and consequence of failure. The fourth phase involves evaluating if the estimated level of risk or reliability is acceptable, and if not, to rank remedial options through risk cost-benefit analysis. The fifth phase involves implementation of the chosen risk control measures, monitoring the results, and assessing if the desired level of risk reduction has been achieved.

Phase I

For each type of natural hazard, subjective estimates of hazard likelihood and system vulnerability are assigned at Phase I, II and III. Phase I is designed as a screening level tool. Large segments of a pipeline, typically

extending between mainline valves, are assessed using historical data, air photos and brief field inspections to determine the range of natural hazards that are present and the general characteristics of the pipeline. This information, in conjunction with general rating guidelines, is used to assign order-of-magnitude estimates of hazard likelihood and system vulnerability to each pipeline segment. The results are used to prioritize segments for further evaluation.

Phase II

Phase II utilizes what we refer to as a quantitative risk indexing method. A complete inventory of ground conditions, stream characteristics and natural hazards is developed for the segments selected for Phase II study. Inventory and characterization is carried out using standard engineering geology and geomorphology practices. For example, streams are characterized according to their channel gradient, degree of entrenchment, width-to-depth ratio, and bed and bank materials using techniques such as those described by Rosgen [20]. Observed landslides are classified according to volume, activity, velocity, material type and failure mechanism. The pipeline system is characterized according to crossing type, burial depth, geometry in relation to potential hazards, etc.

Each of the attributes describing the natural environment, identified hazards, and the pipeline are assigned numerical values between 0 and 1 that, when multiplied together give a subjective estimate of the probability of hazard occurrence and the vulnerability of the system. The product of hazard likelihood and system vulnerability provides a measure of the likelihood of pipeline failure that is obtained through a systematic and repeatable process. The attribute scores are calibrated using historical incident data and data obtained from sites with similar characteristics, resulting in probability of failure estimates that are typically accurate to within less than one half order of magnitude. This level of accuracy is more than adequate for this type of study.

Based on the attribute data, the pipeline segments are subdivided into sections of uniform probability of failure for each hazard type using a dynamic segmentation procedure, and again for the total probability of failure from all types of natural hazard. An example for a South American pipeline subject to an extreme level of exposure to natural hazards is illustrated in Figure 6.

The resulting estimated probability of pipeline failure at each location can be multiplied by an approximate consequence of failure value to obtain a distribution of risk across the pipeline.

In addition to natural hazards, the quantitative risk indexing approach can be extended to incorporate other hazard types such as corrosion and third party impact. If all estimates of the likelihood of pipeline failure are presented in a quantitative form, the combined effect of all hazards can be determined using probability theory.

Qualitative or semi-quantitative methods do not offer this advantage. An detailed example of how such an approach was recently implemented for a Bolivian pipeline is provided in our companion paper [13].

Phase III

At Phase III, detailed geological, geotechnical, hydrotechnical and pipe soil-structure interaction studies may be undertaken for priority sites identified in Phase II. The exact nature of investigation and analysis carried out is hazard and site-specific, but aims to confirm and refine the quantitative estimates of hazard likelihood, system vulnerability, probability of pipeline failure, and risk of failure.

Analysis can be undertaken using an event tree process to evaluate the range of failure consequences, depending on the severity of failure (crack / leak / rupture), the type of product being transported at the time, and the performance of existing emergency response measures such as shut-off valves and site clean-up / repair activities.

Conceptual risk control options involving reduction of hazard likelihood, system vulnerability or consequence of failure can be identified, and potential costs and degree of effectiveness can be estimated.

Phases IV and V

In Phase IV, the risks identified in Phases I-III can be evaluated to determine if they are acceptable. If the risks posed by specific hazards are deemed unacceptable, then risk cost-benefit analysis can be undertaken to select the most appropriate remedial strategy.

In Phase V, the selected remedial options are implemented. In some cases, these may be as simple as increasing the frequency of visual inspection or monitoring of instrumentation. In other cases, they might involve construction of erosion protection measures, stabilization of slopes, or a change in pipe burial depth. In extreme circumstances where these options are not practical, variants or alternate techniques such as directional drills may be required. Corporate and government approval for these projects is easier to gain with the results of a sound risk assessment to back up the proposal.

