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LA INTEGRIDAD DE DUCTOS EN ZONAS DE ALTA COMPLEJIDAD GEOTECNICA

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ABSTRACT

Landslides are part of the natural processes of denudation of the earth and as such, are not considered to be fully manageable, but the risks they can generate can eventually be avoided. In hydrocarbon transport lines, landslides are one of the main threats causing damage.

A detailed analysis is presented for an area of high geotechnical complexity, where the pipeline is constantly affected by ground movements. Considering the geometry of the pipeline and the topographic conditions of this sector, in the area where the pipeline is buried it is mainly subjected to axial loads, with a slight lateral component, displacements and, consequently to deformation stresses that can lead the line to exceed its elastic limit and break, as has occurred on three occasions. In the aerial section, the pipeline is installed on H-frames and is isolated from ground movements; however, the movements have significantly changed the design conditions of the pipeline; additionally, there is a 250 m long pipeline bridge, with evidence of ground movements at more than 20 m depth.

Keywords: Landslides, creeping, and numerical modeling

1. INTRODUCTION

Mass movements or landslides are part of the natural processes of denudation of the earth's crust and as such are not considered to be fully manageable, but the risks they can generate can eventually be avoided. In hydrocarbon transport lines, landslides are one of the main threats causing damage.

Many linear hydrocarbon transport projects have to cross areas of high geotechnical complexity, which makes it necessary to undertake detailed geological and geotechnical studies to understand the intrinsic factors of the terrain (related to lithology and rock structure, groundwater conditions and vegetation cover) and external agents (climatic and seismic conditions, anthropic activity, among others) that may affect the stability of slopes and their effects on the pipelines.

The occurrence of landslides on the slopes crossed by the pipeline right-of-way (ROW) or adjacent to it, is one of the main factors that affect the social, environmental, and economic impact of the construction and operation of hydrocarbon pipelines.

This paper analyzes the integrity of a hydrocarbon transport line in a sector where the pipeline crosses a valley with multiple active landslides and residual soils of significant thickness resting on highly fractured metamorphic rocks due to the presence of active regional geological faults.

To describe the results in detail, the following sectorization of the pipeline was established, associated with the way the pipeline was installed and the problems analyzed:

Sector	Approx. Abscissa		Type of installation	Geotechnical condition	Approx. length
1	K29+000	K29+435	Buried	Landslide Creeping	435 m
2	K29+435	K29+830	Aerial pipeline over H-Frames	Rocky ridges - Active landslides on the DDV	395 m
3	K29+830	K30+080	Suspension bridge	Suspension bridge	250 m
4	K30+080	K30+410	Aerial pipeline over H-Frames	Lomos rocosos - Deslizamientos activos aledaños al DDV	330 m
5	K30+410	K31+060	Buried	Landslide Creeping	650 m

TABLE 1: DESCRIPTION OF PIPELINE SECTORS

FIGURE 1: GENERAL VIEW OF SECTORS 1 AND 2.

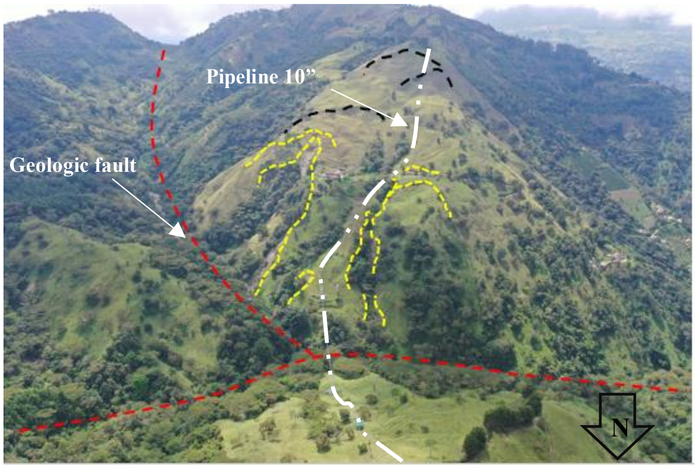

FIGURE 2: GENERAL VIEW OF SECTORS 3, 4 Y 5.

