MANAGING GEOTECHNICAL RISK IN ANDEAN PIPELINES: MONITORING, COMPUTATIONAL MODELLING AND ASSESSMENT

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Background

The hydrocarbon transmission system that belongs to Transportadora de Gas del Perú (TGP), comprise two parallel pipelines: a natural gas (NG) pipeline, which runs from the upstream facilities at Malvinas, in the Amazonian jungle of Cusco-Peru, to a reception station at Lurín (south of Lima); and a natural gas liquid (NGL) pipeline, which transports the condensed liquids from Malvinas to Pisco, on the coast of Peru. The right-of-way (ROW) crosses the Peruvian jungle with both pipelines in its firsts 200 kilometres. It is a very complicated land where the soil movements are frequent mainly due to heavy rains. Figure 1 indicates the alignment of the ROW which, after crossing the jungle, climbs over the Andes Mountains at an elevation of 4827 masl, and descends steeply toward the coast along the Pacific Ocean

The NGL pipeline is approximately 557 km long, and the NG pipeline is approximately 731 km long. Along this route, the NGL pipeline telescopes from a nominal pipe diameter of 14 to 10¾ inches and the larger NG pipeline telescopes from a nominal pipe diameter of 32 to 24 to 18 inches. The NG pipeline has a 24 inches loop of 105Km. Along their route both pipelines cross the jungle in their first 200 kilometres, where soil movements are frequent. Those movements increase in rainy season.

Our main concern about the pipeline integrity is the overload caused by the soil movements. Geotechnical instability caused or substantially contributed to three of four ruptures of our NGL pipeline (KP 8+800 on December 2004, KP125+900 on March 2006, KP 200+800 on September 2005). The geotechnical and geologic conditions were key factors in the risk level of the system since the beginning of the operation.

Since 2006 TgP has performed specific geotechnical stabilization measures additional to that performed during construction. We also developed an adequate Pipeline Integrity Management System, which has a special treatment for the geotechnical threat. Both activities contribute to reduce the risk and the incidence of ruptures in the system.

The development process and all the field work performed in this matter give to the TgP´s personal an exceptional training and knowledge. All the new challenges are confronted thanks to the expertise reached in all the years of operation.

