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UPDATED ESTIMATES OF FREQUENCIES OF PIPELINE FAILURES CAUSED BY GEOHAZARDS

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ABSTRACT

This paper provides an updated compilation of geohazard-related pipeline failure frequencies for onshore hydrocarbon gathering and transmission pipelines, with a particular emphasis on the analysis of data from Western Europe, Western Canada, the US, and South America. The results will be of interest to owners, operators, regulators and insurers who wish to calibrate estimates of geohazard failure frequency and risk on planned and operating pipelines, particularly for pipelines traversing mountainous terrain. It concludes with an estimate of the global annual frequency of failures caused by geohazards on hydrocarbon gathering and transmission pipelines, and postulates that this failure frequency should continue to decline when measured on a per kilometer basis due to ongoing improvements in geohazard recognition, routing and design of new pipelines, and improvements to integrity management practices for operating pipelines.

Keywords: Geohazard, Pipeline, Failure, Statistics, Frequency, Risk

INTRODUCTION

Within the context of the pipeline industry, geohazards comprise a subgroup of natural hazards associated with geotechnical, hydrotechnical, tectonic, snow and ice, and geochemical processes that can affect the safety of construction or operational personnel, impact construction schedules and costs, threaten the integrity of operating pipelines and associated infrastructure, and/or impact the environment [1]. Most are natural processes triggered by storms or seismic activity, while others, such as cut and fill slope failures or mine subsidence along pipeline rights-of-way, can be triggered or exacerbated by project construction and site remediation activities or by third party activities.

A partial list of geohazards, adapted from [1] and [2], that may need to be considered in onshore pipeline development projects and in pipeline integrity management programs, is provided in Table 1.

Table 1. Partial list of geohazards affecting onshore pipeline projects

Hazard Class	Type, Name
Geotechnical Hazards	Frost Heave Thaw Settlement Solifluction Rock Fall Rock Slide/Creep Earth Slide/Creep Earth Flow Debris Slide Ground Subsidence (Karst/Mines)
Hydrotechnical Hazards	Debris Flow Scour Channel Degradation Bank Erosion Encroachment Avulsion Shoreline Wave Erosion
Tectonic Hazards	Liquefaction

	Lateral Spreading Surface Fault Rupture Strong Ground Motion Volcanic Eruption/Lava Flow
Snow and Ice Hazards	Snow Avalanche Ice Fall
Erosion Hazards	Surface Water Erosion Groundwater Erosion Wind Erosion and Dune Migration
Geochemical Hazards	Acid Rock Drainage and Metal Leaching

A subset of geohazards that have caused pipeline failure due to unintended loads, often referred to as ground movement hazards, are the focus of the remainder of this paper.

Quantitative predictions of the frequency of pipeline failure caused by geohazards are fraught with uncertainty. Prediction of the failure frequency of a proposed or operating pipeline system is typically based on an evaluation of several hundred individual geohazard locations, the geohazard and pipeline attributes at those locations, and predictions of future performance. Due to uncertainty in the models, the results should be calibrated by way of comparison of the system's predicted failure frequency to pipeline industry statistics. If carried out appropriately, this calibration allows owners to rationally prioritize pipeline design or integrity management efforts between geohazards and other types of threats. In practice this means that a predicted frequency of failure based on a summation of the frequencies determined for identified geohazard sites needs to be compared with the historical frequency of failure for "similar pipelines." "Similar pipelines" are defined as those crossing similar types of geohazards in similar climatic and geographic settings, and having been designed, constructed and maintained according to similar standards. Because the length of pipelines crossing geohazard-prone terrain and the frequency of failures caused by geohazards are often relatively low (compared to other terrain types and failure causes) it can be very challenging to find relevant failure statistics, particularly those that reflect similar routing, design and operational standards.

The European Gas Pipeline Incident Data Group (EGIG) compiles statistics on gas pipeline failures in Western Europe, and provides useful summaries of those caused by ground movement (or geohazards). EGIG [3] data suggest the current industry average failure rate caused by geohazards is on the order of 0.02 failures per 1,000 km per year. Sweeney et al. [4] and Porter et al. [5, 6] recognized that the Western European gas pipeline network contains a high percentage of pipelines crossing relatively benign terrain, and that failure frequencies caused by geohazards in mountainous terrain can be as much as 10 to 100 times higher than measured by the EGIG. Clearly, caution must be exercised when applying failure statistics obtained from one region to pipelines operated in another.

