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GEOHAZARD RISK MANAGEMENT FOR THE NOR ANDINO GAS PIPELINE

Michael Porter, BGC Engineering Inc.

Rodolfo Reale, Gasoducto Nor Andino

Gabriel Marcuz, Gasoducto Nor Andino

K. Wayne Savigny, BGC Engineering Inc.

ABSTRACT

A 1,050 km long 20" pipeline was constructed to transport natural gas from northern Argentina to the coast of Chile. On the Argentine side, significant portions of the route traverse rugged mountainous terrain subject to landslides, debris flows, flash floods, and earthquakes. On the Chilean side (situated up to 5,000 m above sea level), the pipeline crosses active faults and terminates at locations historically subject to tsunami.

The pipeline began operation in 1999. An outburst flood in a steep mountain stream caused the pipeline to rupture in 2001. Reactivation of a large rock slide in 2002 caused a second rupture. It appeared that the original design had underestimated the route's exposure to geohazards, and efforts were required to improve pipeline safety and reliability.

A geohazard risk management program was initiated in April 2002. Geohazards were identified and characterized through airphoto interpretation and field inspection. Sites were initially ranked using semi-quantitative risk estimates. Risk cost-benefit analyses were used to select optimal risk control measures at high ranking geohazard sites. These included monitoring programs, reconstruction of stream crossings, re-routes, and in one instance, landslide avoidance using a horizontal directional drill. Risk control measures were implemented between 2002 and 2006, and additional efforts are ongoing.

An updated assessment of geohazard exposure was completed in 2005 with the objective of quantifying the level of risk reduction that had been achieved and prioritizing further risk reduction efforts.

This paper describes implementation of the geohazard risk management program using a case history format. It highlights the techniques used to control the range of hazards that were identified in 2002 and to quantify the improvements achieved by 2006. The paper concludes with an overview of additional risk reduction initiatives that are in progress or under consideration.

INTRODUCTION

Gasoducto Nor Andino belongs to the Suez Group. It comprises a 1,050 km long pipeline that transports natural gas from northern Argentina to the coast of Chile. During the first three years of operation, floods and landslides caused two pipeline ruptures. This paper describes the implementation of a geohazard risk management program that was designed to identify and characterize hazards, estimate the potential for pipeline failure, prioritize remedial works, and monitor residual risks along the Nor Andino pipeline.

PIPELINE DESCRIPTION

The Nor Andino pipeline was constructed to transport natural gas from gas basins in the northern region of Argentina to the Chilean cities of Tocopilla, Mejillones and Coloso on the Pacific Ocean (Figure 1). It supplies gas to two combined cycle power generation facilities, numerous industrial clients, and the cities of Humahuaca (Argentina) and Calama (Chile).

Fully constructed of 20" diameter, three-layer extruded polyethylene coated steel pipe, the mainline runs 380 km through Argentine territory to Paso de Jama, and continues in Chile for about 330 km to the town of Crucero. It then splits into two branches: 1) a 16" diameter pipeline from Crucero to Mejillones; and 2) a 12" diameter pipeline from Crucero to Tocopilla. A third branch off the 16" pipe at Ordoñez extends to Coloso.

The first pipeline section begins in the Sub-Andean Ranges geological province and crosses the forest of Yungas where elevations typically range from 300 to 600 metres above sea level (masl). It then climbs up into the Eastern Cordillera to more than 4,000 masl over a distance of less than 100 km. These areas experience heavy rainfalls up to 1,500 mm per year, most of which occurs over a 5 month rainy season. The pipeline crosses rivers that are subject to debris floods and debris flows, as well as slopes subject to debris and rock slides.

Figure 1. Location Map



The pipeline continues across a high plateau (the Puna) and the Western Cordillera at elevations near 5,000 masl. Geohazard exposure is diminished through this section, although the pipeline crosses the base of several volcanoes that have erupted throughout the Holocene.