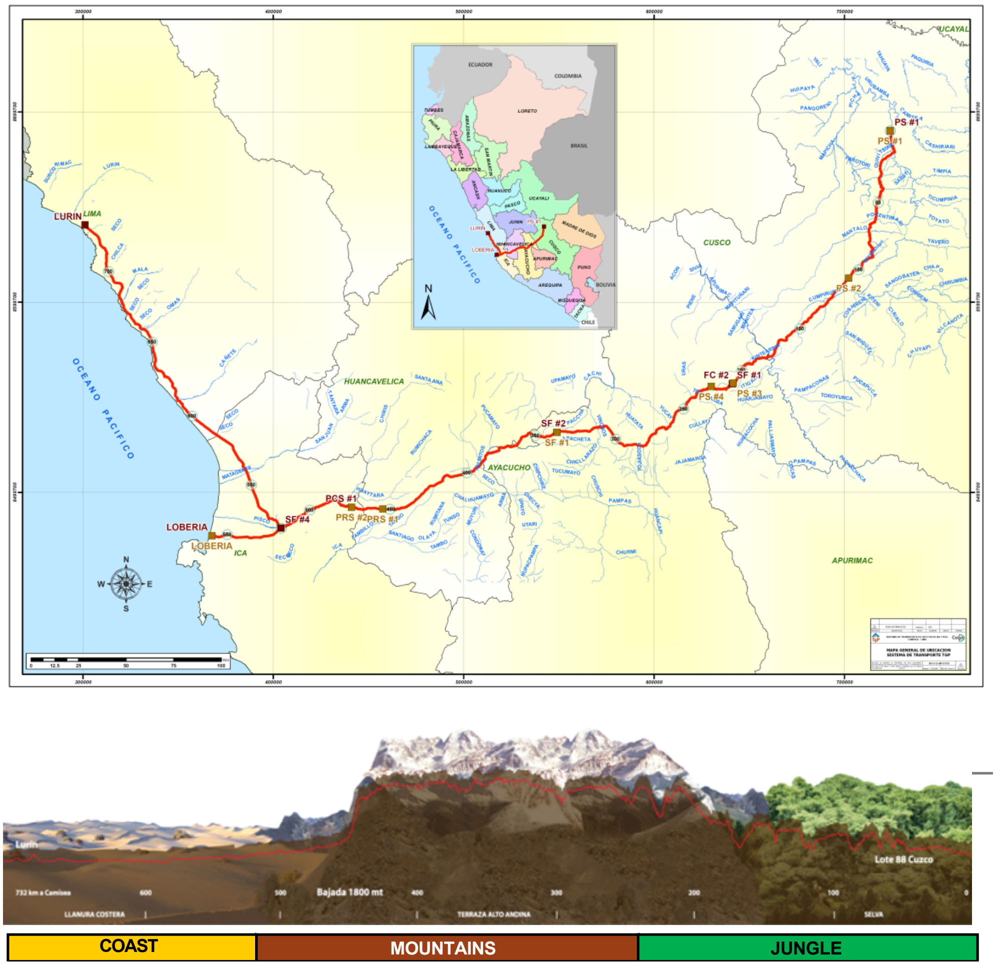


Figure 1: Alignment and profile of the Camisea Transportation System.

Aims

After the incidents mentioned before, our main objective was to reduce the occurrence of ruptures in our pipelines, especially those related to geotechnical threats by developing an Integrity Management System adequate for our very unique conditions.

By reducing the occurrence of ruptures we also achieve to operate our pipelines in a safer way, minimizing any affectation to people, environment and business. The Risk Assessment results, part of the integrity system, allow us to redirect economical resources to the right areas, optimizing and progressively reducing the expenses for the company with a reasonable reduction of the risk.

Methods

Every pipeline Integrity Management System evaluates and controls various threats. On pipelines which have particular characteristics as it is the case of the Andean pipel ines and pipelines that cross jungles, one of the main threats are the weather and outside forces. Even, in this kind of systems, this threat causes a greater number of ruptures than other threats like corrosion or the third part damage. Facing this situat ion, the pipeline Integrity Management System of TgP has achieved an important development in the use and suitable handling of the information provided by diverse techniques of pipeline mechanical and the geotechnical inspection and monitoring of the ROW.

Our work methodology consists basically of interrelating information from construction, operating conditions, in-line inspection (using an Inertial Navigation System (INS) tool which detects zones with possible pipeline deformation), geotechn ical inspections of the Right of Way, rainfall surveillance, instrumentation (Strain Gages, inclinometers and piezometers), topographic monitoring and soil stress monitoring (by installing special Fiber Optic Cables). All this information is supported in a Geographic Information System (GIS) which allows us to integrate the information in a more efficient way. In our GIS we include the identification of high consequence areas and the result of the risk evaluation of the system.

INS/GPS tool information analysis

Any pipeline can be subjected to a tensional state that might cause strains. There are two main components of the strains that act over the pipe wall:

- Longitudinal strain component (parallel to pipeline axis) .
- Hoop strain component, caused mainly by the internal pressure.

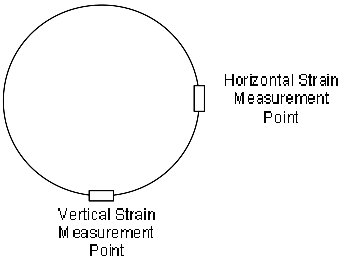
Longitudinal strains produced by tension that exceeds the strain capacity of the pipeline causes ruptures. Longitudinal strain produced by compression causes wrinkles or undulations, and if they exceed the strain capacity of the pipeline, they can cause failures. At the same time, longitudinal strains (both by tension or compression) present two components: Normal and Bending:

- The normal subcomponent of the longitudinal strain is constant in all the transversal section of the pip eline. It is caused by internal pressure, temperature variations, external loads and mainly by the interaction between soil and pipeline in a soil movement parallel to the pipeline axis.
- The bending subcomponent of the longitudinal strain is not uniform in the transversal section of the pipeline because the bending loads causes compression at one side and tension in the other side of the section. The bending component prevails in those cases where the pipeline crosses steep areas with lateral loads.
  INS tool allows identify only the bending component of the longitudinal strain.

