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IMPACT OF ROCKFALL ON HYDROCARBON TRANSPORTATION PIPELINES

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ABSTRACT

Among the various alternatives aimed at reducing pipeline vulnerability to slow-moving landslides (soil creep), a commonly adopted measure is the installation of pipelines on H-frame structures. However, this raises a critical question: Are pipelines located on H-frames or exposed on the surface susceptible to damage or rupture due to rockfall from adjacent slopes?

This paper presents a case study evaluating the impact energy generated by a rock block falling from a certain distance on a steep slope and compares it to the energy threshold required to cause denting or rupture in a gas pipeline. Furthermore, a methodology is proposed for identifying aerial pipeline sections potentially at risk of rockfall damage, considering the management of geohazards. The analysis includes: local geomorphology (slopes, slope lengths), geology (rock types, structural geology), pipeline exposure (alignment direction, location), and pipeline characteristics (diameter, wall thickness, strength).

Finally, the article presents a review of mitigation alternatives against rockfall threats to prevent denting or rupture of hydrocarbon transportation pipelines, incorporating technical feasibility, construction requirements, access, and economic considerations.

Keywords: Aerial pipeline, Rockfall, Block impact, Rupture, Denting.

NOMENCLATURE

Ec	Kinetic energy
m	Mass
v	Velocity
θ	Slope angle
L	Slope lenght
g	Gravitational acceleration
μ	Dynamic friction coefficient
D	Pipe diameter
mp	Plastic moment of the pipe
t	Pipe wall thickness
σy	Yield strength

1. INTRODUCTION

The passage of hydrocarbon transportation pipelines through mountainous and tectonically active regions in Colombia presents significant challenges due to the interaction between linear infrastructure and geohazards such as landslides, soil creep, and rockfall. One of the critical scenarios is the impact of rock blocks, resulting from mass movements, on aerial or exposed pipelines transporting gas or liquid fuels. Although these events are sporadic, they can cause pipeline failures, compromising the structural integrity of the system, environmental safety, and operational continuity.

In Colombia, the presence of oil and gas pipelines crossing the high mountain ranges of the Central and Eastern Cordilleras—areas characterized by steep slopes, unstable soils, and seismic activity—has prompted various analyses and investigations into geotechnical hazards associated with pipeline routes. Documented cases of rockfalls and landslides damaging pipelines underscore the importance of integrating geological and geomorphological analysis tools, numerical modeling, and impact assessment methodologies.

Typically, rockfalls can affect pipelines in two ways: by removing supporting terrain when occurring upslope, or through block accumulation (talus) and direct impact, potentially affecting even buried pipelines if located at the toe of the slope. This paper presents a technical review of rockfall mechanisms and their potential impact on hydrocarbon pipelines in unstable hillsides, with a focus on a case study located in Miraflores municipality (Boyacá, Colombia). The study analyzes terrain conditioning factors, critical pipeline parameters, and methodologies for evaluating and mitigating these threats to support geohazard management for hydrocarbon transport in mountainous regions.

An effective methodology for estimating rockfall risk on engineered slopes must consider both the physical properties of the hazard and its potential consequences and reach, along with the characteristics and resilience of the exposed elements. This enables the identification of all contributing factors and the full spectrum of possible direct and indirect consequences to at-risk infrastructure [2].

2. CASE STUDY

As part of the integrity management strategy of Transportadora de Gas Internacional TGI S.A. ESP, aerial, ground, and geotechnical monitoring inspections are conducted on its gas pipelines. The case study focuses on the Cusiana–El Porvenir–La Belleza gas pipeline, specifically the Miraflores–Sutamarchán segment, located in the municipality of Miraflores, Boyacá, Colombia. In this segment, TGI operates two 20-inch diameter pipelines: the Miraflores–Sutamarchán trunk line and the Miraflores–Puente Guillermo. Geologically, the area is located on the Une Formation (Kiu), composed of fine to coarse-grained quartz sandstones with thin interbedded black shales. Locally, the gas pipeline lies on Quaternary colluvial deposits dissected by parallel drainage channels, with extremely slow movement rates as recorded by geotechnical monitoring. The trunk pipeline is buried at a depth of 2.1 meters, while the 20” loop pipeline is supported on H-frames to reduce vulnerability to soil creep from the colluvial deposit (see FIGURE 1).

