

IPC04-0327

## A RISK ASSESSMENT MODEL FOR PIPELINES EXPOSED TO GEOHAZARDS

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### ABSTRACT

Transredes S.A. currently operates over 5,500 km of natural gas and liquids pipelines throughout Bolivia. These traverse geologically active terrain, subject to earthquakes, floods and landslides. Construction of these pipelines dates as far back as 1955, with some currently operating under conditions not foreseen at design.

A quantitative risk assessment procedure was developed to rank the threats to the pipelines and target locations exposed to the highest level of risk. The objective was to implement a systematic means of prioritizing capital and maintenance activities based on risk management principles. The procedure was implemented on the OSSA-1 pipeline as part of a pilot study.

This paper describes the OSSA-1 Pilot Project, with emphasis on how risk assessment procedures were customized to address the pipeline's elevated exposure to 'geohazards'.

Keywords: Geohazards, Natural Hazards, Integrity, Quantitative Risk Assessment, Risk Management, Bolivia

### INTRODUCTION

Transporte de Hidrocarburos Sociedad Anónima (Transredes S.A.) is Bolivia's major hydrocarbon transportation company. Transredes currently operates over 5,500 km of natural gas and liquids pipelines throughout Bolivia many of which traverse geologically active terrain, subject to floods, landslides and earthquakes. Construction of some of these pipelines dates back to 1955.

In 2003, Transredes began the process of implementing a more systematic means of prioritizing capital and maintenance activities for their Bolivian

pipeline network based on risk management principles. It was decided to implement a comprehensive risk assessment model to characterize and manage their risks associated with pipeline operations based on the system first published by Kent Muhlbauer in 1992 [1].

The basic risk assessment model has seen wide use and forms the basis for many pipeline integrity and risk management efforts in the industry. This approach uses a systematic procedure to assign numerical scores to hazard types, which are then combined with consequence values to determine relative risk along the pipeline.

The influence of natural hazards, or 'geohazards' was assigned a relatively low weight in the originally published Muhlbauer Model examples. Since some pipelines constructed in parts of western North America, South America, Asia and eastern Europe face significant risks from geohazards, additional effort is required to fully characterize and rank these risks [2, 3, 4].

The OSSA-1 Pilot Project provided an excellent opportunity to expand the basic Muhlbauer approach to more fully assess geohazard threats. A quantitative risk assessment procedure was developed to rank threats to the pipeline network and target locations exposed to the highest level of risk. The procedure was implemented on the OSSA-1 pipeline as part of a pilot study. This paper describes the OSSA-1 Pilot Project, with an emphasis on how risk assessment procedures were customized to address elevated exposure to geohazards.

### TRANSREDES SYSTEM

Transredes was formed in 1997 under the Capitalization process that saw State-owned assets transferred to the private sector. During the process, Transredes acquired management control of the natural gas and liquids transportation pipelines and associated

facilities of Yacimientos Petroliferos Fiscales Bolivianos (YPFB), the former state monopoly [5].

Transredes currently operates 2,744 km of liquids pipelines and 2,920 km of gas pipelines throughout Bolivia (Figure 1). The pipelines range in size from 4” to 36” in diameter. Construction of some of the liquids pipelines dates back to 1955, while some of the gas pipelines were constructed as early as 1968. Transredes faces challenges that typically accompany the maintenance and protection of an aging infrastructure in a sometimes inhospitable environment.

### OSSA-1 PIPELINE Operating Details

The OSSA-1 pipeline operates between Santa Cruz and Cochabamba, Bolivia (Figure 1). It is approximately 415 km in length and was constructed with 10” and 12” diameter pipe. The system provides for the westerly transport of crude oil and batches of LPG to Cochabamba.

A significant portion (~50%) of the OSSA-1 Pipeline is located above ground surface on low level supports, and the majority of river crossings are aerial. The pipeline operates at a maximum pressure of 1500 psig with a design factor of 0.72, as is commonly used for hazardous liquid pipelines in many countries.

### Geological Setting and Geohazards

The OSSA-1 pipeline traverses three geological regions. It starts near the western margin of the Beni Basin lowlands. This geologic region comprises a subsiding foreland basin that is located on the southern margin of the Amazon rain forest and is filled with alluvial sediment. Active tectonics within the basin are believed to contribute to locally extreme rates of river channel migration [6].

Seismicity within the Beni Basin is moderate, with the peak horizontal ground acceleration for the 1 in 475 year return period (1:475 year) earthquake expected to exceed 0.18 g. Annual precipitation averages between 800 and 1200 mm, with most of this falling between the months of October and April.

Within the Beni Basin, geohazards along the OSSA-1 pipeline predominantly relate to bank erosion at stream crossings and encroachment hazards where the pipeline is located in close proximity to streams.