This paper provides an updated compilation of geohazard-related pipeline failure frequencies for hydrocarbon gathering and transmission pipelines with a particular emphasis on the analysis of data from Western Europe, Western Canada, the US, and South America. The results will be of interest to owners, operators, regulators and insurers who wish to calibrate estimates of geohazard failure frequency and risk on planned and operating pipelines, particularly for pipelines traversing mountainous terrain. It concludes with a rough estimate of the global annual frequency of failures caused by geohazards on hydrocarbon gathering and transmission pipelines, and postulates that this failure frequency should continue to decline when measured on a per kilometer basis as the result of ongoing improvements in hazard recognition, routing and design of new pipelines, and improvements to integrity management practices for operating pipelines.

WESTERN EUROPE

The European Gas Pipeline Incident Data Group (EGIG) comprises 15 operators of a combined 143,000 km of natural gas transmission pipelines [3]. Their data reports document failures of onshore steel pipelines with a maximum operating pressure greater than 15 bar and located outside the fences of the gas installations.

Pipeline incidents (also referred to as failures or loss of containment in this paper) result in an unintentional release of gas and are assigned to one of three leak size classes by EGIG:

- Pinhole/crack: diameter of the hole is less than 2 cm;
- Hole: diameter of the hole is between 2 cm and the diameter of the pipe; and
- Rupture: the diameter of the hole is larger than the pipe diameter.

EGIG refers to geohazards as 'ground movement' hazards. The following useful conclusions can be drawn from their 9th report documenting failures between 1970 and 2013 [3] and from their 8th report covering the period between 1970 and 2010 [7]:

- Geohazards are the cause of about 7 to 8% of incidents, and are the 4th leading cause of failure.
- The frequency of incidents caused by geohazards has slowly decreased over time, but more slowly than reductions in incident frequency caused by external interference, corrosion, and construction defect/material failure. As a result, the percentage of failures caused by geohazards is slowly increasing.
- The geohazard failure frequency between 1970 and 2013 was 0.026 per 1,000 km per year, while the ten-year moving average ending in 2013 was 0.02 per 1,000 km per year (Figure 1).
- Because geohazard failures are relatively rare, a small number of failures can have a big impact on the failure statistics. For example, the five-year moving average

ending in 2010 was 0.015 per 1,000 km per year, while the five-year moving average ending 2013 was 0.024 per 1,000 km per year.

- Geohazards cause proportionally more ruptures than cracks and holes, and are the second leading cause of larger failures such as holes and ruptures.
- There is a relationship between pipe diameter and geohazard failure frequency, though it is less pronounced than for other failure causes. The normalized geohazard failure frequency per 1,000 km per year of smaller diameter pipes (less than 11 inches) is about 4 times higher than for pipe diameters greater than 23 inches. This might be a result of the greater stress capacity of larger diameter pipes, but may also reflect a history of more rigorous geohazard design and management effort for larger diameter pipelines.
- Over 60% of the geohazard failures were attributed to landslides, while about 22% were attributed to rivers, floods and dike breaches (hydrotechnical hazards), 4% were attributed to mine subsidence, and about 4% were attributed to lightning. (note: where possible, lightning related pipeline failures have been removed by the authors from the compilation of failure frequency estimates – particularly for failures in Australia and the US where a high percentage of lightning-related failures have been reported).

Cunha [8] summarized geohazard-related failure frequencies from other European databases: 0.015 per 1,000 km per year on liquids pipelines (CONCAWE) and 0.009 per 1,000 km per year on UK gas pipelines (UKOPA) (Figure 1).

In 2004, Sweeney et al. [4] observed that most of Western European terrain is relatively benign and that most pipeline failures due to geohazards have occurred in the mountainous Alps. Normalizing the failure database by the length of (mostly older) pipelines in the Alps yielded an estimated failure frequency of 0.8 failures per 1,000 km per year for pipelines built without the benefit of modern geotechnical practice (Figure 1). This failure frequency is about 40 times higher than the “all pipelines” frequency for Europe.