FIGURE 1: Location of the 20” loop on H-frames

In February 2025, right-of-way patrol and geotechnical monitoring technicians identified a sandstone block approximately 2 meters in diameter located on the hillside adjacent to the pipeline, next to a tree situated 45 meters from the loop. The tree trunk was bearing the block’s weight (see FIGURE 2 y 3).

FIGURE 2: Rock block approximately 2 meters high supported by the trunk of a tree

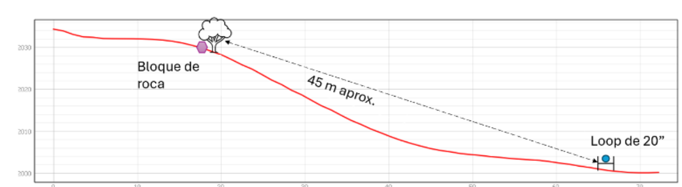

FIGURE 3: A-A terrain profile, showing the distance relationship between the rock block and the pipeline

Subsequently, through aerial inspection using a UAV (Unmanned Aerial Vehicle), the path of the rock block was traced from an approximate distance of 228 meters upslope, as shown in FIGURE 4.

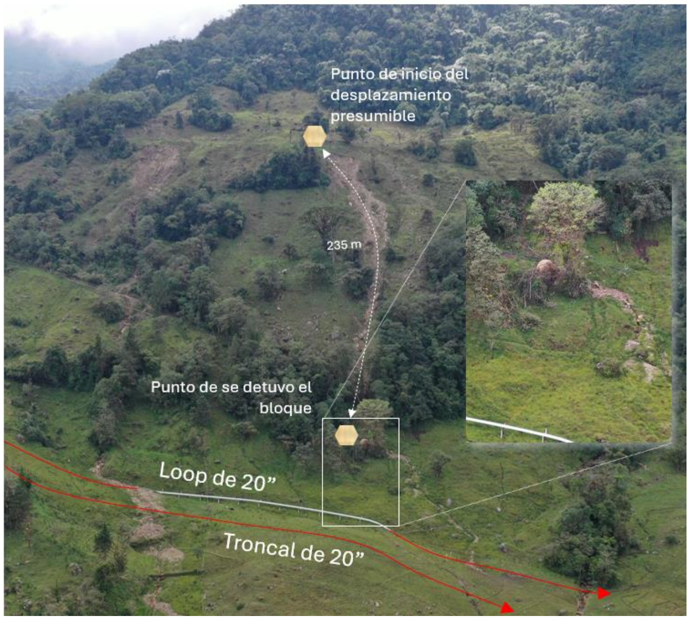

FIGURE 4: Aerial inspection image showing the path traced by the rock block

Using the digital elevation model (DEM) obtained from LiDAR (Light Detection and Ranging) topography, the terrain profile, path, and slope of the hillside along which the block descended were defined, up to the point where it was stopped by the tree. The trajectory was directed toward the aerial 20” loop pipeline. Ver FIGURE 5 Plan and Profile.

2.1 Impact Energy Evaluation of the Rock Block

A continuación, se presenta el cálculo de la energía de impacto que podía desarrollar el bloque de roca identificado, si este no hubiese sido detenido por el árbol.

The kinetic energy of the rigid rock block is described as the sum of translational energy (when sliding) and rotational energy, calculated using Equation (1) [5]. In this equation, I is the moment of inertia of the block—assumed to be angular in shape for this study—and is computed via Equation (2). Here, m is the mass of the block, w is the angular velocity, and r is the block’s radius. Given the angular shape assumption, the value of k is taken as 2/5 [5].