The pipeline descends from the Western Cordillera into the Atacama desert. Although extremely arid, rare rainfall events can cause flash flooding with potential to expose and damage the pipeline. This region is also one of the most seismically active areas in the world. The pipeline crosses several active and capable faults, including the Atacama fault that ruptured in 1995, producing displacements at the ground surface of several metres.

The pipelines terminate on the Chilean coast after an abrupt descent from the mountains. The terminus of all lines is located below 30 masl, and within the zone that has historically been subject to tsunamis.

In many locations the pipeline is not accessible by public roads and can only be accessed via 4-wheel drive vehicles along the right-of-way (RoW), or by helicopter.

The pipeline's current transport capacity is 4.90 Mm³/day, which can be extended to 8 Mm³/day, operating at a 97 bar maximum allowable operating pressure. The system includes two compressor stations, block valves with low-pressure closure located every 30 km, scraper traps located every 130 km, and a remote supervisory control and data acquisition system. An impressed current cathodic protection system operates over the full length of the pipeline.

Construction of the pipeline was carried out via a design-build contract. Construction on multiple fronts began in May 1998 and was completed in October 1999.

GEOTECHNICAL FAILURES

2001 Failure Caused by Outburst Flooding

In March 2001 a pipeline rupture occurred at a crossing of the San Andrés river, Argentina, near KP 97 (Figure 2). The crossing was located at the end of a 15 m wide gorge that extends upstream for about 300 m. The river drops about 50 m over this short section. At the terminus of the gorge there is a transition from bedrock walls to sand and gravel banks that have been incised about 20 m.

Figure 2. Looking Upstream at the Failed Crossing



It is believed that the pipeline failure was caused by the breaching of a landslide dam that led to an outburst flood or high intensity debris flow. The first damage at the crossing likely entailed bank erosion caused by flooding, while the actual rupture of the pipeline was caused by the debris flow. The debris flow had a peak discharge of at least twice the calculated discharge for the 50-year water flood, consistent with observations by Jakob et al. (2004). Debris flow velocity was estimated at between 6 and 8 m/s. Debris densities were observed to exceed 1,500 kg/m³.

A temporary 6" bypass pipeline was constructed downstream and was operated until the damaged crossing could be repaired. The incident caused 25 days of business interruption.

Erosion occurred at a second crossing of the San Andrés located about 3 km downstream. Although the pipeline was not damaged, significant erosion control and pipeline protection measures were subsequently installed.

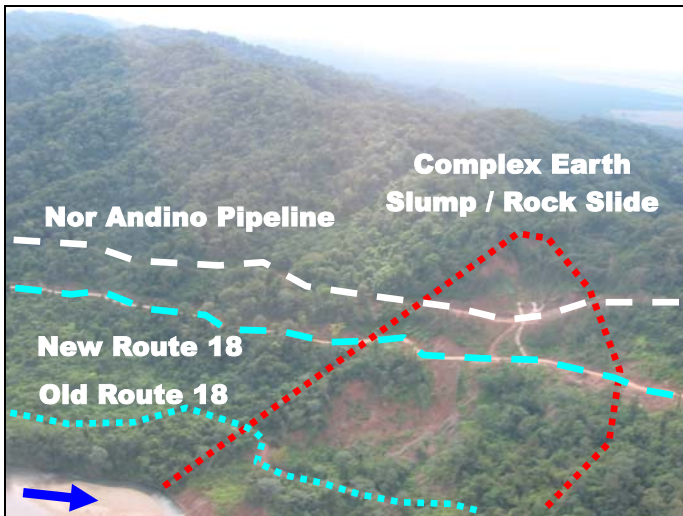
2002 Failure Caused by Rock Slope Deformation

A second pipeline rupture, also on the Argentine side, occurred near KP 40 at the end of January 2002. The region in the vicinity of the failure is characterized by low hills formed predominantly in Tertiary sedimentary bedrock including sandstone, siltstone and shale. The hills formed by folding and faulting, resulting in bedding planes inclined at between 15 and

45°. Despite only moderate relief, landslides are common as a result of weak bedrock containing adversely-oriented bedding planes, the presence of residual soils, heavy rainfall (typically 1,500 mm/yr), and active fluvial processes.

