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EARTHQUAKE LOSS ESTIMATION FOR A GAS LIFELINE TRANSPORTATION SYSTEM IN COLOMBIA

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SUMMARY

Recent earthquakes have demonstrated the vulnerability and risks associated with gas transportation and distribution systems. Adequate methodologies for seismic risk estimation are required to establish insurance and risk management strategies, as well as emergency and contingency plans. Inadequate estimations of the seismic risk for this type of systems could lead to the overestimation of the possible losses caused by natural disasters resulting in high insurance coverage costs.

This paper presents the methodology and results obtained from the estimation of the maximum probable losses associated with a gas transportation system in Colombia. The 770 km long system is exposed to considerable action: seismic events, volcanic eruptions, extreme hydrological conditions, and indirect effects such as landslides, liquefaction and avalanches.

Earthquake loss estimates for the system are carried out using a geographic information system (GIS) which includes seismic, volcanic, landslide and liquefaction hazards. The vulnerability of the system's different components (pipes, bridges, underground crossings, citygates, valves and others) is evaluated based on elastic and inelastic finite element models. The risk evaluation is carried out by incorporating these results into the GIS.

The results from this study allow the quantification of probable maximum losses (PML) for the system, the most critical associated event, the system's critical zones and the probable damage scenarios, on the basis of which it is possible to define insurance strategies, emergency and contingency plans.

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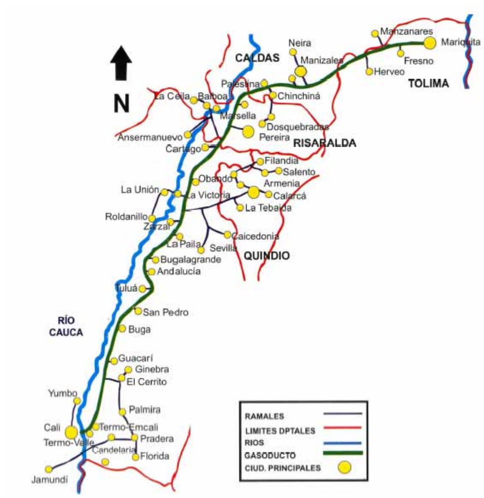
INTRODUCTION

Based on the discoveries of large reserves of natural gas in the country, the Colombian government has developed an ambitious program for its mass consumption. Therefore, it has supported the exploitation of several new fields such as the Chuchupa and Ballena fields located in the department of Guajira north of Colombia. Simultaneously the Apiay and Cusiana fields have increased the production of natural gas offering more capabilities, lowering its costs and increasing its coverage. At the same time, several gas pipelines have been built to supply some of the country's main cities. Therefore, gas pipelines like the Occidente pipeline, the TransMetano pipeline and several other networks on the country's central and eastern regions, as well as in the Atlantic Coast have been built.

Gas transportation is carried out through distribution pipes and includes handling the gas from the production field all the way to points of mass distribution known as "city-gates". The gas is then carried from the "city-gate" and delivered to the final user by urban distribution networks.

This paper deals with the gas pipeline running from Mariquita to Cali in the south-west region of Colombia. The main pipeline is made up of 20"diameter steel pipes and has a total length of 344 km. Its maximum capacity is about 200 mmcf/d. Figure 1 shows the gas distribution system in Colombia's west region.

Figure 1.
Gas distribution and transportation system in the western region of Colombia



BACKGROUND

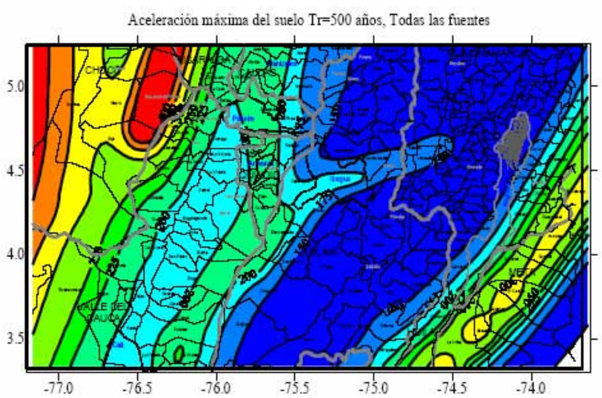
There is worldwide evidence related to seismic behavior of the gas transportation and distribution systems. Life-line's seismic vulnerability has been demonstrated in several earthquakes which have occurred in Parkfield (USA) in 1966, in Japan 1970, 1975, 1979, in Alaska 1971, in San Fernando (USA) in 1971, in Nicaragua in 1973, the earthquake of the Imperial Valley (USA) in 1979, earthquakes at different intensity levels which have affected the city of Los Angeles, the earthquake of Kobe (Japan) in 1995, the earthquake of Kocaeli (Turkey) in 1999 and many others. The March 5, 1987 earthquake in Ecuador (Ms = 6.9) caused the destruction of more than 40 km of the Trans-Ecuatorian Gas pipeline and the road connecting Quito to the very important Lago Agrio oil field, with evidence of great damage due to landslides and liquefaction.