$$\mathrm{Ec} = \frac{1}{2}mv^2 + \frac{1}{2}Iw^2 \qquad (1)$$

$$I = kmr^2 \qquad (2)$$

Under the principle of energy conservation, by equating the potential energy of the rock to its kinetic energy—accounting for friction during its fall along the slope—the block’s velocity can be expressed as a function of slope length, terrain gradient, dynamic friction coefficient between the rock and soil, gravity, and the k value related to the block shape, calculated via Equation (3). A dynamic friction coefficient of 0.35 was assumed for wet grass and vegetation [8].

$$v = \sqrt[2]{\frac{2gL(seno(\theta)-\mu\cos(\theta))}{(1+k)}} \qquad (3)$$

Table 1 presents the results for calculating the kinetic energy of the rock block. A 2-meter side sandstone block falling along a 21° slope over a 280-meter length would develop a kinetic energy of 1377 kJ.

FIGURE 5: Plan view showing the location of the block. Bottom – Profile B-B’ of the block’s trajectory.

Kinematic friction coefficient, μ	0.35	
Slope length, L	280	m
Block height	2.0	m
Unit weight of rock	2200	kg/m³

Slope angle θ	21	°
Gravity g	9.81	m/s²
Block velocity with friction, v	12.5	m/s
Volume V	8.0	m³
Block weight	17600	Kg
Block kinetic energy, Ec	1377	kJ

TABLA 1: Determination of the kinetic energy of the rock block

2.2 Pipeline damage energy threshold evaluation

Based on the pipe's characteristics and its material resistance, the ability to withstand the impact of a falling rock block can be evaluated.

To determine the energy required to cause a dent (Dent/D = 5%) or rupture (Dent/D = 20%) in the pipe, Equation (4) from references [6] and [7] was used.

$$\mathrm{E} = 16\left(\frac{2\pi}{9}\right)^{1/2} mp\left(\frac{D}{t}\right)^{1/2} D\left(\frac{\delta}{D}\right)^{3/2} \qquad (4)$$

Where mp is the plastic moment of the pipe ($^{1}/_{4}\,\sigma y t^{2}$); δ is the pipe deformation, t is pipe wall thickness, σy, is yield strength y D is pipe diameter.

External diameter D		20.00	"
External diameter D		0.508	m
Nominal pipe wall thickness t		0.375	"
Nominal pipe wall thickness t		0.0095	m
Steel grade		X65	
Yield strength	σy	448	Mpa
D/t ratio		53	
Plastic moment		10161	
Dent/D ratio	*Minor damage*	0.05	
Pipe deformation, dent depth		0.0254	m
Absorbed energy for denting [3]. *E*		5.6	kJ

TABLA 2: Determination of the energy required to produce a 5% dent

Table 2 presents the pipe's characteristics from the case study, including the energy required to produce a 5% dent. Table 3 shows the energy required for a 20% rupture. According to the results, 5.6 kJ is sufficient to produce a 5% dent, while 45.0 kJ is required to generate a severe 20% rupture.

External diameter D		20.00	"
External diameter D		0.508	m
Nominal pipe wall thickness t		0.375	"
Nominal pipe wall thickness t		0.0095	m
Steel grade		X65	
Yield strength	σy	448	MPa
D/t ratio		53	
Plastic moment		10161	
Dent/D ratio	*Dent*	0.20	
Pipe deformation, dent depth		0.1016	m
Absorbed energy for denting [3]. *E*		45.0	kJ

TABLA 3: Determination of the energy required to produce a 20% rupture-type damage

According to the results from Table 1 and Table 2, the energy required to produce a 5% dent is 5.6 kJ, and to produce a severe 20% rupture is 45.0 kJ.

Considering that the kinetic energy developed by the block falling from the described slope is 1377 kJ, this energy is significantly greater than what is needed to cause denting or rupture. Therefore, it is concluded that such field condition could have caused severe damage to the pipeline.

Given these results, which confirm the possibility or probability of failure in sections where pipelines are installed on H-frames—originally conceived to prevent undesirable deformations due to creep or sliding—the need arose to evaluate the vulnerability of gas pipelines to the threat of rockfall from adjacent slopes.