AUSTRALIA

Tuft and Cunha [9] report on pipeline loss of containment events recorded by the Pipeline Operators Group in Australia. Between 2002 and 2012, a total of 11 loss of containment events were recorded on approximately 32,000 km of Australian hydrocarbon pipelines. Five of these events (nearly 50%) were caused by natural hazards, although four of these involved lightning strikes and only one was caused by earth movement.

Tuft and Cunha’s analysis suggests that geohazards are responsible for approximately 9% of Australian pipeline failures, with a corresponding geohazard failure frequency of approximately 0.003 per 1,000 km per year (Figure 1). The Australian geohazard failure frequency is nearly seven times lower than that reported by EGIG for Western Europe, presumably because geohazard exposure is extremely low as a result of the topography, climate and pipeline routing practices in Australia.

CANADA

Similar to Western Europe, much of the terrain traversed by pipelines in Canada is relatively benign from a geohazards-perspective. Notable exceptions include crossings of rivers and valley slopes that have been deeply incised in weak glacial sediments and sedimentary bedrock in the prairies, and crossings of the mountainous terrain in Western Alberta and through British Columbia.

Responsibility for compilation of pipeline failure statistics in Canada rests with the National Energy Board (NEB) for pipelines that cross provincial or federal boarders, and with various provincial agencies for all other pipelines. Data published by the NEB indicates the leading cause of failure during the period 1991 to 2009 was stress corrosion cracking (38%), followed by metal loss (27%), with geohazards contributing to between 5 and 9% of incidents [10, 11]. An analysis of the NEB incident data from 2000 to 2009 with gas and liquid releases greater than 1.5 m^3 from river erosion and ground movement results in an annual failure frequency of 0.005 per 1,000 km of pipeline. This frequency is about four times lower than reported by EGIG.

The BC Oil and Gas Commission (BC OGC) is the regulatory agency responsible for overseeing pipeline performance in the mountainous province of British Columbia. In pipeline performance reports for the years 2009 to 2013, the BC OGC recorded 13 geotechnical incidents on approximately 193,000 km-years of pipeline exposure [12]. This equates to approximately 2.6 geohazard incidents per year, and an incident frequency of approximately 0.07 per 1,000 km per year. This frequency is about 3.5 times higher than the EGIG data.

Of special note is a 587 km long NPS10 gas pipeline traversing interior plateau and the extreme Coast Mountains in central and western British Columbia. This pipeline was constructed in the 1960s under frontier conditions. Publicly available data such as BC OGC incident data, technical geohazard papers, and regional and local news reports indicate that at least six confirmed failures from geohazards have occurred between 1991 and 2013. One is from a large rock avalanche, two from debris flows, two from earth slides, and one from river erosion. Based in this data, the current annual failure frequency is about 0.45 per 1,000 km.

The Alberta Energy Regulator (AER) is the regulatory agency responsible for overseeing pipeline performance of about 259,000 km of pipeline traversing predominantly prairie terrain in the province of Alberta. Performance data from 1990 to 2012 compiled by AER indicates an annual failure frequency from earth movements of 0.08 per 1,000 km of liquids and gas pipeline, all diameters, ages and statuses [13]. This frequency is similar to the OGC frequency generated for the mountainous terrain of neighboring British Columbia. It is worth noting that the AER database includes mostly (90%) gas pipelines with diameters less than NPS12.

Since 2002, the BGC authors have been involved in helping onshore oil and gas transmission pipeline operators manage geohazards along currently ~67,000 km of pipeline and ~18,000 geohazard sites in Canada and the United States [14]. Since 2003, the geohazard management program has recorded six geohazard related failures resulting in an averaged annual failure frequency of 0.03 per 1,000 km of gas and liquid pipelines traversing all terrain types, all pipeline diameters, ages and statuses. This frequency is close to the EGIG failure frequency.