CONCLUSION

Reliability and risk-based design appear to be gaining acceptance in Canada and internationally. As natural hazards may present a significant risk to the safe and efficient operation of pipelines, when compared to other hazard types, integrity and risk management programs should give them due consideration. This is especially true where pipelines traverse geomorphically active terrain such as across streams, mountains, areas subject to active tectonic processes, or locations with a high potential for frost heave and thaw settlement.

Few published procedures exist that adequately incorporate natural hazards as part of route selection or integrity management programs. A phased risk

management approach that utilises a quantitative indexing method to estimate the reliability and risk associated with natural hazards appears well suited to meet the objectives of such programs.

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Figure 1. EGIG Pipeline Incident Data [10]

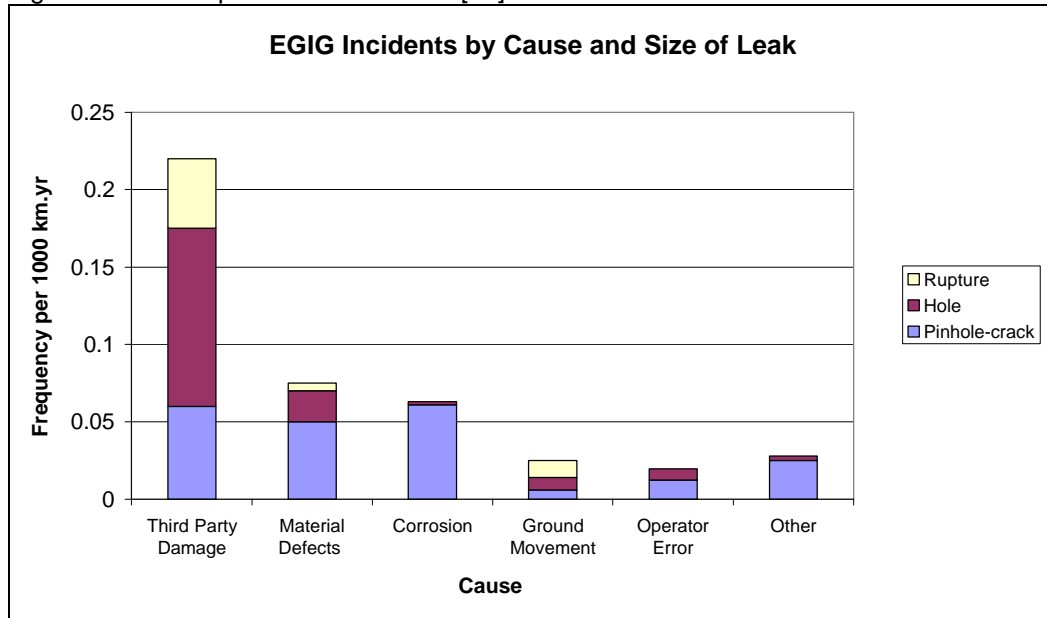


Figure 2. US DOT Incident Data for Gas Transmission Pipelines [11]