From a technical perspective, rockfall hazard analysis for pipelines involves the geomorphological characterization of the terrain, identification of potential rockfall source areas, modeling of block trajectories, and assessment of the impact and damage potential. Methodologies such as the use of simulation software (e.g., Rockfall Analyst, RAMMS: Rockfall, RocFall) and Geographic Information Systems (GIS) have been proposed to evaluate these threats based on topographic, geomechanical, and structural criteria (Dorren, 2003; Agliardi & Crosta, 2003) [4].

The following section presents a methodology implemented by the Geo-Hazards Division of TGI S.A. ESP to identify pipeline segments potentially affected by rockfall events.

3. METODOLOGÍA DE ANÁLISIS

The objective of this analytical methodology is to identify which aerial pipeline segments owned by TGI S.A. ESP are susceptible to denting or rupture due to potential rockfall impacts.

3.1 Definition of aerial segments on H-Frames or surface-level

TGI S.A. ESP operates 4033 km of gas pipelines of various diameters. Among them, 20.57 km are aerial pipelines distributed over 200 segments. Of these, 77 segments (totaling 10.18 km) are located either on H-frames or at surface level, with diameters of 2”, 4”, 6”, 12”, 16”, 20”, and 22”, and are distributed across the entire pipeline network. FIGURE 6 shows the geographic location of these aerial segments.

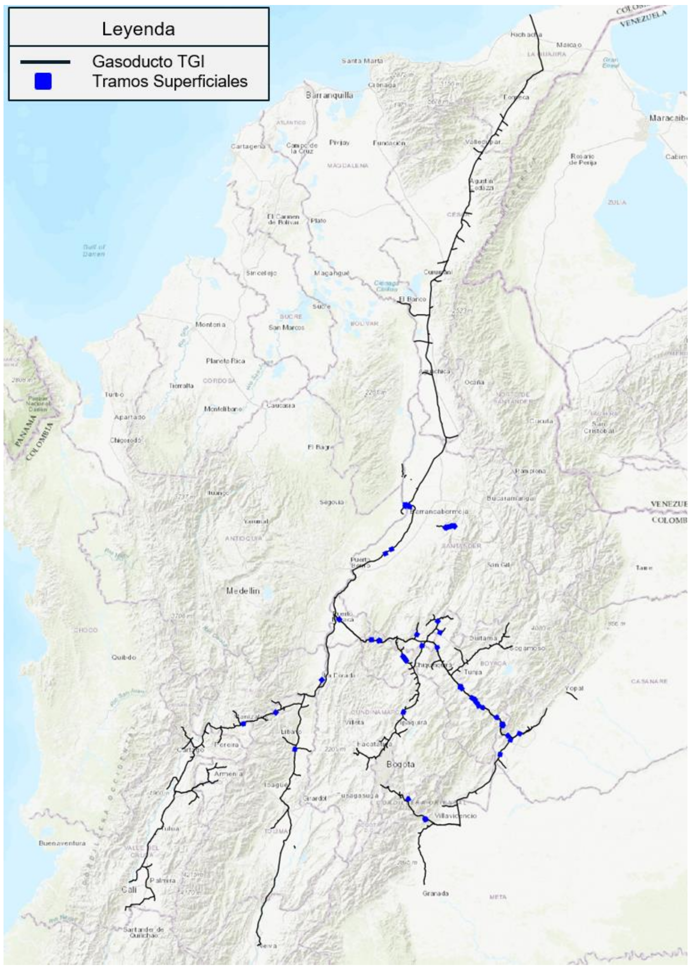

FIGURE 6: Aerial or surface-level pipeline segments on H-frames operated by TGI S.A. ESP.

3.2 Pipeline exposure vs. geomorphological conditions

Among the surface-level segments, some are located at the upper parts of slopes, broad ridges, or flat areas where rockfall is not possible. FIGURE 7 illustrates examples of segments excluded from the analysis due to their location in areas with no adjacent contributing slopes.

FIGURE 7: Top – Surface-level segment excluded from the analysis due to its location at the top of a slope composed of volcanic deposits, near the ridge, where the possibility of rockfall impact is null and there are no adjacent slopes contributing rocky material. Bottom – Surface-level segment excluded from the analysis for the same reason: located at the upper part of a slope with volcanic deposits, near the ridge, with no potential for rockfall impact or contributing rock sources from adjacent slopes.