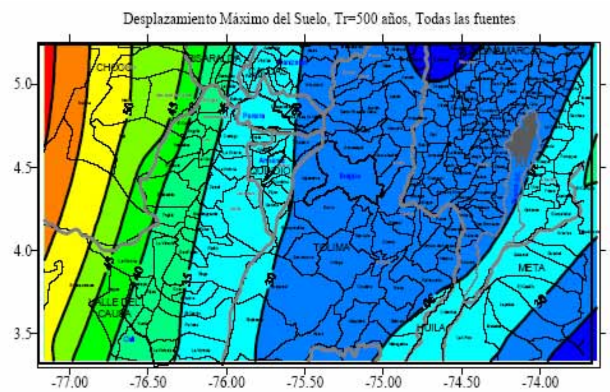
Natural hazards

This gas transportation system is exposed to several natural hazards including seismic, volcanic and hydrological events. In addition, consideration should be given to indirect seismic effects such as landslides, liquefaction, avalanches and extraordinary debris flows caused by volcanic eruptions.Aspects related to terrorism or other human related hazards were not included in the analysis.

Seismic hazards were valuated for a return period of 500 years, corresponding to a 3% probability of exceedance in a fifteen year period which corresponds approximately to the time period selected for the analysis. Figure 2 presents typical regional hazard results in terms of expected acceleration and maximum ground displacements.

Figure 2.
Accelerations [cm/s²] and maximum displacements [cm] of the ground for a 500 year return period





A similar return period was considered for hydrological hazards. However, for volcanic hazards the return period used for analysis was in the order of thousands of years because of the absence of more detailed information. The specific hazards taken into account by this study include, intense rainfall, avalanches/flows, important volcanic eruptions, seismic scenarios, direct seismic surface wave action on the system's infrastructure, surface geological fault action, slope stability along the pipeline's path generated by seismic events in combination with extreme hydrological conditions and liquefaction induced phenomenon on saturated sand deposits.

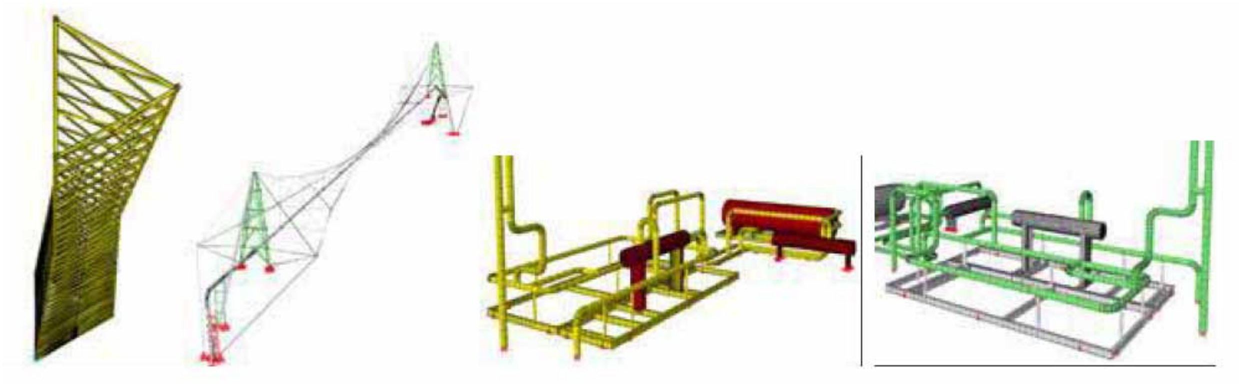
Infrastructure components

The system components included on the analyses are:

(a) Main Gas pipeline (underground steel pipe): 344 km
(b) Important laterals (underground steel pipe): 437 km
(c) Important aerial crossings: 39 consisting of 6 main types
(d) Bogotá administration offices
(e) Bogotá control center
(f) Operation and maintenance centers: 2
(g) City-Gates: 51 types 1, 2 and 3
(h) Communication systems: 13 communication antennas, 7 antenna transceivers and equipment

Some examples of the main components mentioned are presented on Figure 3.