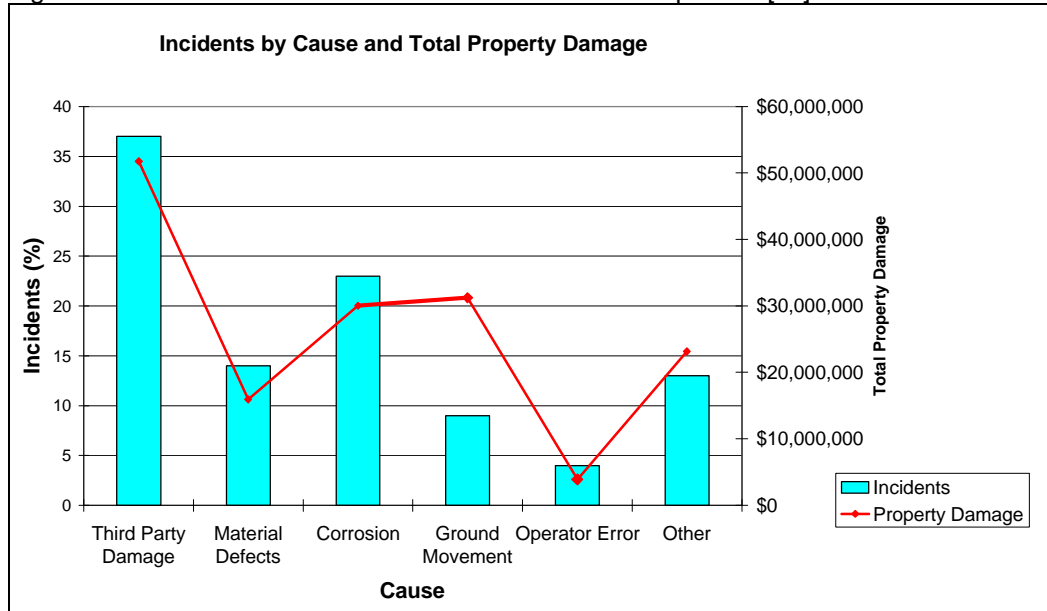


Figure 3. NEB Incident Data for Nationally Regulated Canadian Pipelines [12]

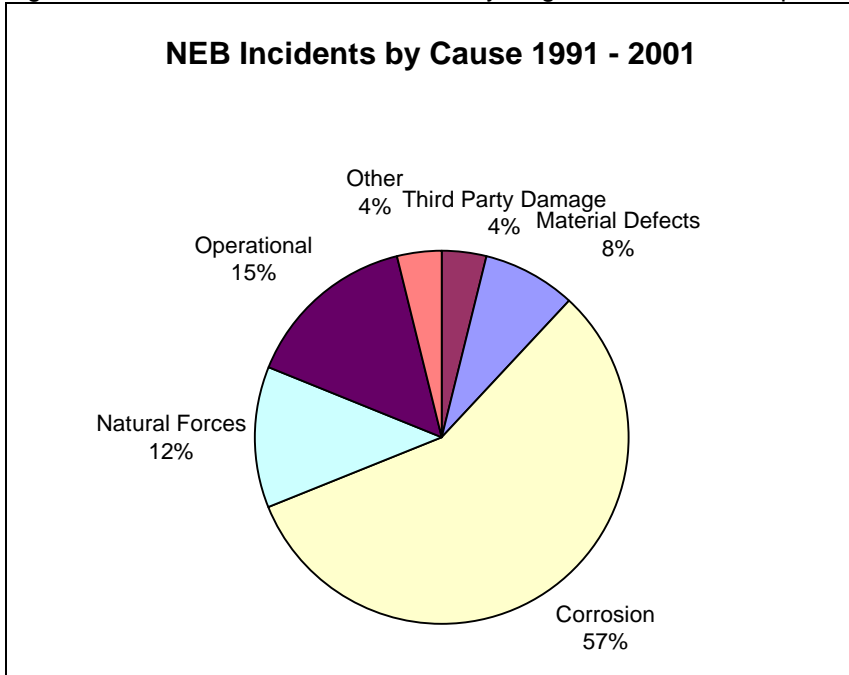


Figure 4. Incident Data for a Typical Andean Pipeline [13]