As part of this analysis, 35 segments were excluded (marked in red in Figure 8) where the relationship between pipeline exposure and the area's geomorphological conditions indicated no possibility of rockfall impact. Figure 8 shows the geographic location of the aerial segments excluded under this criterion, as well as those that remained valid for the next stage of analysis. The segments with potential for impact due to the pipeline exposure versus geomorphological conditions totaled 42 (marked green in Figure 8).

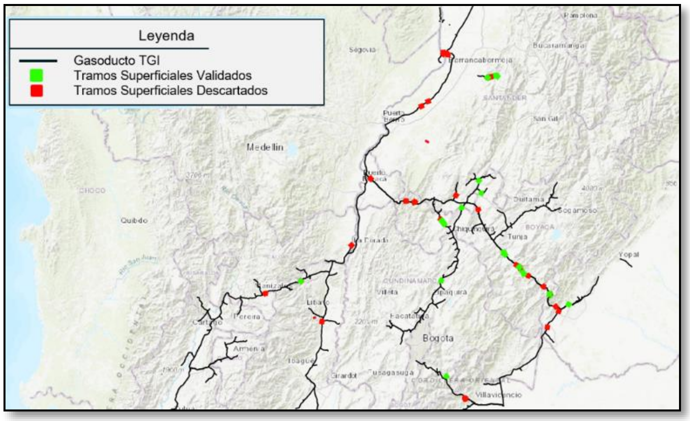

FIGURE 8: Aerial segments excluded and validated based on the criterion of pipeline exposure versus geomorphological condition.

3.3 Geomorphological characterization of the segments

To assess the kinematic potential for block movement on slopes adjacent to exposed pipeline segments, it is necessary to characterize the slopes using at least the following variables: predominant slope angle (θ), slope length (L), block size (D), rock type and shape, unit weight of the rock, and the characteristics of the rolling surface to estimate the dynamic friction coefficient (k). Slope angle and length data are estimated using Digital Elevation Models (DEMs), conventional topographic surveys, LiDAR topography, and other available digital terrain models. Rock type, maximum block size, and unit weight are determined through geological analyses of the area, as well as ground or aerial inspections.

3.4 Kinematic verification of displacement

The dynamic friction coefficient (k) is estimated based on the characteristic surface conditions of the slopes. In this case, a value of 0.35 was assumed for grass and moist vegetation.

For a block to move and the velocity defined in Equation (3) to be greater than zero, tan(θ) must be greater than 0.35. This means that, under the assumed dynamic friction coefficient, slopes with angles less than 19.3° do not allow kinematic block movement. Based on this criterion and the geomorphological characterization, out of the 42 segments validated in the previous step, only 9 segments have slopes greater than 19.3° (as validated by Equation (3)). The remaining segments were discarded under this criterion.

At this stage, a more detailed review can be made of the surface roughness or characteristics of the vegetation cover and terrain surface. This allows for the exclusion of segments with dense or semi-dense forest or shrub cover, as shown in FIGURE 9. Under this condition, 1 segment was excluded, leaving 8 potentially susceptible segments.

FIGURE 9: PK96+263 of the 20” Loop in the Miraflores – Puente Guillermo section, showing a 280 m slope on the left side with a 21° gradient and dense vegetation cover, where block displacement is not possible.

In subsequent analysis, 5 additional segments were excluded due to being subject to operational considerations or other geotechnical factors. Finally, out of the initial 77 segments, only 3 were found to have the necessary geomorphological conditions for potential rock block impact on the pipeline. These 3 segments are located in the Porvenir – La Belleza gas pipeline, and one of them corresponds to the case study presented in section 2. Table 4 presents the segments with suitable geomorphological conditions for potential block impact on the pipeline, after applying the filtering criteria described.