UNITED STATES

The U.S. Department of Transportation Pipeline and Hazardous Materials Safety Administration (PHMSA), collects reports of pipeline mileage and incidents on federally and state-regulated pipelines in the United States. Annual reports of pipeline mileage for the period 2005 to 2014 were accessed to obtain estimates of pipeline length (converted to kilometers) for onshore gas transmission and onshore hazardous liquids pipelines, as summarized in Table 2 and 3, respectively [15]. Summaries of the respective ‘all reported incidents’ for transmission pipelines were also queried to estimate the annual frequency of incidents caused by geohazards (excluding those attributed to lightning, strong wind, or temperature).

Table 2. US onshore gas transmission pipeline data

Year	**Number of Geohazard Incidents**	**Length of Pipeline (km)**	**Incident Frequency (per 1,000 km per year)**
2014	6	476,528	0.013
2013	4	477,259	0.008
2012	3	477,714	0.006
2011	11	479,568	0.023
2010	0	478,973	0.000
2009	5	478,363	0.010
2008	8	475,627	0.017
2007	2	471,902	0.004
2006	2	469,930	0.004
2005	17	471,680	0.036
Average	*5.8*	*475,754*	*0.012*

Table 3. US onshore hazardous liquids pipeline data

Year	**Number of Geohazard Incidents**	**Length of Pipeline (km)**	**Incident Frequency (per 1,000 km per year)**
2014	5	318,934	0.016
2013	5	307,867	0.016
2012	6	297,954	0.020
2011	5	293,728	0.017
2010	3	291,178	0.010
2009	7	281,544	0.025
2008	12	278,062	0.043
2007	10	271,754	0.037
2006	7	266,750	0.026
2005	17	266,816	0.064
Average	*7.7*	*287,459*	*0.027*

On average, the failure frequencies are similar to those recorded in the EGIG data from Western Europe (Figure 1). Failures by geohazard sub-type varied from year to year, but overall were roughly equally divided between earth movement (i.e. geotechnical hazards), and rains and floods (i.e. hydrotechnical hazards).

When all pipeline types are included (e.g. gas distribution, gas gathering added to the pipeline types) then PHMSA data appear to suggest that the number of failures due to rains and floods is nearly twice that of earth movement. In this larger data set comprising 140 failures due to rainfall / floods, 89 occurred in two years (2005 and 2008) whereas other years had on average 6.3 failures per year caused by heavy rains / floods. In the 10 year period the average failure rate caused by ground movement was 7.2, which is similar to the number of failures caused by heavy rains / floods (excluding 2005 and 2008).

In 2004, Sweeney et al. [4] reviewed US pipeline failure databases and route maps, and postulated that most pipeline failures caused by geohazards have occurred in mountainous regions comprising about 5% of the US pipeline network. Normalizing the failure database by the length of (mostly older) pipelines in the mountainous regions yielded an estimated failure rate of 0.32 failures per 1,000 km per year for pipelines built without the benefit of modern geotechnical practice (Figure 1). This frequency is close the geohazard related failure frequency of 0.45 for the pipeline discussed in north central British Columbia.

SOUTH AMERICA

Numerous hydrocarbon basins are situated along the eastern foot of the South American Andes, extending from Venezuela to the southern tip of Argentina. A significant proportion of the market for these hydrocarbons resides along the Pacific coast of South America, as well as the United States. Consequently, to meet market demands several trans-Andean pipelines have been constructed and many others are proposed [16]. The Andes are steep, tectonically active, and (outside of the Atacama Desert) are subject to heavy precipitation. As a result, they pose formidable challenges to the design, construction and safe operation of pipelines. Where these challenges are not fully appreciated, the end product is often an elevated and unacceptable level of exposure to geohazards such as landslides and river erosion.

In 2004, Sweeney et al. [4] reviewed pipeline failure reports from the Colombian and Ecuadorian Andes. They estimated annual failure frequencies of 2.8 failures per 1,000 km for older pipelines built without the benefit of modern geotechnical practice and 0.33 failures per 1,000 km per year for modern Andean pipelines (Figure 1). They noted, however, that many of the modern pipelines had experienced no ruptures to date and that estimate of 0.33 was an upper bound.