Between KP 40 and 41, the pipeline descends a west-facing slope from the ridgeline to the valley bottom, running sub-parallel to the slope contours (Figure 3). The left bank of the Rio Blanco aggressively erodes the toe of this slope.

Figure 3. Slope Stability Issues near KP 40



On January 27, 2002, a pipeline rupture occurred following several metres of slope deformation, later determined to be caused by a complex deep-seated earth slump and rock slide.

The crest of the rock slide escarpment was located 30 m above the RoW. At the RoW the slide experienced downward displacements varying between 5 and 15 m. In turn, the base of the slope was located at the level of the left margin of Rio Blanco. The slide displayed lateral displacements of approximately 20 m at the toe, which comprised thick colluvial soils that slumped into the river.

The main causes and triggers of the landslide and, therefore, the pipeline rupture were:

- increased pore pressure as a consequence of 200 mm of rainfall in less than 24 hours on the day prior to the incident;
- unfavorable geological conditions, including the presence of clay-rich rock strata oriented sub-parallel to the slope inclination; and,
- excavation for the new routing of Provincial Route No. 18, located immediately below the RoW.

A metallographic analysis showed that the rupture was not caused by manufacturing or construction defects, or due to the existence of spots prone to fissures.

As a consequence of this rupture, gas flow was interrupted for 90 days until a slope stability analysis was performed, the necessary emergency repair measures were determined, and repairs to the damaged pipe were completed. The pipeline was operated above ground for several months in order to reduce the potential transfer of loads to the pipe in case the slope continued to deform.

GEOHAZARD RISK MANAGEMENT FRAMEWORK

Based on the incidents in 2001 and 2002, a need for a comprehensive geohazard risk management program was identified by Nor Andino. The program implemented was designed to identify and manage geohazard risks in an efficient and transparent manner, consistent with Canadian guidelines and other international practice standards.

The Canadian Standards Association (CAN/CSA-Q850 1997) framework for risk management calls for a combination of risk assessment and risk control. The Association goes farther with respect to oil and gas pipeline systems, specifying that risk assessment shall be a formalized process comprising the following components (CSA Z622 2003):

- a. Risk analysis:
 - i) definition of objectives;
 - ii) system description;
 - iii) hazard identification;
 - iv) frequency analysis;
 - v) consequence analysis; and,
 - vi) risk estimation; and,
- b. Risk evaluation:
 - i) risk significance;
 - ii) options evaluation; and,
 - iii) action / monitoring.

In practice, corporations typically define their objectives and assemble their system descriptions. These are given to specialists who develop formal risk analysis programs for geohazards and other system-wide hazards. Once complete, the hazard-specific risks are subjected to risk evaluation wherein the estimated risks are considered in relation to social, environmental and economic consequences and a variety of options for risk control are assessed and prioritized. Once a risk control decision is made and implemented, the CSA guidelines (1997, 2003) call for assessment as to whether it had the desired affect. This leads to an ongoing cycle in which the risk estimation and evaluation components are regularly reassessed.

Following is a brief description of each of the risk management components and how they were incorporated in the Nor Andino geohazard risk management program.

Geohazard Identification

Geohazard identification in its simplest reactive form involves location, identification, and comparative assessment of historical failure incidents caused by geohazards.

The trend toward proactive management has resulted in emphasis on terrain analysis using stereo aerial photographs and satellite imagery, as was carried out for the Nor Andino pipeline. Historical geohazard features were identified and other terrain polygons were mapped within a zone of potential influence on the pipeline. In many cases, the study area was extended beyond the limits of the pipeline RoW; for example, extending many kilometers into watersheds above stream crossings where there was evidence of debris flow activity or landslide dam bursts. The results not only identified existing geohazard features but also information on the geohazard potential of other terrain polygons.