Figure 3.
Examples of the analyzed infrastructure



EVALUATION OF DAMAGE FOR DIFFERENT HAZARDS

Avalanches and flows

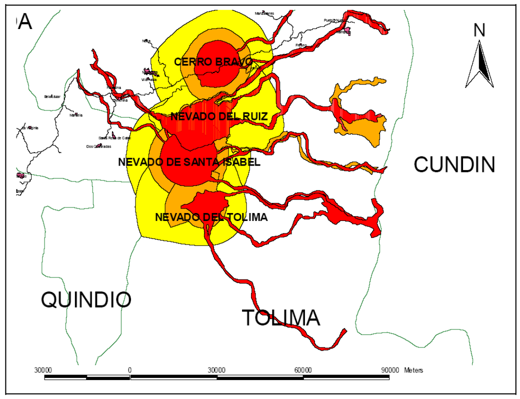
The avalanches or flows also known as debris flow carry all type of materials, from granular materials of all sizes, up to fine particles, logs, vegetal material, construction debris and other. These flows are characterized for also causing surface destruction in river beds, carrying away the surface material of the slopes in its path. The debris flow has the tendency to deposit all this load of sediments when the flow velocity tends to diminish. This type of phenomena occurred in the Nevado del Ruiz's volcanic eruption of 1986 and later in the Paez earthquake of 1994 during a long rainy period. Taking into consideration the particular characteristics of the analyzed system and the potential for destruction of this type of phenomena, damages associated with this kind of analysis are location specific and time limited and therefore not critical to the evaluation effects of PML.

Volcanic eruptions

The existing volcanoes within the influence zone of the project correspond to the Ruiz-Tolima volcanic group better known as the "Parque Nacional Natural Los Nevados". From this group of volcanoes, the Cerro Bravo, Nevado del Ruiz, Nevado Santa Isabel, and Nevado del Tolima volcanoes were considered for this study. Figure 4 shows the map covering the volcanic hazards of the four volcanoes.

Any of these volcanoes may present phenomena such as fall of pyroclasts, pyroclasts flow, lava flow, Lahars or mudflows and shock waves. From the evaluated scenarios, the most critical being an eventual eruption of the Cerro Bravo volcano which could have effects along 30 km of the main pipeline (approx.), 2 city-gates, one to four aerial crossings, one antenna and, in extreme cases, it could reach the Manizales operation and maintenance center. A potential eruption of the Nevado del Ruiz volcano could also be critical, although minor effects could be expected due to its geographic location in relation to the infrastructure.

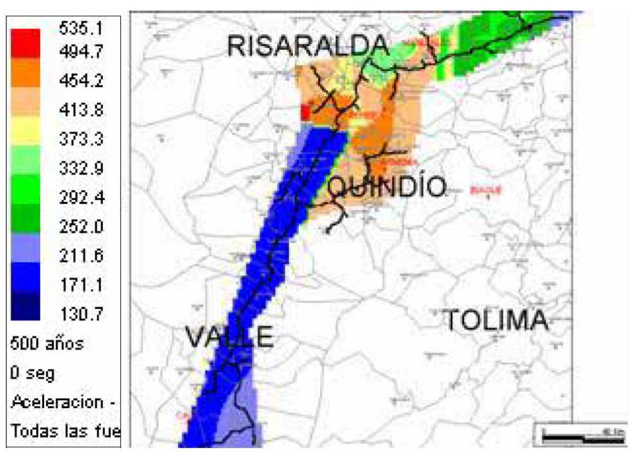
Figure 4
Volcanic Hazard Map – Area of Study



Geotechnical zoning

Geotechnical aspects are fundamental to estimate the damages within the gas distribution system. From the geotechnical point of view the effects of seismic amplification by dynamic response of the surface deposits are considered. The zones of instability associated with deposits of low shear strength and unfavorable topographic and hydrologic conditions, and liquefaction phenomena in deposits of saturated fine granular soils are also considered in the evaluation. Figure 5 presents a typical result of seismic hazard including the effects of subsoil amplification.