In 2004, Esford et al. [17] reported on an integrity management system being developed for the Transredes pipeline network in Bolivia (now operated by YPFB Transporte SA). As part of the pilot study, the new management system was implemented on the OSSA-1 pipeline, a 415 km long, NPS 10 and 12 pipeline between Santa Cruz and Cochabamba. The OSSA-1 pipeline crosses terrain with high geohazard exposure and was built without the benefit of modern geotechnical practice. As a result, between 1983 and 2003 the pipeline had experienced about 21 geohazard-related failures with a corresponding failure frequency of approximately 2.5 per 1,000 km per year (Figure 1) – nearly identical to that estimated for older Andean pipelines by Sweeney et al. [4].

To the authors' knowledge, an additional 4 failures have occurred on the OSSA-1 pipeline since 2003. As a result, the long-term geohazard failure frequency has been reduced to approximately 1.88 per 1,000 km per year (Figure 1).

YPFB is in the process of implementing the above-referenced integrity management program on all of their pipelines. Recent failure statistics for the entire 5,500 km long YPFB pipeline network in Bolivia indicate approximately 20 geohazard-related failures over a seven year period. This yields a failure frequency of about 0.52 per 1,000 km per year (Figure 1). It is expected that this number will continue to decline as geohazard management efforts are increasingly focused on high priority geohazard sites.

In 2006, Porter et al. [6] reported on geohazard failure frequencies for the NorAndino gas pipeline in northern Argentina and Chile. Following two ruptures caused by geohazards, the failure frequency was estimated at 0.67 per 1,000 km per year in 2002. After completion of a comprehensive geohazard assessment and implementation of mitigation measures at priority geohazard sites, the failure frequency in 2005 was estimated to have dropped to about 0.28 per 1,000 km per year – in line with estimates reported by Sweeney et al. [3] for modern Andean pipelines (Figure 1).

Since 2006, the NorAndino pipeline has only experienced one additional rupture caused by geohazards, and this was at a site where failure was anticipated and the line had been recently abandoned. Conservatively accounting for this third rupture, the geohazard failure frequency for the NorAndino pipeline is currently around 0.18 per 1,000 km per year (Figure 1).

Cunha [8] provides failure statistics compiled from about 70,000 km of gas and liquids pipelines in Brazil between 1978 and 2010. He reports a historical geohazard failure frequency of 0.073 per 1,000 km per year for Brazilian pipelines (Figure 1). All of the geohazard failures were attributed to earth movement, landslides and subsidence.

CHALLENGES WITH INCIDENT DATABASES

Bolt [18] cautions that the use of pipeline incident data is often not fit for purpose. This is particularly true for geohazard incident frequencies [4, 5, 6]. As noted in Figure 1, the pipeline failure frequencies caused by geohazards and compiled herein range over nearly three orders of magnitude. Clearly, use of reported geohazard failure frequencies from a large regional database must be applied with extreme caution when predicting the failure frequency of a specific pipeline. Not only must terrain conditions along the specific pipeline be understood, but so must the routing, design and operational practices employed.

Another challenge with incident databases that is perhaps more pronounced for geohazards than for other failure causes, is that failures caused by geohazards are often misdiagnosed. For example, in Western Canada and other parts of the world, landslides in weak clay shales can occur on slopes as flat as 3 degrees and have resulted in failures of pipelines. Without specialist geotechnical input, and particularly before the advent of LiDAR, it was very difficult to recognize that these sites were located on a slope, let alone a landslide. Consequently, several of these types of failures are likely classified in historical databases as having been caused by design or installation defects, temperature extremes, stress corrosion, or simply 'unknown or other'.

To facilitate better estimates of geohazard-related pipeline failure frequencies, and more robust algorithms to predict the vulnerability of pipelines to geohazards, the following additional improvements to incident reporting databases would be helpful:

- consistent definitions of what constitutes a pipeline failure (e.g. serviceability limits, pinholes, leaks or ruptures), and the reporting thresholds used
- more details on the cause and trigger for the geohazard
- better characterization of geohazard type, dimensions, and movement rates or intensities
- the orientation of the pipeline relative to the geohazard
- UTM or LAT/LONG coordinates of failure sites to facilitate external review of site conditions such as surficial and bedrock geology, site geometry, etc.