2. MATERIALS AND METHODS

A detailed inventory of the instability processes, a characterization of the geological-geotechnical profile, analysis and interpretation of geotechnical and topographical instrumentation were carried out, to finally structure FEM computational models that allow a better understanding of the soil-pipe interaction in areas of high geotechnical complexity. For this sector, there is evidence of slope creep (extremely slow earth flow), probably of translational type; where three pipeline failures have occurred.

In this project, it is essential to quantify the landslide hazard, leading to the study of current or potential geological-geotechnical risks in the pipeline, in order to establish the technical recommendations that tend to reduce or mitigate such risks, according to the possible effects on the integrity of the pipeline.

3. RESULTS AND DISCUSSION

This is a summary of the analyses, carried out for a section of a 10" pipeline in API5LX52 steel of 0.375" thickness, the section studied has a length of approximately 2 km and has been in operation since 1987. The pipeline occupies a terrain affected by a system of regional and local geological faults that cross the rock massif and have reached a significant degree of neotectonic affectation in soils and recent deposits, generating steps and escarpments that have subsequently become the beginning of large landslide surfaces.

2.1 Stability analysis and hazard assessment

The geological-geotechnical model of the RoW of the pipeline was elaborated, in which the field control, the lithological profiles of the drillings and the interpretation with electrical tomographies were integrated, the horizons of materials present in each of the slopes are identified, as follows:

- Earth flow - colluvium (1 to 5 meters thick on average).
- Residual soil (8 to 15 meters).
- Transition zone residual soil - weathered and fractured phyllites (15 to 20 meters).
- Fractured and deformed phyllites.

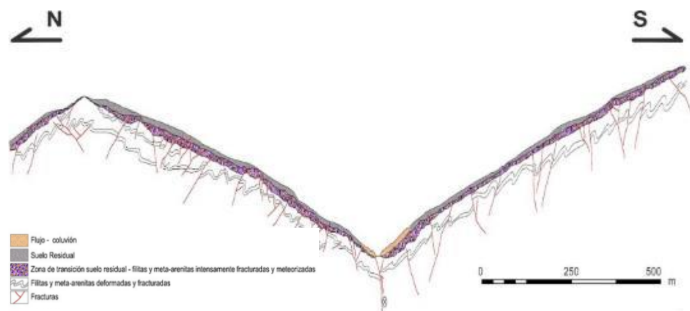

FIGURE 3: CONCEPTUAL GEOLOGICAL-GEOTECHNICAL MODEL ALONG THE PIPELINE

As a complementary aspect for the characterization of the area of interest, there are cairns for topographic monitoring installed in sectors 2, 3 and 4. The position of these cairns is known for the time of their installation, year 2015, and they were reconsidered for the current time, year 2023; in such a way that from this information it was possible to determine the vectors and rates of ground movement at surface level.

The number of cairns used to establish these movement vectors is around 60 elements. During the analysis of the information, several of the vectors were discarded because they presented inconsistencies, generating displacements with magnitudes that did not correspond to reality. With the remaining cairns, it was possible to establish a movement vector that made it possible to define ranges of displacements and predominant directions of surface movements on the slopes.

In the same way, the actual location of the foundations were compared with the location of the as-built plans of this structure. With this information, the magnitude and the movement vectors in depth were estimated, given that the structure has foundations with caissons of 20 m on the north side and 11 m on the south side.

In Figure 4, the displacement vectors established along the slope (scaled by 100) can be observed together with the results from which a zonation is established.

On the north slope, 3 zones are defined according to the magnitude and direction of the displacement vectors:

i) High zone with displacement magnitudes in the range between 0.20m and 0.40m, and predominant directions towards the southeast. The buried pipeline and the aerial transition are present in this zone.

ii) Intermediate zone, characterized by displacement magnitudes in the range of 0.60m to 1.0m and predominant directions to the southeast. In this zone the pipeline is aerial supported on H-frames founded on caissons; the north valve house is also located here. Some cairns present movement magnitudes between 1.20m and 1.60m, which are associated with the position of the cairns near escarpments of active movements in the slope associated with erosive processes, of deep gullies of great magnitude (See Figure 1).