Strain Calculus Methodology

Our in-line inspection is based on the identification of areas where the pipeline is subjected to strain by bending and which value (ε) exceeds to 0.1% in more than one pipe, this is because

strain by bending due to external forces changes gradually and it extends in more than one pipe in contrast to field bends (abrupt change and only one pipe).
Bending subcomponent o f longitudinal strain (ε), measured by in-line inspection tool – INS/GPS, can be determinate from bending strain measured at two points of the pipeline transversal section: vertical strain (ε_v) and horizontal strain (ε_h).
In order to determinate vertical strain (ε_v) we have to consider a point located at the bottom of the pipe (6 o'clock) and for the horizontal strain (ε_h) a point at the right of the pipe considering the flux direction (3 o'clock).



	Curvature		Possible Soil Movement Direction	
Strain	+	-	+	-
Horizontal	Left	Right	Right	Left
Vertical	SAG	OVER	Downwards	Upwards

Figure 2: Conventions and Correlation of Strain with possible soil movements.

Strain indicates stress. If we have positive horizontal strain (+ ε_h), that means the right fiber of the pipeline is subjected to tension, that indicates also we have a left curve. In the same way, a negative horizontal strain (-ε_h) means the right fiber of the pipeline is subjected to compression, that indicates also we have a right curve.
If we have a positive vertical strain (+ ε_v), that means the bottom fiber of the pipeline is subjected to tension, that indicates also we have an ascendant curve or SAG curve. In the same way, a negative vertical strain (-ε_v) means the bottom fiber of the pipeline is subjected to compression, so we have a descendant curve or OVER curve.

The relationship between the informed bending strain (ε) and curvature (k) is the following (D: Pipe diameter):

$$\varepsilon = \frac{Dk}{2} \qquad \varepsilon_v = \frac{Dk_v}{2} \qquad \varepsilon_h = \frac{Dk_h}{2} \tag{1}$$

Strain Limits
We use as a reference the standard CSA Z662/96 "Oil and Gas Pipeline Systems" of the Canadian Standard Association. This standard establishes the following:

- Tensile Strain
  In the appendix C, points 6.3.1 and 8.10 of the standard determine a limit value for the factored tensile strain (ε_{tf}) equals to 0.525% to prevent any rupture in the pipeline due to tension loads. To find this limit we use equ ation 2:

$$\phi_{\varepsilon t} \times \varepsilon_{tcrit} \geq \varepsilon_{tf} \tag{2}$$

Where:
$\Phi_{\varepsilon t}$ = resistance factor for tensile strain.
$\varepsilon_{t\,crit}$ = ultimate tensile strain capacity of the pipe wall or weldment.

ε_{tf} = factored tensile strain in the longitudinal or hoop direction.

This limit value consider $\varepsilon_{t\ crit}$ = 0.0075 and $\Phi_{\varepsilon t}$ = 0.7. A value of 0.525% is considered conservative and it is not a realistic failure limit. We developed some full scale test and found tensile strains greater than 3% before rupture in a API 5L X70 pipe. We can use this values also for establish strain limits more accurate to reality.

- Compressive Strain

  In the appendix C, point 6.3.3.2 of the standard determines a limit value for the factored compressive strain (ε_{cf}) to prevent the formation of wrinkles:

$$\Phi_{\varepsilon c} \times \varepsilon_{c\,crit} \geq \varepsilon_{cf} \tag{3}$$

Where:

$\Phi_{\varepsilon c}$ = resistance factor for compressive strain.

$\varepsilon_{c\,crit}$ = ultimate compressive strain capacity of the pipe wall or weldment.

ε_{cf} = factored compressive strain in the longitudinal or hoop direction.

This standard recommends to use a value for $\Phi_{\varepsilon c}$ = 0.8 and to determinate $\varepsilon_{c\ crit}$ use equation 4. $\varepsilon_{c\ crit}$ depends on wall thickness, external diameter, internal and external pressure:

$$\varepsilon_{c\,crit} = 0,5 \times \frac{t}{D} - 0,0025 + 3000 \times \left[\frac{(p_i - p_e) \times D}{2 \times t \times E_s}\right] \tag{4}$$

Where:

t = wall thickness

D = external diameter of the pipe

p_i = internal pressure

p_e = external pressure

E_s = Young's Modulus

Using equations 3 and 4, we determinate eas ily the compressive limit strains (ε_{cf}) for all the diameters and wall thickness of our pipelines, when internal pressure = external pressure = 1 bar, that means a decompression of the pipeline maybe due to a rupture or leakag e. The decompression of a pipeline is an unusual situation, but it is the most critical when a pipeline is suffering compressive strains. It is useful also to know compressive limit strains (εcf) for the operation pressure or MAOP, despite these values are bigger.