At approximately KP 40, the OSSA-1 pipeline enters the Sub-Andean Ranges geological region. This consists of an east-dipping foreland fold-thrust belt that lies at the foot of the Eastern Cordillera [7]. Deformation (folding and thrust faulting) began several million years ago and is ongoing. Surficial materials are predominantly uplifted alluvial sands and gravels deposited during the Quaternary<sup>1</sup>. These are underlain by weak sedimentary

<sup>1</sup> The Quaternary extends from the present day to approximately 1.6 million years B.P.

bedrock, typically comprising sandstone, siltstone and claystone.

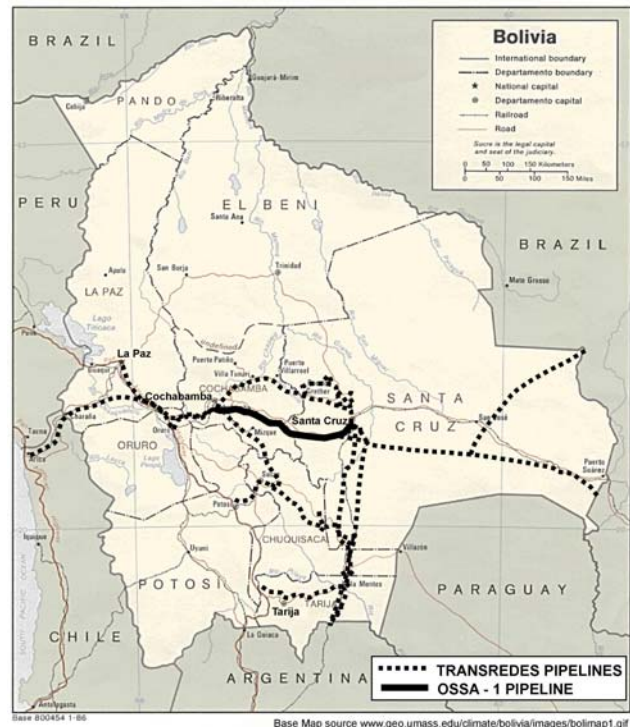


FIGURE 1: TRANSREDES S.A. PIPELINE NETWORK

Seismicity through the Sub-Andean Ranges along the OSSA-1 pipeline is moderate, with the peak horizontal ground acceleration for the 1:475 year earthquake expected to exceed 0.2 g. Annual precipitation averages between 500 and 1000 mm, with most of this falling between the months of November and March.

Ongoing tectonic uplift increases channel gradients and sediment transport capabilities of east and north-flowing rivers. Landslides occur frequently, and where streams undercut the toe of unstable slopes, landslide dams often develop, which in turn can breach, causing outburst floods or debris flows. Earthquakes can also trigger rock falls, rock slides and soil liquefaction.

At approximately KP 250 the OSSA-1 pipeline enters the Eastern Cordillera geological region, and remains there until it terminates in Cochabamba. Within the region, old metamorphic rocks have been uplifted and faulted, representing processes that are ongoing as evidenced by moderate seismicity and uplift rates that range from 1 – 4 mm/yr [8].

Seismicity through the Eastern Cordillera along the OSSA-1 pipeline is moderate, with the peak horizontal ground acceleration for the 1:475 year earthquake expected to exceed 0.2 g. Annual precipitation averages between 400 and 700 mm, with most of this falling between the months of November and March.

Despite these relatively arid conditions, landslide and debris flow hazards exist where slopes are steep. The deeply incised valleys are prone to damming by landslides, potentially followed by catastrophic outburst floods.

Basins such as those occupied by the City of Cochabamba, have a tectonic origin and have continued to undergo deformation through the Quaternary [9]. These basins are relatively arid at the present, but were occupied by large lakes in the past, and the deposits of sand and silt that were left behind are highly erodable.

Geohazards along the OSSA-1 pipeline within the Eastern Cordillera predominantly include hydrotechnical hazards (bank erosion, degradation, and encroachment), landslides, and debris flows.

**Incident Data**

As a result of the active geological terrain, pipeline failures caused by geohazards have historically occurred quite frequently on the OSSA-1 pipeline. It is estimated that approximately 21 geohazard-related pipeline failures have occurred in the 20-year period from 1983 to 2003, resulting in a failure frequency of about 2.5 per 1000 km.\*yrs. This is close to two orders of magnitude greater than experienced on European gas pipelines [10]. Consequently, it was clear that the risk assessment and risk management model selected for implementation by Transredes needed to address geohazards in a comprehensive manner.