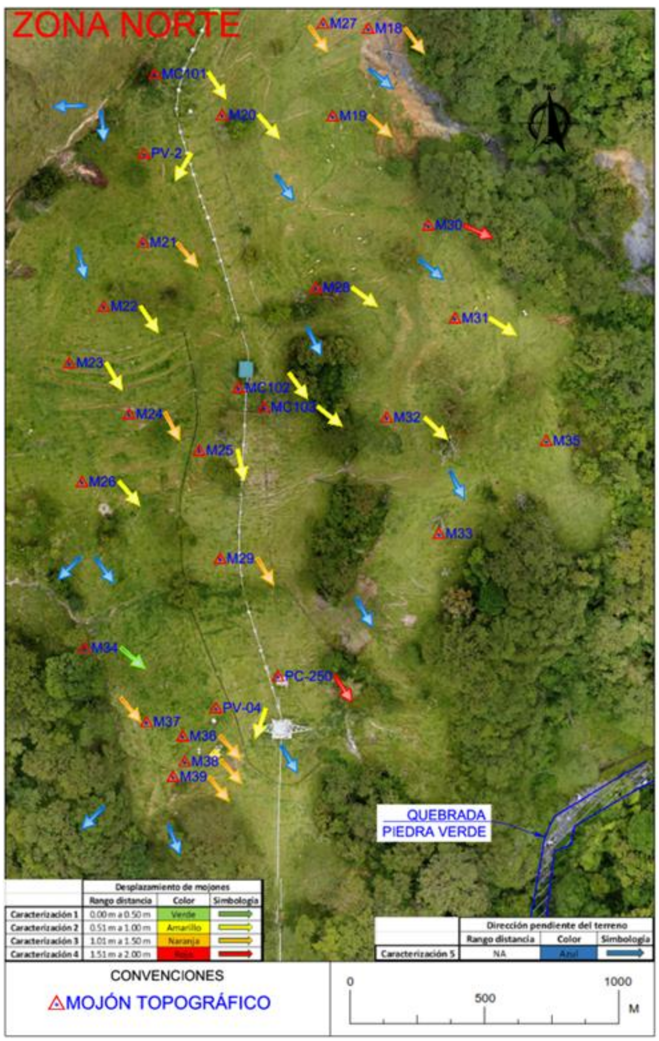

FIGURA 4: TOPOGRAPHIC DISPLACEMENT VECTORS ON THE NORTHERN SLOPE

iii)

iv) Lower zone, next to the aerial crossing over the Esmeralda creek, characterized by movement magnitudes between 0.80m and 1.20m, with predominant directions to the southeast; in this zone is located the north tower of the bridge, which has had movements of 0.5 m downslope.

v) On the southern slope, the magnitudes and directions of the movement vectors are similar, the magnitude varies between 1.00 m and 1.40 m and the direction is towards the northeast.

FIGURA 5: TOPOGRAPHIC DISPLACEMENT VECTORS ON THE SOUTHERN SLOPE

To quantify the magnitude of the geotechnical processes, analysis sections were elaborated in the OptumG2 computational tool, which allows estimating the displacements and safety factors of the slope in different scenarios of piezometric level and earthquake. It is important to highlight that the modeling used "Shear Joint" elements, which represent the fractures in the rock mass according to the stratigraphic profile established for this area of high geological and geotechnical complexity. The shear joints correspond to the dashed lines presented in Figure 2.

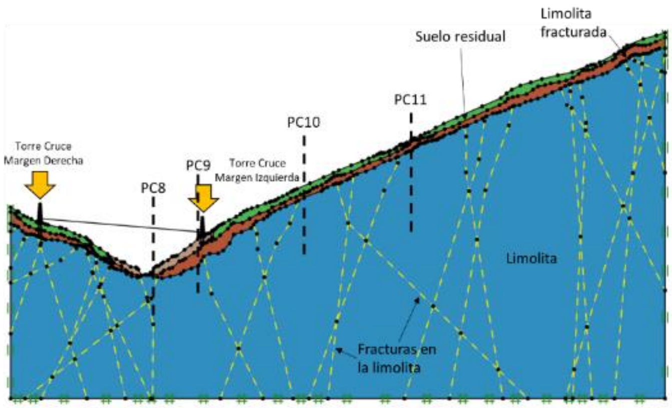

FIGURE 6: FINITE ELEMENT MODEL IN OPTUM G2

With the finite element models structured for the study area, the deformations (slope movements) associated with triggering factors (rainfall and earthquakes) are obtained and analyzed for different return periods between 2 and 100 years.