Geohazards considered were assigned to one of three broad categories: geotechnical (above-RoW slides and falls, on-RoW slides, and debris flows); hydrotechnical (scour, degradation, bank erosion, encroachment and avulsion); and tectonic (tsunami, fault rupture, liquefaction, and volcanic eruption). Porter et al. (2004) provide a description of these hazards. As is typical of many trans-Andean pipelines, all hazard types were identified as having some potential to cause pipeline failure.

Frequency Analysis

Frequency analysis determines the likelihood of the occurrence of geohazard events leading to pipeline failure that may be expressed both qualitatively and quantitatively. Common methods include: analysis of historical incident data; mathematical modelling; and judgement and experience of qualified engineering and operational personnel (CSA 2003).

In the pipeline industry, a long heritage of reactive management has led to misuse of historical frequency values for ground movements, which is how the industry tracks geohazard incidents. Typically expressed as failures per year or failures per kilometer*year, these are often based on industry wide experience spanning many decades and heavily biased to flat land pipelines where geohazards are virtually unknown. Failure frequencies based on pipeline systems in Western Europe and the United States cannot be indiscriminately used for trans-Andean pipeline systems where failure frequencies can be much higher (Figure 4).

At the most detailed level, failure frequency can be estimated through mathematical modelling and 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. The method is not practical for long pipeline networks exposed to a large number and variety of geohazards unless a lengthy period is allowed for phased risk analysis.

The systematic capture of engineering judgement provides a third option for estimating failure frequency. Attributes describing the natural system (e.g. geology, slope angle, historical landslide activity) and the pipeline (e.g. location, depth of burial, presence of protective measures) are recorded through a combination of terrain analysis, field inspection and review of as-built documentation supplied by the designer or the operator. Standardized attribute responses are assigned numerical scores, with score values calibrated using engineering judgement and historical incident data. The scores are multiplied together to obtain estimates of hazard likelihood, vulnerability, and the expected frequency of pipeline failure. Esford et al. (2004) and Porter et al. (2004) give examples.

In the case of the Nor Andino risk management program, a judgement-based approach was applied to assign order-of-magnitude estimates of geohazard occurrence and pipeline failure frequency.

Consequence Analysis

Consequence analysis provides estimates as to the severity of adverse effects, including one or a combination of the following: injury or loss of life, environmental impacts and property damage, repair costs, business interruption costs, fines, loss of reputation, and others. Methods for estimating consequence are improving rapidly and are well documented by Muhlbauer (1996, 2004) and others (e.g. Pluss et al. 2000, Zimmerman et al. 2002).

At this point in time, detailed consequence analyses have not been carried out for the Nor Andino pipeline, rather, the work has focused on the potential for pipeline failure, defined as a pinhole crack, leak, or rupture. Once top-ranking geohazard sites are brought under control, it is anticipated that ongoing prioritization of geohazard mitigation and maintenance will give consideration to both the likelihood and consequences of potential failures.

Risk Estimation

Risk estimation involves combining the results of frequency and consequence analyses to produce a measure of risk. CSA (2003) 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.
2. Risk Index (Semi-quantitative)	Factors that influence frequency and consequence are assigned numerical values and mathematically combined, usually through summation. Separate indices are developed for each potential failure cause.
3. Probabilistic (Quantitative) Risk Analysis	Failure frequencies and consequences are estimated quantitatively and combined using probability theory.

Qualitative (risk matrix) and semi-quantitative (risk index) methods for incorporating hazards in an overall risk management program are well developed (Mulbauer 1996 and 2004, Porter and Savigny 2002, Savigny et al. 2002). They are easy to construct and implement and they produce a relative rating for each hazard that is repeatable and conceptually easy to understand. The absolute value of the relative rating is, however, arbitrary and thus difficult to compare with other hazards. It is also difficult to move from these arbitrary values into quantitative risk determination.