Table 1 presents the relative percentage of failures grouped according to hazard class, for the OSSA-1 Pipeline between 1983 and 2003, based on the best available data. Figure 2 presents a comparison between the European Gas Pipeline Incident Data Group (EGIG) data [10] and OSSA-1 data. Incidents are defined by the EGIG as the unintentional release of product (gas).

Historical incident data for this and other South American pipelines played an integral role in calibrating the different hazard modules.

**Table 1: OSSA-1 Incident Data (1983 – 2003)**

Failure Cause	Percentage of Failures
Geohazards	52.5 %
Corrosion/Fatigue	15 %
Human Error	15 %
Third Party	7.5 %
Sabotage/Theft	10 %
Total	100 %

**RISK ASSESSMENT OBJECTIVES**

In addition to identifying and characterizing geohazards, Transredes identified several objectives for the overall risk assessment and risk management process. These include:

- developing a procedure to competently and systematically manage the risk of pipeline failure and to demonstrate to management, shareholders, regulators, government and insurers that those risks are being managed in accordance with globally accepted best management practices;
- implementing a risk-based methodology for the optimization of mitigation and maintenance activities. This requires identifying locations that would benefit from detailed investigation and more precise monitoring systems to optimise the type and timing of mitigative intervention;
- incorporating a computer-based pipeline data management system with a GIS interface; and,
- undertaking a pilot project to demonstrate proof of concept.

Further objectives for the OSSA-1 Pilot Project included:

- ranking OSSA-1 pipeline sections according to an overall risk score; and,
- producing a program of work to reduce the risks of batching LPG through the pipeline.

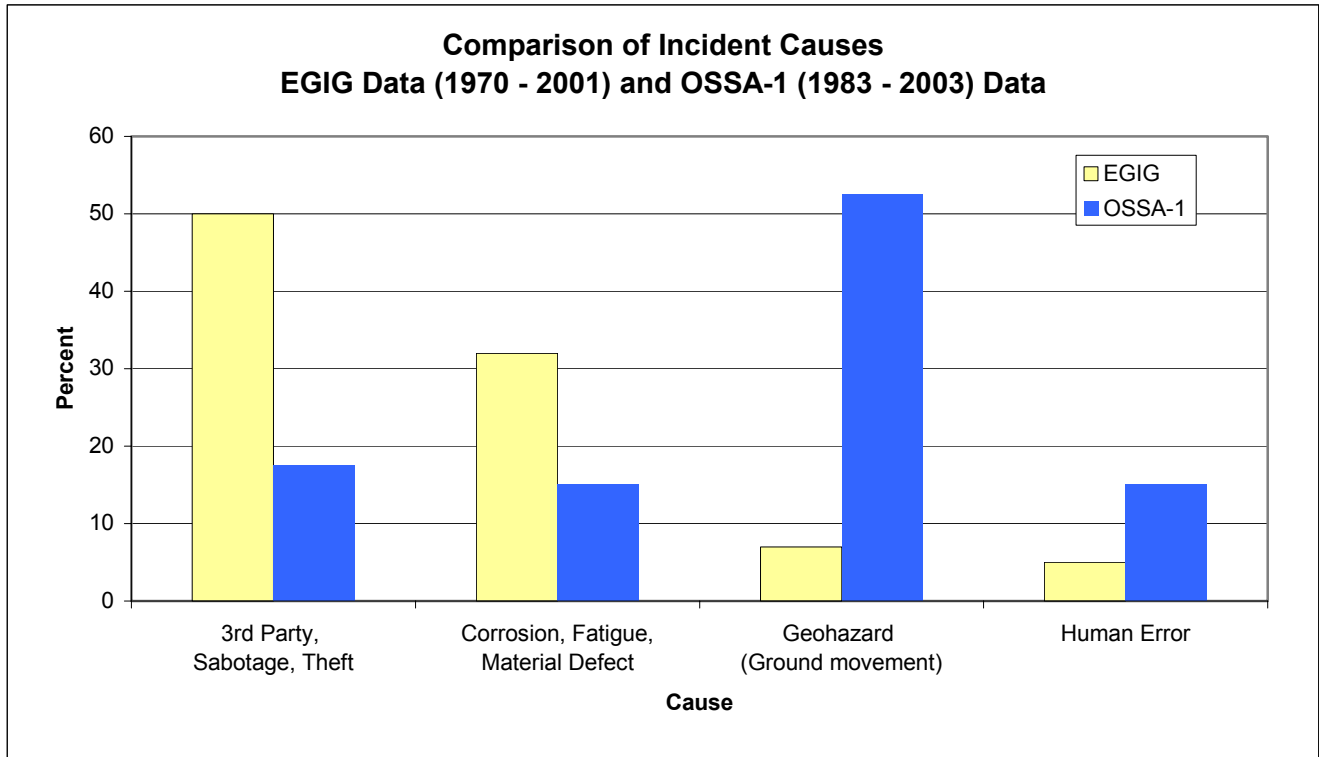
**MUHLBAUER RISK ASSESSMENT MODEL**

The Muhlbauer Model was adopted as the framework for the risk assessment process. As first published, the Muhlbauer Model was used to assign numerical scores to each of four hazard indices: Third Party Damage; Corrosion; Design, and Incorrect Operations. These factors were then numerically combined and a “Leak Impact Factor” (consequence factor) was applied to provide a relative measure of pipeline risk (Figure 3) [1,11].