Gas Pipeline	Initial PK	Diameter (in)	Weighted Slope (°)	Slope Length (m)	Rock Type
PORVENIR - LA BELLEZA	096+663	20	21	280	Colluvial deposit (glacial origin) over claystone, siltstone, with sandstone interbeds
PORVENIR - LA BELLEZA	103+166	20	21	510	Colluvial deposit (glacial origin) over claystone, siltstone, with sandstone interbeds
PORVENIR - LA BELLEZA	121+333	20	27	320	Conglomerates over claystone with sandstone interbeds

TABLA 4: Segments with geomorphological conditions for potential rock block impact on the pipeline

3.5 Impact Energy Evaluation for Identified Segments

As outlined in section 2.1, the energy generated by rock blocks from the upper slopes adjacent to the identified segments was calculated based on slope length, gradient, and block characteristics. Table 5 summarizes the results.

Initial PK	Diameter (in)	Weighted Slope (°)	Slope Length (m)	Block Diameter (m)	Unit Weight of Rock (kN/m^3)	Block Velocity (m/s)	Mass (kg)	Block Energy (kJ)
096+663	20	21	530	2.00	22	17.2	17600	2607
103+166	20	21	510	2.00	22	15.0	17600	1988
121+333	20	27	320	2.00	22	25.2	17600	5609

TABLA 5: Rock Block Impact Energy Results for the Identified Segments**.**

3.6 Pipe Resistance Evaluation for Identified Segments

The energy required to produce denting or rupture is determined as outlined in section 2.2. The results are presented in Table 6.

Initial PK	Diameter (in)	Yield Strength (MPa)	D/t Ratio	Energy Absorbed for Denting (E) (kJ)	Energy Absorbed for Rupture (E) (kJ)
096+663	20	450	53.33	5.66	45.3
103+166	20	450	53.33	5.66	45.3
121+333	20	450	53.33	5.66	45.3

TABLA 6: Energy required to produce denting or rupture from block impact for the identified segments**.**

In all cases, the kinetic energy that can be developed by blocks originating upslope from the pipeline right-of-way (ROW) significantly exceeds the energy required to cause denting or rupture of the pipelines.

Therefore, mitigation measures must be implemented according to the geotechnical conditions of each site, in order to minimize the risk of damage in each segment.

4. MITIGATION ALTERNATIVES

To mitigate the identified threats, a range of mitigation measures can be implemented, from simple to more complex interventions aimed at stopping or preventing block detachment and fall. The most commonly used mitigation alternatives include:

- **LIVING ROCKFALL BARRIERS:** This method, as seen in the case study, involves barriers made of shrubs and trees. Their effectiveness largely depends on the trunk diameter, which must resist the impact energy; the root depth or anchorage, which prevents uprooting or overturning; and the spacing or density of the vegetation, which helps reduce the block's speed and energy.
The main disadvantage of this alternative is its vulnerability to changes in land use caused by human activity, such as livestock grazing and deforestation. Additionally, if implemented in the short term, it functions only as a long-term solution due to the time required for the shrubs and trees to grow.
The following illustrates how vegetation type influences block trajectories, with two modeled scenarios: one where the slope is composed of talus with moderate vegetation (Figure 9), and another where the slope consists of talus with abundant vegetation (trees).

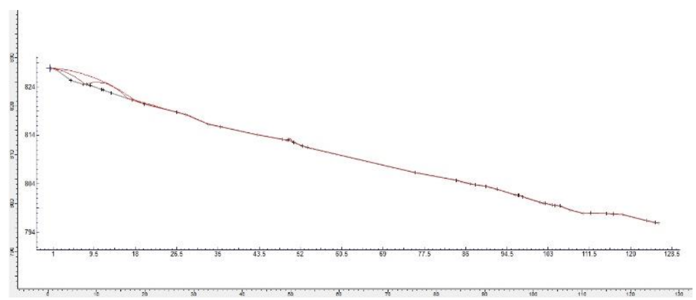

FIGURE 9: Block trajectories on a slope with moderate vegetation cover

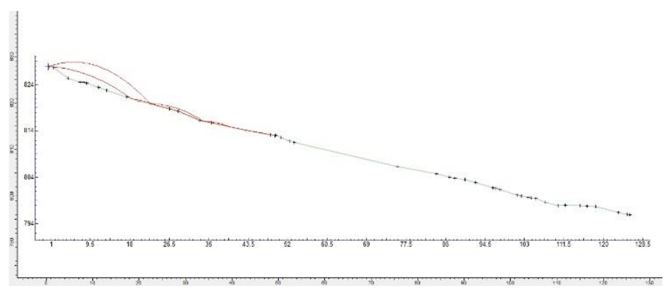

FIGURE 10: Block trajectories on a slope with abundant vegetation cover.