The potential for geohazard occurrence and subsequent potential for pipeline failure can vary over several orders of magnitude. Consequently, risk estimates are best evaluated and communicated using quantitative or probabilistic methods. When quantitative probabilities of failure are combined with explicit consequence valuations to determine the risk cost exposure, the results are meaningful to a wide range of stakeholders with varying technical, environmental, social and business interests. Qualitative or semi-quantitative methods simply do not come close to this level of sophistication.

Geohazard risk assessment for the Nor Andino pipeline was initially undertaken in 2002 using a semi-quantitative (or risk indexing) approach, whereby each potential hazard type at each location along the pipeline was assigned a numerical score out of a possible 100 points. Where multiple hazard types overlapped, scores were summed to give a total hazard rating. A detailed description of the semi-quantitative approach is provided by Porter and Savigny (2002) and Savigny et al. (2002).

The Nor Andino risk assessment was updated in 2005 using quantitative methods. Probabilities of hazard occurrence, spatial probability of hazard impact on the pipeline, and pipeline vulnerability were assigned for each potential hazard at each location along the pipeline. Dynamic segmentation procedures were used to subdivide the pipeline into increments of uniform hazard exposure. Where multiple hazards

overlapped, series summation techniques were used to estimate a total probability of pipeline failure to each hazard increment. Detailed descriptions of the quantitative approach are provided by Porter et al. (2004) and Esford et al. (2004).

Risk Evaluation

Risk evaluation is a structured process to differentiate levels of risk, especially where they are significant in relation to the associated social, environmental, and economic consequences. Where risks exceed tolerable levels, management options are identified and evaluated under the task of Risk Control.

Where linear facilities face a high level of geohazard exposure, resources are often not available to immediately address all sites where tolerable risk levels are exceeded. Instead, sites are prioritized for ongoing inspection, monitoring and stabilization on the basis of their relative risk. In Canada, government agencies and private industry can meet the minimum standard of care required of operators of linear facilities by following of this process in a consistent and transparent manner.

In the case of the Nor Andino pipeline, sites were assigned to one of five priority classes for risk control on the basis of the estimated annual probability of geohazards causing pipeline failure:

- Class ‘A’ – Urgent Priority ($P_{\text{failure}} > 0.25$)
- Class ‘B’ – High Priority ($P_{\text{failure}} = 0.025$ to 0.25)
- Class ‘C’ – Moderate Priority ($P_{\text{failure}} = 0.0025$ to 0.025)
- Class ‘D’ – Low Priority ($P_{\text{failure}} = 0.00025$ to 0.0025) and,
- Class ‘E’ – Very Low to Negligible ($P_{\text{failure}} < 0.00025$).

For the original semi-quantitative risk assessment, sites were assigned to priority classes on the basis of individual and combined hazard ratings. In the quantitative risk update, sites were assigned to classes based directly on the estimated probability of pipeline failure.

Risk Control

Risk control is the process of decision making for managing risk. Where risks exceed tolerable levels, options to control (i.e. reduce) risk are identified. Often, optimal solutions are determined through the use of risk cost-benefit analysis techniques.

In the case of the Nor Andino pipeline, the first priority was to mitigate the risks posed by all Class ‘A’ sites and several of the top ranking Class ‘B’ sites through either physical stabilization of the hazard or re-routing of the pipeline. Inspection and monitoring programs were implemented for lower ranking Class ‘B’ sites as resources permitted. As top ranking sites were brought under control, and as resources became available, greater emphasis was placed on

incorporating Class 'C' and 'D' sites into the management program.

Action and Monitoring (Risk Management Plan)

The action phase relates to the implementation, communication, and monitoring activities required to ensure the continuing effectiveness of the risk management process. Although this is the last component of the risk management process, it is here that its living nature is vested. Neither geohazards or their potential to impact pipeline facilities is static, thus the standard of care for risk management of geohazards demands that it be a living program and not a one-time effort. This requires three essential elements:

- a database that hosts the attribute and analytical data created as part of the risk assessment and risk evaluation components;
- a corporate commitment for ongoing reassessment of right-of-way and operating conditions, including regular comparison of current conditions with those documented in the database; and,
- when supported by this reassessment, modification of the risk control approach.