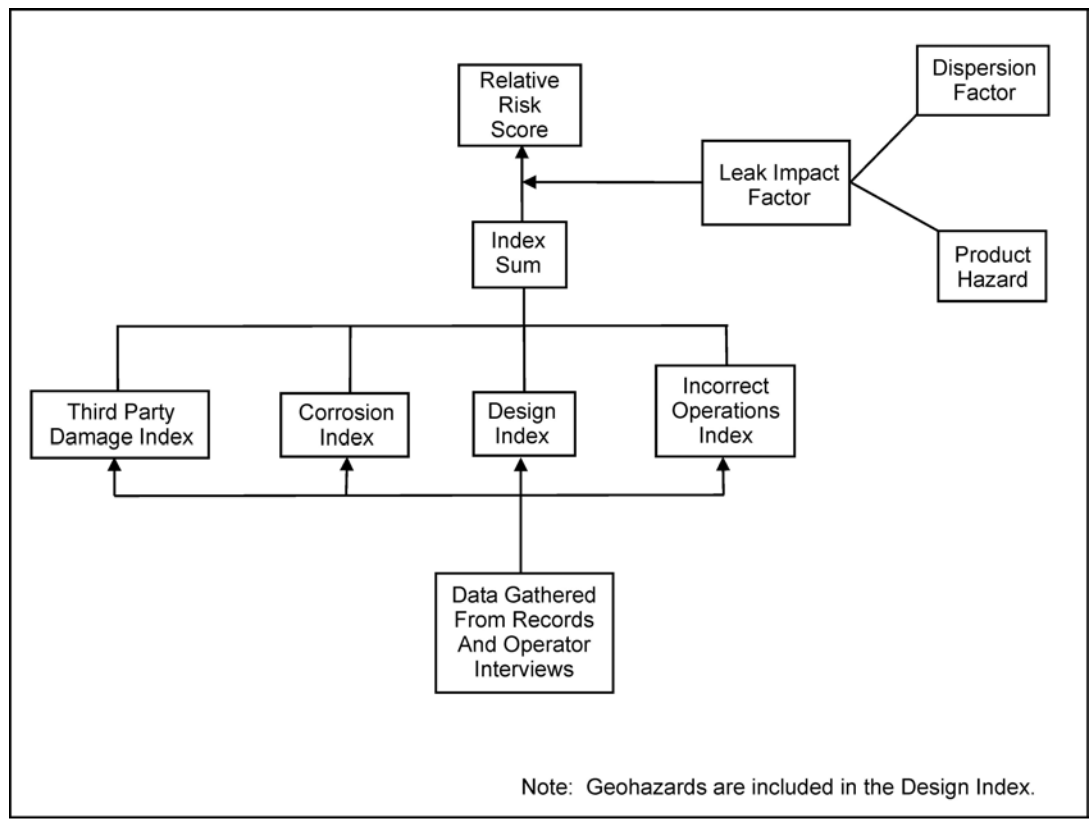
The original approach used a semi-quantitative index method to generate relative risk values. A value for each index hazard was calculated by gathering appropriate information relating to the pipeline and its surroundings, which were judged to either improve or decrease the safety of the pipeline.

The intent of the Muhlbauer Model was to provide a comprehensive framework for conducting pipeline risk assessments that could be modified to adequately account for unique situations, yet still provide a defensible system for relative comparisons between various pipelines or pipeline segments.

Geohazards in the original Muhlbauer example calculations [1] were assigned a low proportion [20 points, maximum] of the total 400 hazard index points. However, it was always anticipated that users of the approach would customize the model to properly reflect a pipeline system’s unique operating environment.



**FIGURE 2: EGIG and OSSA-1 Incident Data [10]**



**FIGURE 3: BASIC MUHLBAUER RISK ASSESSMENT MODEL [1]**

## MODEL ADAPTATION

The OSSA-1 Pilot Project used the Muhlbauer Model as a framework, but the model was modified in the following ways:

- a more probabilistic approach was adopted; and,
- the overall contribution of geohazards to the pipeline safety was increased.