Figure 5.
Seismic hazard including subsoil amplification effects (maximum acceleration [cm/s²])

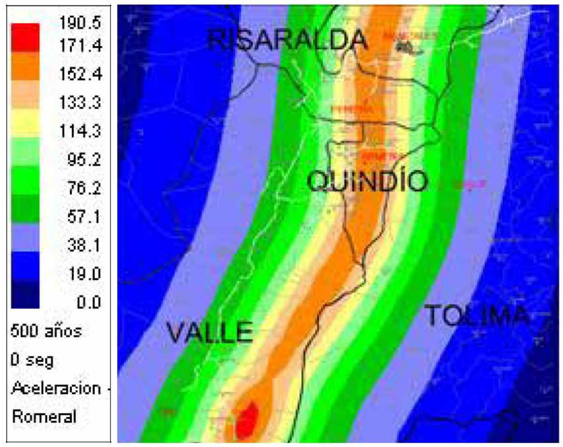


Seismic scenarios

The critical seismic scenarios considered in evaluating the Probable Maximum Loss (PML) correspond to the eventual seismic events occurring in one of the following seismic sources: Frontal eastern range, Romeral and Cauca faults and the Subduction and Benioff zones.

The different hazard scenarios are analyzed and visualized through a geographic information system. Figure 6 presents an example of seismic hazard calculated using GIS.

Figure 6.
Romeral fault's firm soil maximum acceleration map for a 500 year return period [cm/s²]



Active surface geological faults

The pipeline system crosses a series of active seismic faults. The Romeral and Cauca faults represent the greatest damage potential to the system. Although the possibilities of surface rupture exist in these two faults, this eventuality would imply, in the worst case, the occurrence of localized damages in three fault crossing points (considering main pipes and branches crossed by a fault). A maximum localized damage of 20m could be generated on each crossing where surface ruptures may occur. Considering the localized characteristics of this type of damages, this hazard does not represent a critical scenario for the gas distribution system.

Direct effect of seismic waves on infrastructure

Based on hazard evaluation of the study area, an evaluation based on the associated risks in relation to the infrastructure including the pipeline system, the aerial crossings, the sub-fluvial crossings, the "City-Gates", the towers, the operation & maintenance centers, and the administration building & control center in Bogotá was developed.

The analysis of deformations and stresses induced by the seismic waves associated with each seismic scenario was calculated. Due to the high quality of the materials and the type of construction used, the probability of damages by effect of the seismic waves on the pipe itself is very low. Figure 7 shows some of the laboratory tests made on pipe samples in order to evaluate vulnerability functions for the pipelines.

Figure 7.
Laboratory tests to evaluate vulnerability functions for pipes

The damage for each component is estimated based upon vulnerability functions determined by means of elastic and inelasticfinite element analysis for the different characteristic components such as towers, buildings, city-gates (3 types), aerial crossings (5 types), and others.

In general, results for the different analyzed scenarios demonstrated that the infrastructure components present low seismic vulnerability and would present very limited damages under the direct effect of seismic waves.

Landslides

The landslides associated with extreme hydrological phenomena and simultaneous seismic events constitute one of the critical risk factors for the gas distribution system in the Colombian western region. Figure 8 shows an example of the results of slope stability security factors obtained with the system of analysis for one of the steepest zones of the study area.

Figure 8.
Example of stability analysis results for slopes subjected to seismic action

The resulting critical scenario consists of an intense earthquake (magnitude 6.0 or higher) in the Romeral fault system, during a rainy season during which a great number of instabilities are generated because of high pore pressure generation and high degree of saturation of the soil mass. It is estimated that 8 to 10 km of the main pipeline could be affected in this scenario. The scenario associated to a high magnitude earthquake in the Subduction-Benioff zones could cause a similar effect.