The remainder of this paper focuses on some of the risk control, action and monitoring activities undertaken to manage geohazard risks identified along the Nor Andino pipeline. The Nor Andino Risk Management Plan involves three main components:

1. Predictive Actions – risk assessment, coupled with instrumentation and measurement;
2. Preventative Actions – continuous surveillance to look for and respond to changed conditions; and,
3. Corrective Actions – remedial works at top-ranking sites.

PREDICTIVE ACTIONS

In addition to the geohazard risk assessment, activities were undertaken to detect geotechnical and hydrotechnical hazards and their impacts on the pipeline.

Three Caliper and Geopig runs were performed in 2002, 2003 and 2005, in order to measure pipeline displacements, deformations, and stresses.

In several locations a RoW instrumentation system was implemented, including extensometers, inclinometers, and more than 30 fixed point survey monuments that are measured monthly to detect geotechnical movements over an area that extends beyond the width of the pipeline RoW.

PREVENTATIVE ACTIONS

A program of continuous surveillance was implemented over the first 120 km of the pipeline where geohazard exposure

was deemed to be greatest. It consisted of construction and outfitting of three base camps (located close to block valves) with heavy machinery, emergency repair equipment and materials, and inspection personnel in order to:

- a. obtain near real-time information from the field regarding weather and environmental conditions, pipeline integrity, and observations of developing geohazard events;
- b. maintain access along the RoW to permit rapid response in case of emergencies; and,
- c. quickly perform repairs to the RoW and, if necessary, the pipeline.

To complement these activities three new block valves with remote control were installed in order to block, vent and isolate shorter sections of the pipeline.

CORRECTIVE ACTIONS

Following the 2002 risk assessment over 400 minor repairs were made to the pipeline RoW, most of these involving the construction of erosion control measures on slopes and at minor stream crossings. More elaborate remedial works were undertaken at about ten of the Class 'A' priority sites and detailed monitoring programs were established for several of the Class 'B' sites. Some examples are described below.

KP 40 Horizontal Directional Drill

Detailed surficial mapping demonstrated that the area of historical deep-seated rock slope deformation extended up to and beyond the ridge line above the RoW. Recurring shallow debris slides to a depth of about 3 m were ubiquitous in the steep residual soil slopes for several hundred metres either side of the pipeline rupture site. A secure route for a conventional buried re-alignment of the pipeline could not be located.

A preliminary evaluation of a route to avoid the landslide prone slope by crossing the Rio Blanco downstream and upstream of the rupture site was undertaken. Aggressive scour and bank erosion would have negated the viability of conventional trenched crossings, requiring two horizontal directional drills (HDD's) each exceeding 750 m in length. The pipeline route along the right bank of the Rio Blanco would have still faced high exposure to encroachment and channel avulsion.

A third option involved a re-route following the east side of the landslide prone ridge until reaching a point north of the rupture site, and a 1,400 m long HDD from east to west beneath the ridge to avoid all of the unstable slopes. This option had the second lowest construction cost and the lowest operational risk cost of all the options considered. It was identified as the preferred option via risk cost benefit analysis.

Detailed geotechnical investigations at the drill entrance and exit points were undertaken, as well as airphoto

interpretation and mapping of bedrock exposures along the proposed alignment. Mud rotary drilling was completed to obtain core samples for geomechanical classification. A capable fault was identified running sub-parallel to the proposed HDD drill path, and the final alignment was located to minimize vulnerability to fault movement.

The re-route and HDD were started in September 2002 and completed successfully in December 2002.

San Andrés River Crossings

Further evaluation of the San Andrés river demonstrated it was subject to frequent cycles of channel aggradation during periods on increased sediment supply, followed by rapid degradation and scour, especially following outburst floods from failed landslide dams. Outburst floods regularly generate hyperconcentrated flows and / or debris flows capable of transporting the largest boulders stored in the channel. Therefore, use of local materials to armour the banks and channel bottom would not provide adequate protection for the pipeline.