Both modifications were undertaken to suit the operating environment of the Transredes pipeline network in Bolivia.

Similar to the initial Model, data relating to each index category (i.e. third party damage) was gathered. The data was used in various ways to create risk variables and then measure each variable's potential impact either increasing or decreasing the likelihood of the threat leading to a pipeline failure. The algorithms produce an estimated failure rate accompanying each threat at all points along the pipeline. Subsequently, reliability theory was applied, under the assumption that each threat is relatively independent and that the pipeline could be modelled as a series system, using:

$$P_f (\text{overall}) = 1 - [(1 - P_f (\text{3rd Party})) \times (1 - P_f (\text{cor/fatigue})) \times (1 - P_f (\text{theft/sabotage})) \times (1 - P_f (\text{error})) \times (1 - P_f (\text{geohazard}))]$$

(Eq. 1)

where  $P_f$  (hazard) represents the probability of failure for each threat or hazard type considered [12].

The assumption of independence between hazards located in close proximity to each other generally provides conservative results, especially if the hazards share a common triggering event [13].

Through adopting this approach for calculating the relative probabilities of failure for each hazard type, each hazard type automatically assumes an appropriate "weighting" in the overall calculation. For example, if any one hazard type presents a high probability of failure the contribution of this hazard to the overall probability of failure will not be masked in the case where the other hazards are negligible. This presents a significant advantage over the original index summation approach, where examination of each index independently was required.

Additionally, an extensive set of geohazard risk variables was created and assigned weightings so that this threat could be assessed in a more detailed and objective fashion.

Therefore, the modified Muhlbauer system adopted for the OSSA-1 Pilot Project (Figure 4) has enhanced the original approach, and more fully considers geohazards.

## Threats Considered

Hazards (or threats) to the pipeline were grouped into the following five classes:

- Geohazards;
- Corrosion and Fatigue (Integrity);
- Human Error /Incorrect Operations;
- Third Party Damages; and
- Theft/ Sabotage.

## Geohazard Module

Geohazards have been subdivided into three broad categories:

1. Tectonic Hazards – Fault Rupture, Liquefaction, Volcanic Eruption, and Tsunami (only fault rupture and liquefaction apply to the OSSA-1 Pipeline).
2. Geotechnical Hazards – Above-Right-of-Way (ROW) Slides and Rock falls, Through-ROW Slides, Below-ROW Slides (with the potential to retrogress back to the ROW) and Debris Flows.
3. Hydrotechnical Hazards – Scour, Degradation, Bank Erosion, Encroachment, Avulsion, and Debris Impact.

Additionally, situations where compound hazards exist, such as bank erosion destabilizing slopes and promoting through-ROW landslides, were incorporated into the analysis.

A more detailed description of each of these individual hazards can be found in previous publications [2,3,4]. Figure 5 presents a flow chart outlining how each category of geohazard was considered for the OSSA-1 Pilot Project.

## Geohazard Algorithms

OSSA-1 and other South American pipelines are exposed to a wide range of geohazards. Some, such as rock falls, occur rapidly and cause stress-related pipeline damage. Others, such as slow-moving landslides, cause gradual deformation leading to strain-related damage. Geohazard rating algorithms were developed that account for the type of failure mechanism associated with each hazard.

For each hazard type, a list of questions and potential (standardized) responses was developed to systematically gather information relating to either the likelihood of the hazard occurring and/or the vulnerability of the pipeline. Information was gathered at each location along the pipeline where a potential geohazard was identified, and entered directly into the database using a customized system interface (Figure 6).

As an example, for a location where an Above-ROW rock fall or slide was identified, information to answer the following questions was gathered:

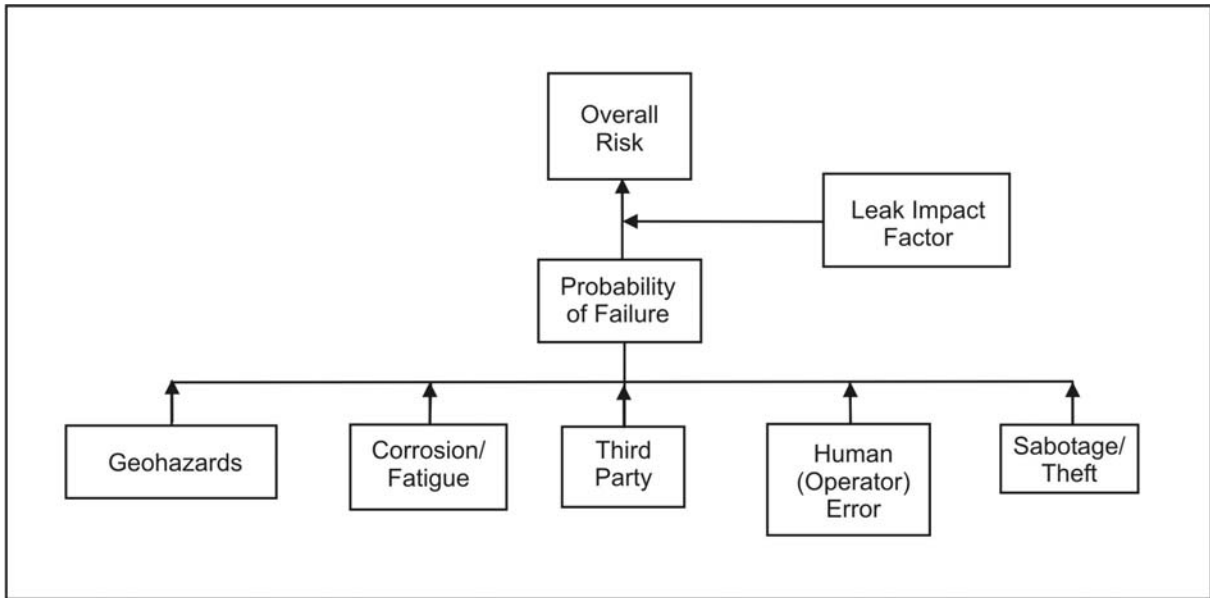


FIGURE 4: OSSA-1 MODIFIED RISK ASSESSMENT MODEL

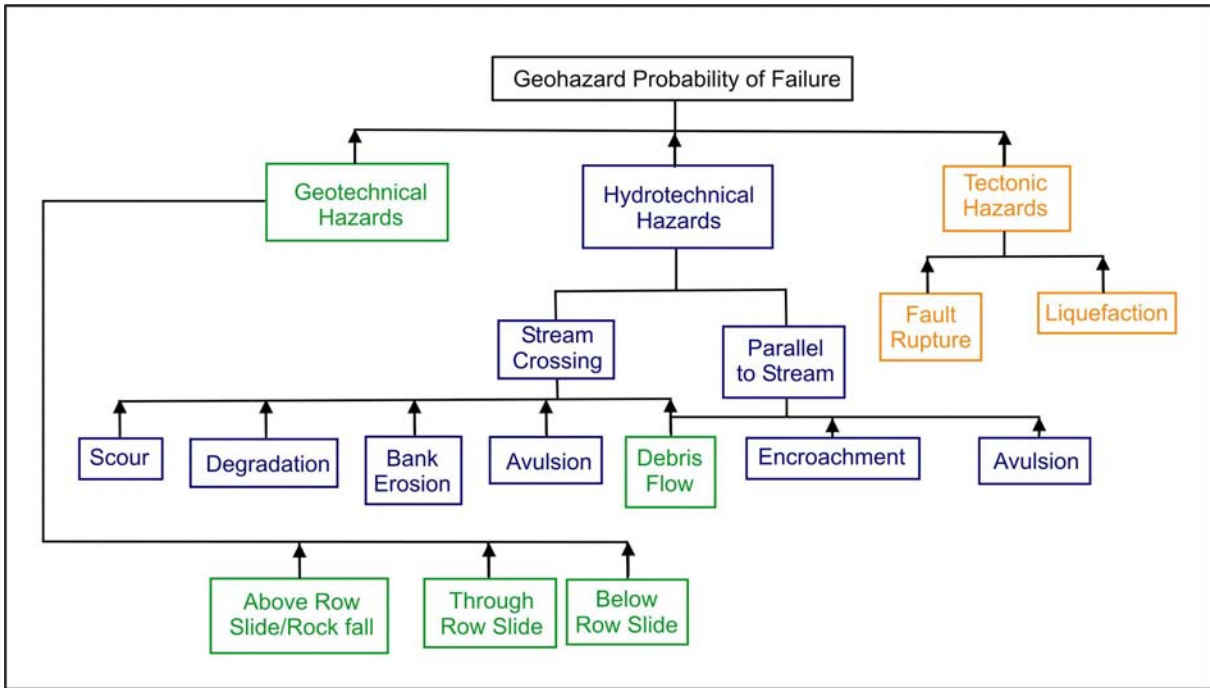


FIGURE 5: FLOW CHART FOR GEOHAZARD ASSESSMENT

### Likelihood of Hazard Occurring

What is the activity level?

(Active, Relict, Dormant/Suspended, Potential)

Is there evidence of an elevated water table condition? (Yes, No) Are there processes happening to destabilize the slope?

(Yes, No)

How is the terrain best described (after BC Terrain Classification System)[14]?