Liquefaction

Based on the data of historical seismicity, on the geomorphology of the zone and on the available geotechnical information, it is expected that localized liquefaction phenomena could occur due to an earthquake in the Cauca river valley. The liquefaction phenomenon could produce serious problems to infrastructure located within a 20 km radius which corresponds to the area with maximum ground acceleration, above 0.13 g. Such radius could be located along any point of the critical seismic sources, including the Cauca fault, the Romeral fault and the Benioff zone. The effects will be limited to localized zones where liquefaction can occur.

Any infrastructure component of the system located within the influence zone will be susceptible to suffer high settlements, overturning or collapses if the local soil deposit presents liquefaction potential. Pipeline systems buried in these deposits could suffer minor damages eventually, although this type of phenomenon has not been subjected to modeling, due to great difficulties associated and the highly unpredictable character of the effects.

EVALUATION OF THE PROBABLE MAXIMUM LOSS

Once the individual losses for each one of the critical analysis scenarios were analyzed, the losses associated with each scenario are aggregated, including the direct losses on the gas pipeline, the losses associated with landslides, complementary factors of risk such as liquefaction, surface rupture of active faults, avalanches and flows produced by volcanic eruptions and earthquakes in rainy seasons. The analyses also considered the losses in specific infrastructure components of the system, such as administration buildings, operation and maintenance centers, aerial crossings, City-Gates, etc. The aggregate loss due to the different factors mentioned for each of the critical analysis scenarios allows an estimate of the PML value for the system and the seismic event that could produce this type of losses.

EXPOSED VALUE AND EVALUATION OF LOSSES

In the case of direct damages on the infrastructure components, the losses are calculated based on the corresponding global replacement value of each affected component. The losses in contents are related to the amount of gas lost at the time of the event when damages occur on the pipeline system, and to the losses in equipment and in the inventories in the case of the control center or the operation and maintenance centers.For landslides the replacement cost includes the costs associated with the emergency reconnection and the construction of a by-pass in order to avoid the unstable zone. The maximum aggregated loss is evaluated for the different critical scenarios. The consequential losses and the losses of revenue have not been taken into account in the present analysis. Table 1 shows a general summary of the results.

Table 1.
General summary of losses for critical scenarios

CRITICAL SCENARIO	LOSS AS % OF EXPOSED VALUES		
	DIRECT COSTS	CONTENTS	TOTAL EXPOSURE
Earthquake in Cauca Fault	9.0%	11.5%	9.0%
Earthquake Romeral Fault	10.8%	12.5%	10.8%
Eartquake in Subduction Zone	9.2%	12.9%	9.3%
Volcano Nevado del Ruiz eruption	3.1%	0.0%	3.1%
Volcano Cerro Bravo eruption	5.4%	0.8%	5.4%
Volcano Nevado St. Isabel eruption	1.7%	0.0%	1.7%

Note: The direct costs of the gas lifeline transportation system are considerably greater than the costs associated with the contents. For this reason the total loss of exposure values is almost the same than the direct costs.

The maximum losses associated with the system correspond to the case of an intense earthquake in the Romeral Fault, in the Subduction-Benioff zone or in the Cauca Fault and they would correspond to an approximate loss of 10 to 12% of the gas transportation system's total exposed value.

CONCLUSIONS

The inspection and study of the characteristics of different components of the infrastructure of the gas transportation system in the western region of Colombia indicate an excellent quality of the materials and the construction techniques employed, which result in a low intrinsic vulnerability of the system, for the welded steel pipe and other infrastructure components. However natural hazards are present resulting in a moderate risk for the system in spite of the low vulnerability of its components. Volcanic eruptions and earthquakes of great magnitude could produce indirect phenomena such as landslides and liquefaction. These phenomena could generate considerable effects to the system, reason why the companies in charge of the systems should protect themselves through adequate risk management programmes.

Based on the calculated estimates, it is concluded that the worst damage scenario for the analyzed system corresponds to the occurrence of an intense earthquake in any of the nearby seismogenic sources (Romeral fault system, Cauca fault and Subducción-Benioff zones). Any of these sources could generate seismic events that could cause landslides (from 10 to 15 km of instable zones) and liquefaction affected areas. Combining all different possible effects over all, the system's components for the different critical analysis scenarios, an estimate is obtained for the Probable Maximum Loss (PML) in the order of 10 to 12% of the total gas transportation system's total exposed value.

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