ESTIMATED GLOBAL FREQUENCY OF FAILURES

Estimates of the lengths of hydrocarbon pipelines around the world have been compiled by various organizations, including CEPA [19], PHMSA [15], and the Central Intelligence Agency's World Factbook [20]. Approximate lengths of onshore gathering and transmission pipelines (i.e. excluding gas distribution pipelines) are as follows:

- Canada – 390,000 km (including 115,000 km of transmission lines) [19]
- US – 814,000 km [15]
- South America –110,000 km [20]
- Global – 2,324,000 km

Combining pipeline length estimates by country or region with historical pipeline failure frequencies summarized in Figure 1 (and recognizing the limitations of the databases as reported above) can shed some light on the potential number of global pipeline failures caused by geohazards. In the estimates below, we have assumed:

- 0.02 per 1,000 km per year for Canada, US, and western Europe
- 0.003 per 1,000 km per year for Australia
- 0.07 per 1,000 km per year for Brazil
- 0.5 per 1,000 km per year for Bolivia
- 0.2 per 1,000 km per year for all other South American pipelines
- 0.03 per 1,000 km per year for all remaining pipelines.

The results are as follows:

- Canada – 8 failures per year
- US – 16 failures per year
- South America – 22 failures per year
- Global – 74 failures per year

These estimates are admittedly simplistic. They likely overstate the predicted frequency of failures in some regions, but may also underestimate the frequency of failures in others. And even within regions, some areas will have higher geohazard exposure while others will have virtually none. None-the-less, the failure frequency estimates provide a rough indication of the scale of the problem, and the opportunity for future improvement.

PREDICTIONS OF FUTURE TRENDS

In the authors' experience, rigorous inclusion of geohazards in pipeline integrity management programs began in the early 2000s and over the past 5 years is quickly becoming an accepted standard of practice in North America. Geohazard management programs are being implemented by many South American pipeline operators, and presumably in other parts of the world as well.

A rigorous geohazard management program begins with a review of historical records, the development of a detailed inventory of credible geohazards, baseline characterization in the field, and establishing a mechanism for data storage and retrieval usually in the form of an on-line database linked to a geographic information or map-based system [21, 22, 23, 24].

Baseline characterization, during field inspections, is used to establish a screening level assessment and quantification of all geohazards that could affect the pipeline. The screening level assessment is used to establish the general scale of importance of the geohazard, both from a likelihood of occurrence and a pipeline vulnerability standpoint. Once this screening level is completed then detailed assessment of geohazard sites can begin.

Risk-based concepts are used to prioritize geohazard sites for further management including office or field inspection, more detailed assessment, monitoring, and/or mitigation: some operators are conservative and prioritize based on the estimated likelihood of pipeline exposure or impact while others use estimates of the potential for geohazards to cause pipeline failure. In the authors' experience, few pipeline operators currently use explicit estimates of geohazard risk (which would include estimates of safety impacts or cost of a pipeline failure), although we anticipate that the industry may move in this direction within the next decade.

As reported herein, the results of the pipeline industry's geohazard management efforts are starting to appear in the failure statistics, particularly for regions and pipeline systems with elevated geohazard exposure. It is in the pipeline industry and society's best interest that these trends continue, and we expect they will, but for this to occur at least two opposing factors must be overcome:

The first, and of lesser significance in our opinion, are the effects of an aging pipeline infrastructure. Over time, the strain capacity of aging pipelines may diminish as a result of corrosion or crack growth, making them more vulnerable to failure if impacted by a geohazard. This can be overcome through ongoing improvements to in-line survey techniques and gradual replacement of pipelines in areas of high geohazard exposure.

The second is climate change which is impacting our ability to predict the location, frequency and magnitude of future geohazard events. Overcoming uncertainties imposed by climate change will require improvements in predictive models that link climate change scenarios with secondary and tertiary effects like precipitation, flooding, and landslide activity. It will also require that the industry implement emerging best practices for frequent and/or real-time monitoring of floods, slope movements and pipe strains in locations that are most susceptible to geohazards.

Ongoing reporting of geohazard-related failures and incidents by industry and regulators, ideally with the benefit of some of the incident reporting improvements recommended herein, will provide valuable data to support these initiatives.

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Figure 1. Compilation of frequency of pipeline failures caused by geohazards