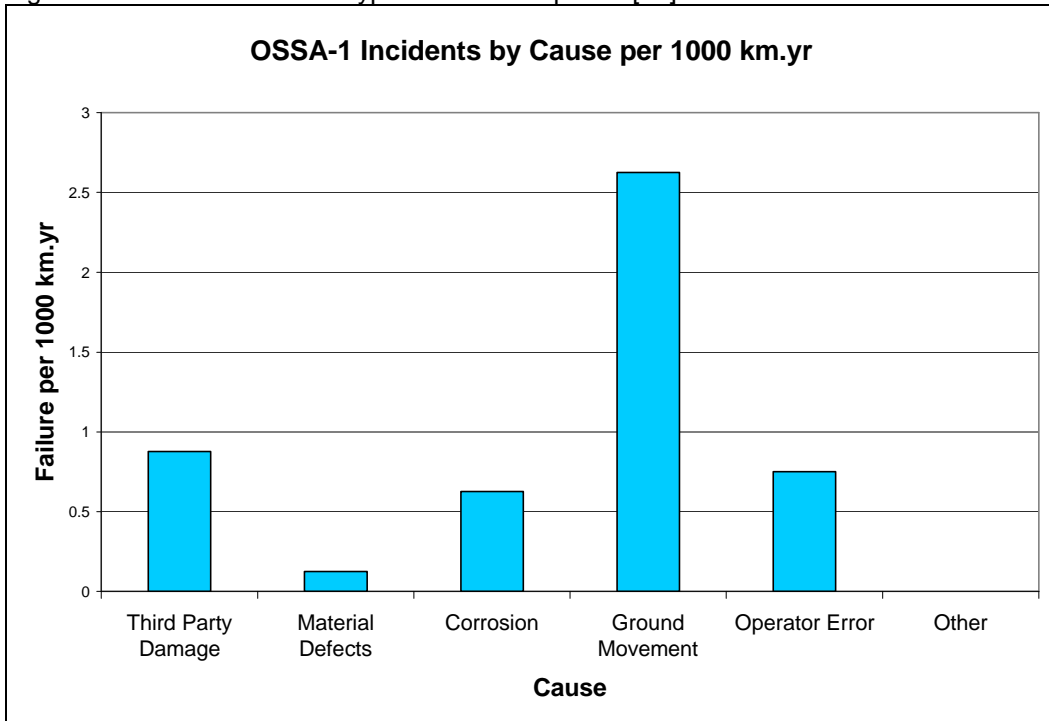


Figure 5. Incident Data for Oil and Gas Transmission Pipelines in British Columbia [12, 14]

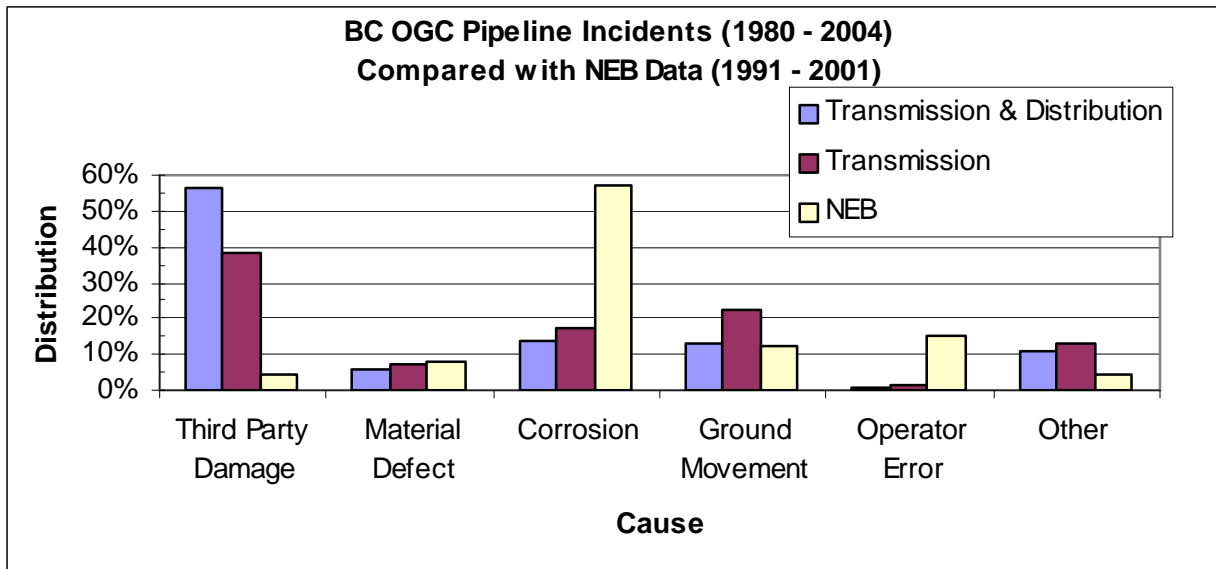


Figure 6. Probability of Failure Estimates for a Pipeline Subject to Extreme Natural Hazard Exposure