The results of the slope stability and displacement analyses in each sector are summarized in Table 2, which shows the maximum total displacements and safety factors obtained for each return period in each analysis section. The safety factors presented refer to a critical condition of the slope, which does not necessarily represent the stability condition of the pipeline or its right-of-way. From Figure 7 to Figure 9, the sectors with the highest displacement rate obtained in each analysis section are presented.

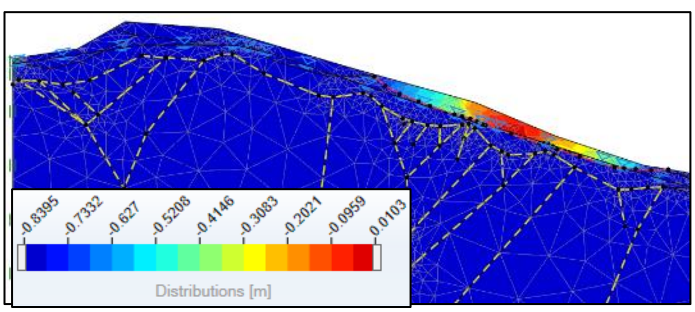

FIGURE 7: DISPLACEMENTS NORTH SLOPE SECTOR 1

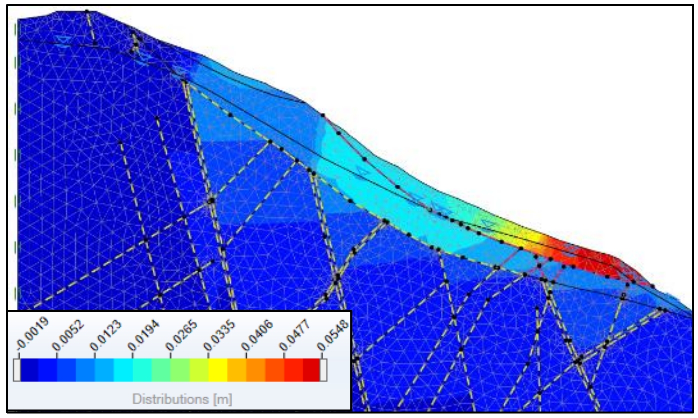

FIGURE 8: DISPLACEMENTS NORTH SLOPE SECTOR 2 Y 3

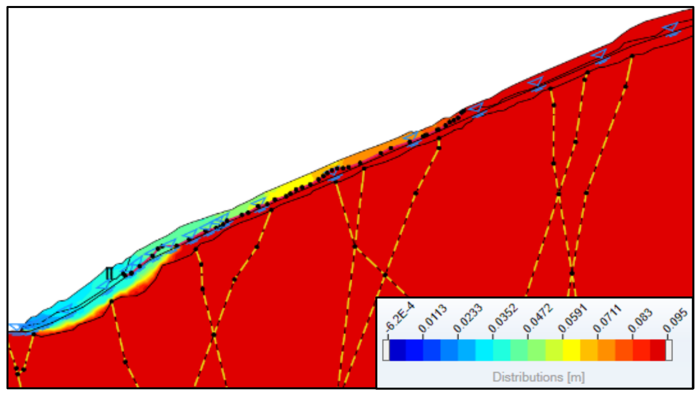

FIGURE 9: DISPLACEMENTS SOUTH SLOPE SECTOR 4 Y 5

Based on the field inspection and the modeling performed, it is identified how the surface deposits are mobilized in the first instance together with the residual soils almost as a single body with displacement rates of up to 15 cm per year, and that in the second instance, due to the inertia of the slopes and the high fracturing of the rock mass, they end up including within the sliding mass the weathered rock horizon (at approximately 20 m depth), on the fracture planes and unfavorable foliation of the phyllites.