Monitoring

An important part of our integrity management system is the monitoring of the different variables that involved in the pipeline risk, and one of them is the strains of the pipes. From our own experience, we know that the most reliable way of monitoring pipeline longitudinal stresses under field conditions is installing Vibrating Wire Strain Gages. They are also suitable for a long term operatio n.

As it is mentioned above, the stress of main interest on soil movement areas is the longitudinal stress. That is why the Strain Gages are installed parallel to the pipeline axis. We used an array of three sensors separated 120 degrees from one another (at 4, 8 and 12 o'clock). These sensors reveal information only in the place where they are installed and they only measure the strain variations from the installation onward. That means the initial cero of the SG readings is not real, for that reason we e stimate the initial strain over the pipeline using topographic surveys and finite element analysis.

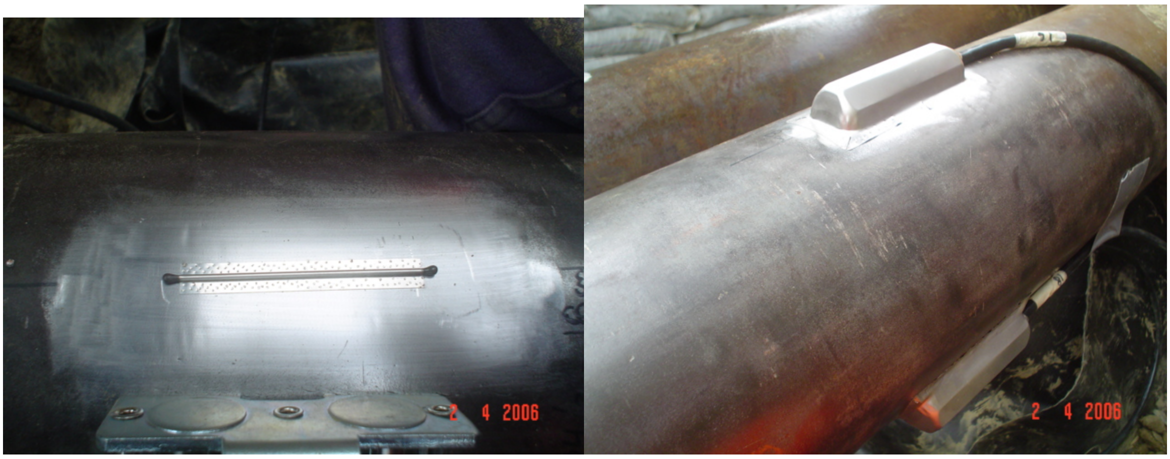


Figure 3: Strain Gages - Installation.

Other types of instrumentations are also useful but not essential because they do not have a direct relation with the pipeline stress. Such instrumentation includes inclinometers and piezometers.

Computational Modelling

Additionally Computational Model ling is a key factor in our system. With this activity we are not only able to monitor or remediate a critical situation, besides we are able to predict situations before they become critical. That is why our company developed a Soil/Pipeline Interaction model, with finite element software. This model was validated and its effectiveness was tested to reproduce reality taking into account some of the ruptures our pipeline has undergone. This model also allows us to install the instrumentation like Strain Gag es in the most adequate zones of the pipeline after an evaluation of the stresses.

We developed a pipe -soil interaction study which uses a non -linear finite element model. In contrast to the traditional Wrinkler model, our research concludes that we must use a hybrid model (between continuous and structural). It includes “pipe” type elements to represent the pipeline and a solid continuous element to represent the soil. Both types of elements interact by a shared node. We call this system as “solid -beam model”; it proved to have a very reliable behaviour when it was tested in the representation of real cases.