The adopted risk control approach involved deep burial of both crossings and an extended setback of the sag bends well into the gravel river terraces. At the channel thalweg, the depth of burial exceeded 6 m at the time of construction, although as indicated earlier, the depth of cover can change dramatically in a single flood event. A concrete slab reinforced with a grid of heavy steel beams was placed over the pipeline as a means of additional protection.

Monitoring and helicopter inspections are carried out regularly during the rainy season for the purpose of monitoring channel degradation at the crossing and the potential formation of landslide dams upstream.

Rio Volcan Crossing

Like the San Andrés crossings, the Rio Volcan crossing was damaged by erosion from outburst floods. This crossing is located about 10 km upstream of the upper San Andres crossing, on a tributary stream. The Rio Volcan passes through the toe of an extremely large rock slide complex, with several slides exceeding 1 million cubic metres in volume. Consequently, it is prone to frequent landslide damming and outburst floods capable of transporting boulders several metres in diameter.

Unlike the San Andrés crossings, the geometry and depth to bedrock at the Rio Volcan did not permit the re-construction of a deep conventional crossing. Furthermore, the site was not readily conducive to directional drilling as a result of geometric constraints and evidence of large-scale rock slope instability on one of the banks.

Ultimately, a 60 m long aerial crossing was constructed, located about 30 m above the active floodplain. The channel section beneath the aerial crossing appears capable of passing the estimated 500 year flood.

KP 105 – 112 Rock Slides

Beyond the Rio Volcan crossing, the Nor Andino pipeline traverses a mid-slope position subject to a series of deep seated rock slides, each about 1 km wide by 1.5 km long with an estimated depth greater than 100 m (i.e. in excess of 150 million cubic metres). Seasonal or decadal scale reactivation of each of the rock slides appears to be controlled by toe erosion at the valley bottom, as well as increases in pore pressure in years with heavy rainfall. Seismicity may also contribute to large-scale movements as sacking features are common.

The pipeline crosses several zones of active slope movement near the top of the valley, where visible tension cracks across the RoW often ranged from about 10 to 100 cm wide. A geopig run in late 2002 verified the presence of a developing wrinkle in the pipeline at one location.

Engineering geology mapping was carried out to estimate limits of active slides and failure geometry. This involved detailed airphoto interpretation followed by field surveys to map the location and activity of tension crack and graben features. The results were used to design a geotechnical drilling and instrumentation program involving the installation of slope inclinometers and terrestrial survey monuments to monitor slope movement.

In several locations where movements exceeded tolerable levels, the pipeline was re-located to the ridge line where it is much less vulnerable to ongoing rock slope deformation.

POST-MITIGATION RISK UPDATE

In late 2005 a geohazard risk assessment update was carried out with the purpose of achieving several key objectives:

- to transition from a semi-quantitative index based ranking system to one based on quantitative estimates of the potential for pipeline failure;
- to identify areas where hazard exposure may have increased since 2002 as a result of rainfall and flood events; and,
- to evaluate the effectiveness of risk management activities undertaken by Nor Andino, and to account for these in revised estimates of pipeline failure potential.

Where geohazard risks continued to exceed tolerable levels, recommendations for ongoing risk management were provided.

The scope involved four main tasks: review of the new information gathered by Nor Andino since 2002; data transfer from the spreadsheet index-based system to a quantitative system in Microsoft Access; field inspection of high ranking sites, especially those where mitigation activities had been undertaken; and documentation of results.

As part of the scope of work, a static version BGC's proprietary geohazard database was transferred to Nor Andino, providing basic geohazard data review, a photographic record of site conditions, risk ratings, and reporting functionality. The database can be updated on a regular basis, involving a brief field inspection to identify changed conditions and documentation of any improvements made to reduce geohazard risk exposure, satisfying the requirements for a 'living' risk management program.