(0 - 3°, 4 - 15°, 16 - 26°, 27 - 34°, 35 - 45°, >45°)

### Vulnerability of the Pipeline

Which of the following best describes the type of hazard observed?

(Rock fall, Slide/Slump, Both)

What is the position of the pipeline?

(Above ground surface, Buried)

What is the volume of the largest event?

(< 10 m<sup>3</sup>, 10 – 100 m<sup>3</sup>, 100 – 1,000 m<sup>3</sup>, 1,000 – 10,000 m<sup>3</sup>, 10,000 – 100,000 m<sup>3</sup>, 100,000 – 1,000,000 m<sup>3</sup>, > 1,000,000 m<sup>3</sup>)

Is the pipeline effectively protected from the expected movement?

(Yes, No)

At least one question for each hazard type was related to monitoring and design adequacy. Appropriate designs and/or monitoring can reduce the likelihood of hazard occurrence or the vulnerability of pipelines to failure. For example, at locations where geohazards have been recognized, special measures (thick-walled pipe, altered burial depth, optimized alignment with respect to the geohazard, strain monitoring, etc.) may have been implemented. Hence, these questions provide a mechanism to give credit where effective mitigation is in place and properly documented.

Responses to each question were assigned a value between 0 and 1. The weighting or range of these values was set based on the relative importance of each piece of information as it relates to the estimate of hazard likelihood or pipeline vulnerability. Additional consideration was also given to the reliability of the information source. Potentially unreliable data sources were given less weight in the calculations.

The likelihood of the hazard occurring [ $P_{(occurrence)}$ ] was calculated by multiplying together all terms assigned to this category. Similarly, the vulnerability of the pipeline [ $V_{(pipeline)}$ ] was calculated by multiplying all relevant terms together.

Continuing with the Above-ROW rock fall/slide hazard calculation example, the Probability of Failure [ $P_{f(Above\ ROW)}$ ] was calculated using:

$$P_{f(Above\ ROW)} = P_{(occurrence)} * V_{(pipeline)} \quad (Eq. 2)$$

The Probability of Failure due to each elemental type of geohazard was calculated using the reliability theory formula previously outlined. Similarly, the overall Probability of Failure due to all geohazards [ $P_{f(geohazard)}$ ] was calculated using:

$$P_{f(geohazard)} = 1 - [(1 - P_{f(tectonic)}) \times (1 - P_{f(geotech)}) \times (1 - P_{f(hydrotech)})] \quad (Eq. 3)$$

These calculations were carried out within a Microsoft Access database used for data entry, utilizing a combination of SQL and Visual Basic functions, run in sequence, and utilizing dynamic segmentation. Where no geohazards were identified, a very low probability of failure value (equivalent to the annual probability of a comet striking the earth!) was assigned.

### **Data Gathering and Synthesis**

Information used to answer each of the specific geohazard questions was gathered from a combination of: aerial photographs; a cursory inspection of the ROW by geotechnical personnel; maps; as-built pipeline drawings and other pipe details (provided by Transredes); published papers; other engineering studies; and, from specific information collected by Transredes staff.

In order to reduce project cost and improve Transredes operating and maintenance staff's ability to recognize and document potential geohazards, a training program was implemented. Upon completion, Transredes staff collected information on each of the pipeline stream crossings, and some general slope information along the ROW using customized data collection forms. Transredes staff accompanied geotechnical personnel during their cursory inspection of the ROW to receive training and instruction, and an additional one day training program was conducted to provide direct instruction on how to complete the data collection forms.

Following data collection all information was entered into spreadsheets and verified by Transredes staff before it was incorporated into the overall geohazard database.

In addition to reducing costs for the project the program had the added benefit of improving the monitoring skills of Transredes field staff, which will enable Transredes staff to make earlier detections of problems along the ROW.

### **Geohazard Module Calibration**

Calibration of hazard results was performed for each type of geohazard (e.g. Above-ROW hazard), for each category of geohazard (e.g. geotechnical hazard) and for the overall geohazard ratings in comparison to other hazards (e.g. corrosion). Calibration involved reviewing the top rated sites, individual hazard scores, and the distribution of scores for each hazard type. These scores were compared to sites identified as being of high or low concern during the site inspection, and to the incident data. An overall comparison of the predicted geohazard failure frequency to the incident data was also conducted.


Microsoft Access - [frmPipeline : Form]

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Tahoma 8 B I U

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**PIPELINE NATURAL HAZARD RATING**  
PIPELINE DETAILS



Owner Name:

Operator:

Pipeline Name:

From KP:  km Country of Origin:

To KP:  km Country of Termination:

Main Product:

Secondary Product:

Nominal Diameter:  inches







Material Type:

Year of Construction:

Year of Hazard Rating:

BGC Project No.:

What is the owner's discount rate (time value of money or expected return if invested in other projects)?