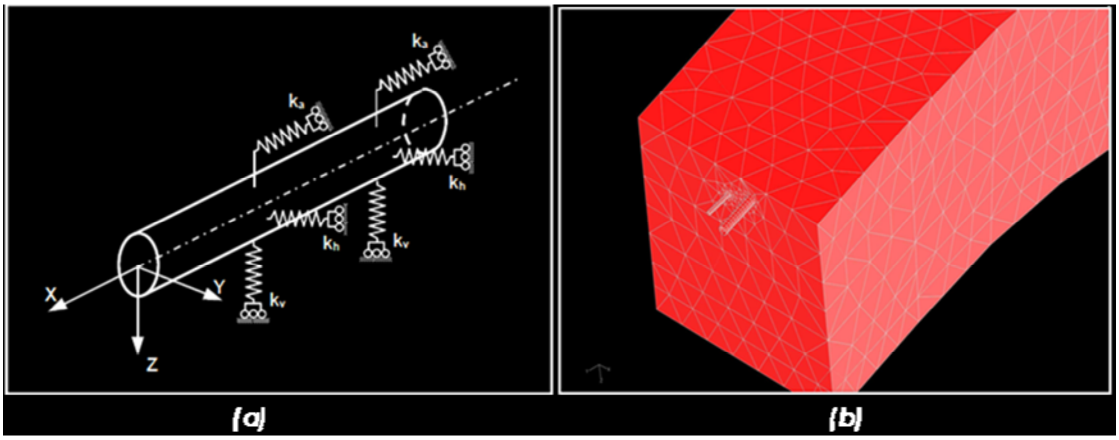


Figure 4: (a) Basic Model (Wrinkler) (b) Solid-Beam Model

The model has the following characteristics:

- Geometry: The pipeline is drawn with the ILI information. The soil is generated around the pipeline according to a field topographic survey. This means that the model represent in a precisely way the terrain and pipeline, with bends and slopes, all in a three dimensional space. This is an advantage over the traditional models.

- Properties: The different soil layers are represented according to soil explorations we execute on field. Its depth depends on how deep we find rock or stable soil. The drainage soil condition is included in the specific weight of the layer. For example:

Layer	Saturated Specific Weight [Kg/cm3]	Cohesion [kg/cm2]	Friction Angle [°]	Elastic Modulus [kg/cm2]
1	1700	0.25	20	20
2	1900	0.3	16	30
3	2000	0.3	16	35
4	2200	0.3	16	10

Table 1: Properties - Soil Layers

For pipeline properties we use the results of real -scale test performed to our pipes:

Metal Base	
Stress [Pa]	Strain
4.80E+08	0
5.50E+08	0.005
6.00E+08	0.017
6.75E+08	0.057
7.00E+08	0.077
7.35E+08	0.117

Table 2: Stress and Strain values – Real Scale Test API 5L X70

- Boundary Conditions:
  They are assumed in agreement with the reality. The translations are fixed in the lowest soil layer and in the extremes of the model.

- Loads: Internal pressure, pipeline and fluid weight, soil weight. The soil movements are represented as node displacements, according to the field inspection.

- Mesh: The model has in average 100 elements by linear meter. Our study concludes that his hybrid model has a good behaviour in comparison with more complex models, because it don't require so much time of processing.