Risk Update Results

Direct comparison between the 2005 risk assessment update and the original 2002 risk assessment is difficult due to the differences in the semi-quantitative and quantitative methods. A comparison of the approximate lengths of pipeline in each priority class is as follows:

Table 2. Comparison of Approximate Pipeline Lengths in Each Priority Class in 2002 and 2005

Priority Class	2002 Length	2005 Length ¹
'A' $P_f > 1:4$ per km	2 km	0 km
'B' $P_f > 1:40$ per km	50 km	2 km
'C' $P_f > 1:400$ per km	100 km	21 km
'D' $P_f > 1:4,000$ per km	300 km	166 km
'E' $P_f < 1:4,000$ per km	594 km	858 km

1. Changes between 2002 and 2005 are attributed to remedial measures implemented by Nor Andino, and to the greater precision of the quantitative ranking procedure.

The dramatic reductions in pipeline length in the higher priority classes are the result of two factors:

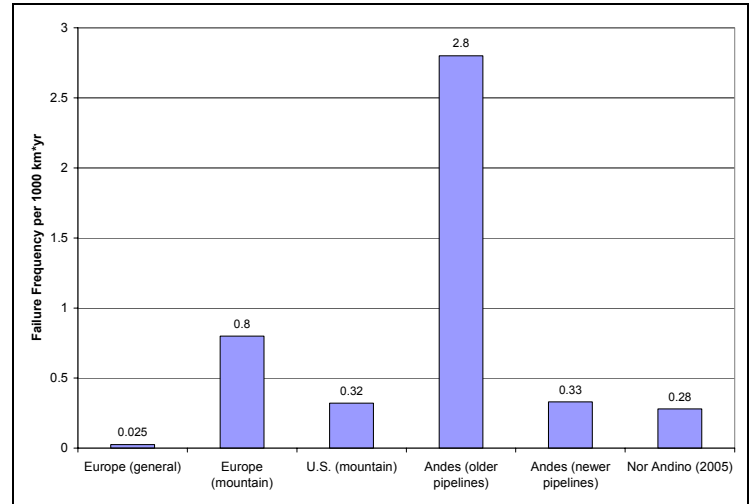
- a) initiatives undertaken by Nor Andino to reduce the exposure to geohazards; and
- b) the greater ability of the quantitative ranking procedure to separate high risk sites from those with a low to moderate potential for pipeline failure.

In 2002, it was subjectively estimated that the total probability of pipeline failure would drop from 0.67 (based on historical performance) to about 0.33 (or one failure every 3 years) in light of the mitigation activities completed and underway at the time of that assessment. The 2005 calculated pipeline failure frequency was 0.29/yr (or one failure every 3.5 years). This, in conjunction with the performance of the pipeline over the past four years supports the assessment that measures implemented by Nor Andino have reduced the probability of future failures by at least a factor of two.

Ongoing Risk Management

A failure frequency of 0.29 over 1,050 km of pipeline is equivalent to 0.28 failures per 1000 km*yr. This is about 10 times less than the failure frequencies reported for poorly constructed pipelines in Columbia and Bolivia, about 10 times greater than the average statistic for Western Europe, and in line with pipelines in mountainous terrain in the United States and newer pipelines constructed in the Andes (Figure 4).

Figure 4. Estimated Nor Andino Failure Frequency versus Other Pipelines (after Sweeney et al. 2004)



While current risk estimates suggest the reliability of the Nor Andino pipeline is now similar to or better than most of the modern pipelines constructed in difficult mountainous terrain, there are still opportunities to further improve its performance. Risk reduction initiatives planned or currently underway include detailed assessment of the stability of known landslides, determination of flood discharge-return periods for several streams prone to debris flow and outburst floods, and, where required, the design of remedial measures to reduce the risks from these hazards. Additionally, repeat geopig surveys are scheduled for every two years to monitor against the early stages of pipe deformation that are difficult to identify through airphoto interpretation and field inspection.

It is believed that the measures implemented by Nor Andino since 2002 in connection with the pipeline's operation, based on the geohazard risk management program described herein, represent the best available option to mitigate the risk of future ruptures and meet the highest international safety standards for pipeline operations.

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