Periodo de Retorno (Tr)	Factor de Seguridad FS (OptumG2)	Desplazamiento del suelo (m) (OptumG2)	
Sector 1 – Tubería enterrada (Antiguo deslizamiento)		Desplazamientos superficiales	
0	1.15	0.04	-
2	1.13	0.28	-
5	1.11	0.31	-
10	1.11	0.38	-
25	1.08	0.51	-
50	1.01	0.63	-
100	0.89	-	-

Periodo de Retorno (Tr)	Factor de Seguridad FS (OptumG2)	Desplazamiento del suelo (m) (OptumG2)	
Sector 2 y 3 Tubería aérea sobre marcos H y torre norte cruce aéreo		Desplazamientos superficiales	Desplazamientos caissons norte
0	1.29	0.15	-
2	1.23	0.21	0.21
5	1.14	0.31	0.27
10	1.06	0.7	0.35
25	1.03	0.98	0.8
50	1.01	1.12	0.44
100	0.91	-	-
Sector 3 y 4 Tubería aérea sobre marcos H y torre sur cruce aéreo		Desplazamientos superficiales	Desplazamientos caissons sur
0	1.2	0.11	-
2	1.1	0.33	0.18
5	1.07	0.79	0.39
10	1.03	1.71	0.86
25	1	2.18	0.92
50	>1.00	-	-
100	> 1.00	-	-

TABLE 2: RESULTS OF THE GEOTECHNICAL MODELING OF THE SECTOR.

2.1 Pipeline vulnerability analysis

The 250 m aerial crossing (sector 3) has been identified as vulnerable for the operation of the pipeline; the geotechnical processes identified involve the foundation of towers and anchorage on both sides (see Figure 10). Based on topographic comparison, in the last 8 years, the tower on the north side has moved 60 cm and the one on the south side has moved approximately 30 cm. The stability analyses and the geotechnical instrumentation show that the area is moving at a depth of more than 20 m, currently the pipeline between the towers has dropped about 5 m, with respect to its construction position, additionally the cables of the pipeline are not working due to the bridge movements, allowing the pipeline to move out of its supports before any horizontal load (operational or external).

In the aerial section (Sector 2 y 3) installed on H-frames, the movement of the ground due to deep landslides generates displacements in the pipe supports (together with its foundation), losing contact in the axial supports and inducing stresses at some points due to the type of support installed with lateral restrictions (See Figure 11).

FIGURE 10: VULNERABILITY OF THE PIPELINE AT THE AERIAL CROSSING..

FIGURE 11: VULNERABILITY OF THE PIPELINE IN SECTOR 2 y 4

In sector 1, the pipeline is installed buried in a regular line, in this sector there is an old landslide in the process of reptation, near the escarpment of this old process there was a break in the pipeline by traction (see Figure 1), and in the lower part of this section, compression marks were identified in the pipeline, manifested as curvatures in the pipeline and dragging in the coating of the pipeline, these anomalies associated with this same process (see asterisks in Figure 12).

FIGURE 12: VULNERABILITY OF THE PIPELINE IN SECTOR 1

4. CONCLUSION

The analyzed sector is located within the zone affected by an overlapping NE-SW and E-W Fault System, which are some of the local elements responsible for the current condition of the rock massif in the sector. This is fractured and deformed, presenting multiple breccia bands, resulting in a poor quality of the massif.

Within the rock massif there are multiple weak zones, at different depths, either very fractured zones or very wet zones, which constitute potential movement surfaces.

It is concluded that there is a complex condition from the geological and geotechnical point of view, where the following adverse factors to stability are added: the existence of highly fractured and weathered rocks, which translates into permeable rock massifs, associated to the regional tectonics and the proximity to the principal fault system. In addition to the evidence of old processes, escarpments, and geomorphological elements that, as historically known, are susceptible to the development of new processes and their reactivation.

On the right bank of the creek (Sectors 1 and 2), two main types of movements were identified, the first affecting the buried section of the pipeline by a reptation and the second by a slow flow and gullies that directly affect the overhead section of the pipeline and the structure of the pipeline bridge.

On the left bank of the creek, a colluvial deposit was identified near the support structure of the aerial crossing, which is highly susceptible to movement in the event of changes in pore pressure or an earthquake. Upslope, there is evidence of a terrain with undulating geoforms and slight escarpments, characteristic of a general reptation process throughout the mountain, which can directly affect the pipeline depending on the type of pipeline installation.

The analyses carried out identify stress concentrations at two critical points: in the buried sections, the upper parts of the slope present tensile stresses that can lead to pipeline rupture; in the sectors above the H-frame and the suspension bridge, the movement of the ground affects the foundations of the existing infrastructure. The movement of the towers generates a high concentration of deformation stresses in the pipeline that can lead to pipeline failure.

5. REFERENCES

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