 General Conditions  
 Landslide Hazards  
 Tectonic Hazards  
 River Hazards  
 Build tblHazardData  
 Costs

Record: 1 of 3  
Form View

FIGURE 6: GEOHAZARD DATA ENTRY AND MANAGEMENT

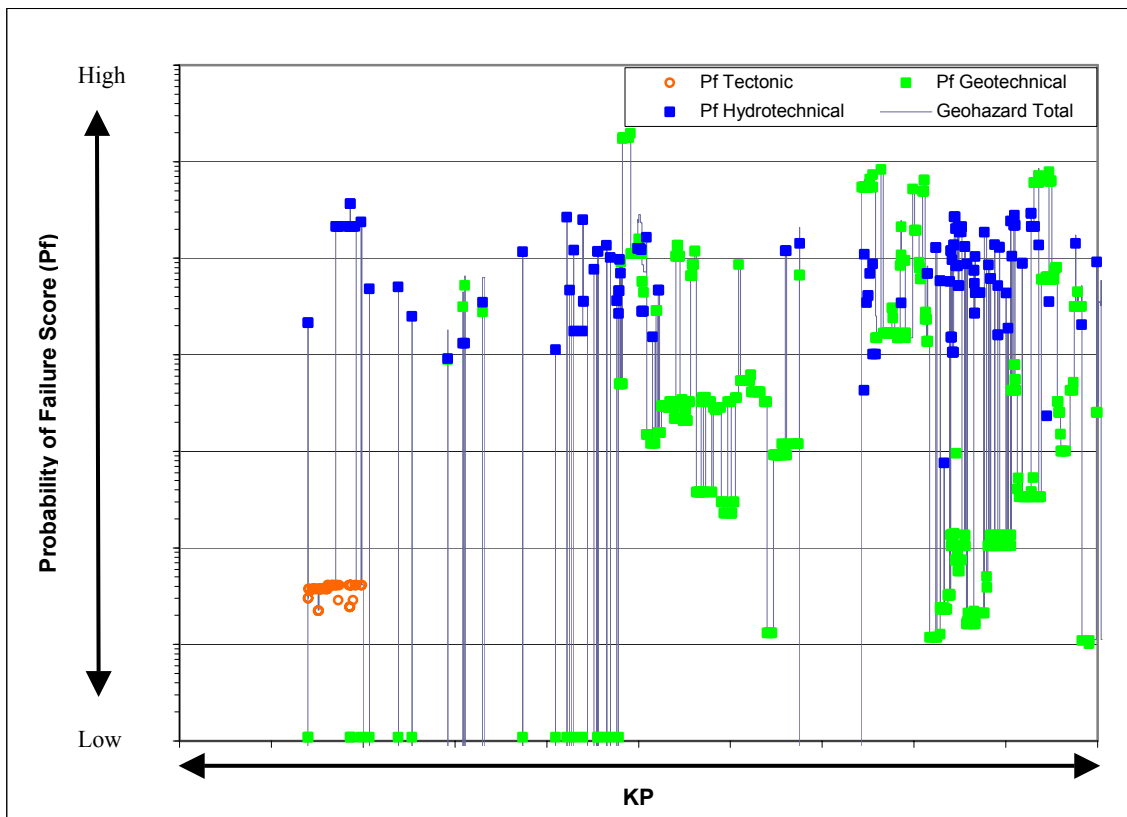


FIGURE 7: SAMPLE OF OSSA-1 GEOHAZARD RESULTS

Based on these reviews, values assigned to each of the standard rating question response scores were adjusted. Adjustment was continued until predicted probability of failure values for individual sites, and for the pipeline system as a whole, provided a reasonable match with historical data.

## PROJECT OUTCOMES

Figure 7 presents a sample plot of the relative geohazard probability of failure scores for a portion of the OSSA-1 pipeline. It effectively illustrates that the probability of geohazard-related pipeline failure is very site specific and can vary over several orders of magnitude.

Twelve sites received high annual probability of failure estimates due to geohazards. These were among the highest ratings along the pipeline due to any hazard type.

Other hazard types showed relatively high probability of failure scores as well; however, many of these high scores were related to information gaps or uncertainties in the condition of the pipeline. Based on the results of the risk assessment three initiatives have been identified for the initial OSSA-1 risk mitigation plan:

- Geohazard mitigation;
- Pipe strength uncertainty resolution; and,
- General uncertainty reduction.

Transredes is now utilizing the information gained from the risk assessment to set capital and maintenance budgets and to develop programs to address these high rated sites in a strategic manner to improve the operational safety of the OSSA-1 Pipeline.

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