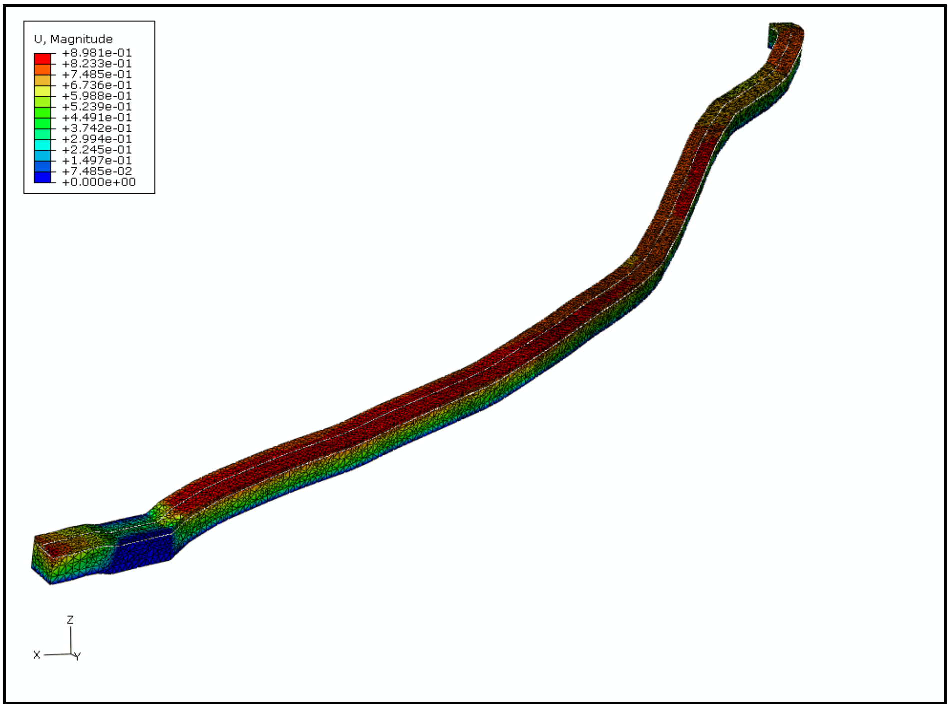


Figure 5: Computational Model: Soil Displacements

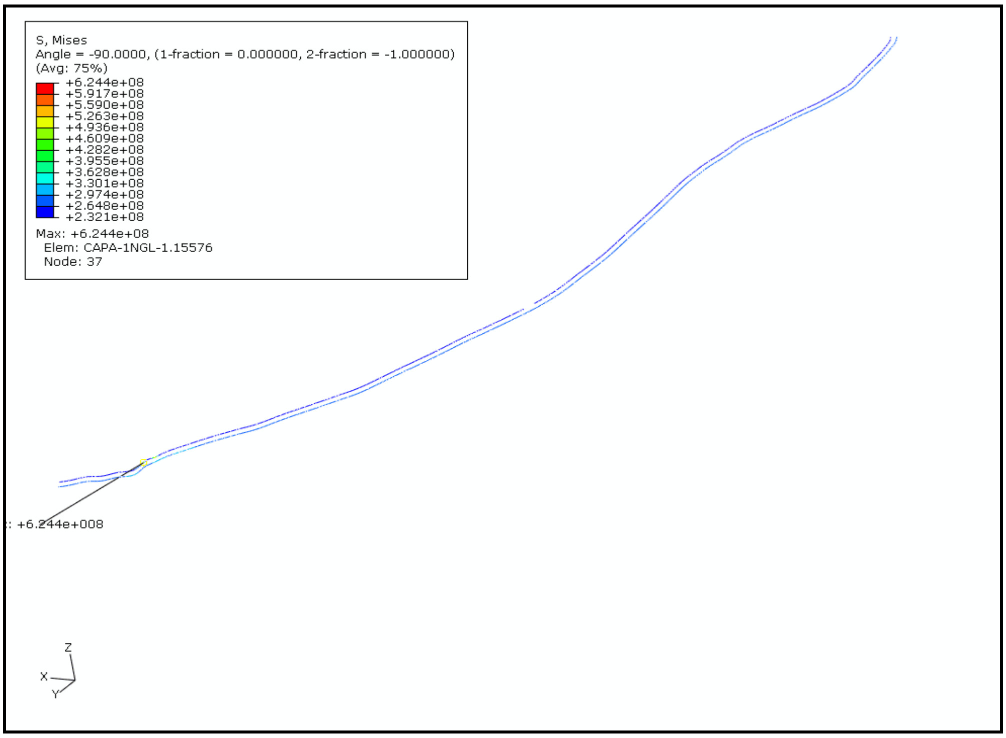


Figure 6: Computational Model: Pipe stress

Risk Assessment

Risk Assessment is an essential part of the Integrity Management System. Our company developed a very comprehensive and detailed Risk Assessment Model based on t he guidelines of API 1160 and ASME B31.8S. Both standards are guidelines of the Peruvian national regulation for hydrocarbon transmission (DS 081 -2007-EM – "Reglamento de Transporte de Hidrocarburos por Ductos"), which establishes that every pipeline opera tor must develop an Integrity Management System. The probability model is based on logic trees instead indexing models (the most commonly used), that is because we want to reflect in the result all the variables and factors: Exposition Factors, Resistance Factors and Mitigation Factors. For the Weather and Outside Forces Logic Tree we take into account several attributes, some of they are: Slope Terrain Angle, Slope Stability, On -slope constructions, Water Course, Rainfall, Scouring, Depth of Cover Survey, Mining, Armoring, ILI Results, among others.

For the Probability of Failure Calculation, we divided the Weather and Outside Forces threat in 9 sub-threats, in order to face our reality:

- Scouring.
- Accretion.
- Inundation.
- Earthquakes.
- Settlement.

- Wind Erosion.
- Mud flow.
- Parallel Water Courses.
- Soil flux Movements, that includes the following type of movements:
  - Drops
  - Rollover
  - Rotational Landslide
  - Translational Landslide
  - Creep
  - Debris Flux
  - Complex Movements

The Probability of Failure due to Weather and Outside Forces are combined with the probability of failure due to the other threats: Internal Corrosion, External Corrosion, Stress Corrosion Cracking, Third Party Damage, Construction Defects, Manufacturing Defects, Equipment Failure and Incorrect Operations. This overall value multiplied by the consequence of failure; give us a risk value for our system.

Results

By means of the pipeline Integrity Management System developed by TgP, we are able to mitigate risks due to outside forces. We have been able to act before any event becomes critical, in other words, with no occurrence of ruptures. This system allows us simultaneously to optimize efforts and preserve the mechanical integrity of the pipelines. It entails not to produce neither personal nor environmental nor economical affectation.

TgP NGL pipeline´s rupture rate (number of ruptures per 1000 kilometres years) decreases substantially from 5.4 to 0.8. For the whole system that rate decreases from 2.3 to 0.4.

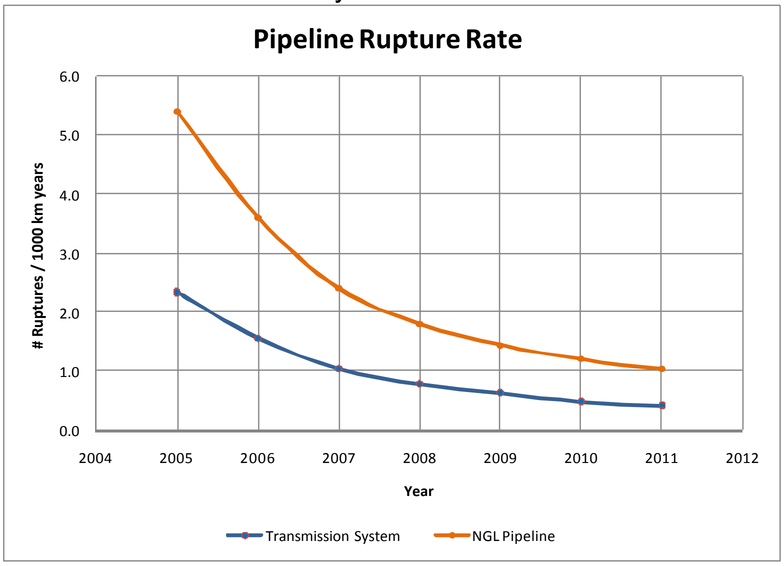


Figure 7: Pipeline Rupture Rate

Summary/Conclusions

When soil movements are a reality in the ROW of pipelines, a well established and structured monitoring system helps us to prevent critical damage on the pipelines . It involves cooperation of several specialties (engineering, geotechnics, topography, etc.), instrumentation and a number of evaluations performed to be closer to the real tensional state of the pipeline.

Instrumentation like Vibrating Wire Strain Gages has proved to be the most reliable instrument in order to know longitudinal stresses in a pipeline because they measure directly the strain on it. These devices plus the information of the soil stress on the soil (by installation of Geotechnical Fiber Optic Cables) are a good source of information for the computational modelling.

The computational modelling tool developed is based in two different concepts solid -shell model and solid-beam model (solid: soil, Shell/beam: pipeline). The solid -shell model is more versatile and allows us to simulate different types of contacts between soil and pipeline, but processing data is slower than the solid-beam model, which has a big calculus velocity due to its less quantity of elements, it is a very fast tool that allows the operator to make early decisions.

When outside forces are a potential risk to face in the ROW of pipelines, the Integrity Management System has to collect all the information (ILI data, topographic surveys, geotechnic surveys, instrumentation and rainfall monitoring) and perform and exigent analysis in order to detect zones with soil movements before they become critical. All this information is supported in a very reliable GIS platform where we can consult the data easily. Our Integrity Management System helped us to prevent critical damage on our pipeline for over five years.