Figure 10 clearly shows how living rockfall barriers can help mitigate the energy, speed, and path of blocks detaching from the upper part of the slope.

- **RETENTION STRUCTURES (Rigid barriers):** As the name suggests, these structures are designed to retain falling or detached blocks. They are typically monolithic and slender to withstand the impact of large blocks without significant structural damage. These embankment-type structures can be built using mechanically stabilized earth walls, gabion walls, or rockfills. However, they tend to be massive and require considerable material for construction and transport.

The placement and geometry (especially height) of these structures must be carefully planned based on a detailed analysis of potential block fall trajectories, focusing on intercepting blocks with low kinetic energy and minimal bounce height.

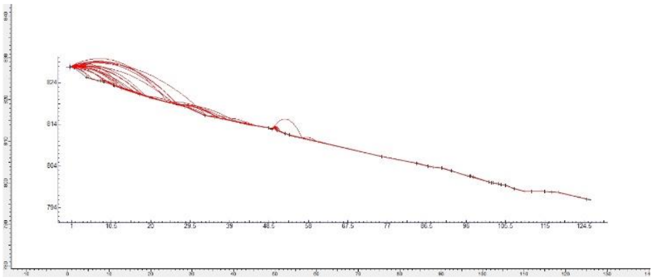

FIGURE 10: Block trajectories on a slope with light vegetation cover.

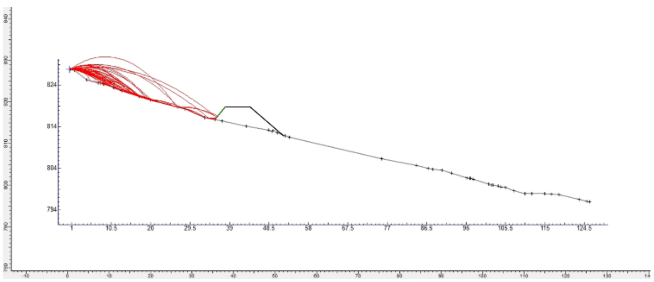

FIGURE 11: Block trajectories on a slope with light vegetation cover and a retention structure

FIGURES 10 and 11 show that retention structures are highly effective mitigation measures against rockfall. However, note the substantial size of the embankment required to contain blocks similar to the one in the case study.

- **RETENTION STRUCTURES (Flexible barriers):**

These mitigation alternatives include curtain meshes, anchored or bolted meshes, dynamic barriers, among others. They are highly effective in areas with difficult access and steep slopes, where rigid structures are impractical. Although considered expensive in the past, their increasing use has made them more affordable and widely adopted in rockfall mitigation.

These systems use high-strength meshes with varying aperture sizes, making them adaptable to different block diameters. The meshes can be anchored directly to the slope or rock mass using bolts and anchors, as shown in FIGURE 12.

FIGURE 12: Example of a rock mass stabilized with mesh and bolts/anchors

They can also be installed as freestanding retention barriers (see FIGURE 13), similar to metallic crib-type structures, where steel posts or tubes are driven into the ground and the high-strength mesh is mounted onto them. These barriers can withstand impact energies of up to 9000 kJ.

FIGURE 13: Example view of a dynamic retention barrier

5. CONCLUSION

Pipelines placed on H-frames or at surface level are susceptible to rupture due to rockfall impacts. Based on a sensitivity analysis of the results, for the segments identified as susceptible and considering their pipeline characteristics, it was determined that rock blocks larger than 0.5 meters can generate enough energy to cause rupture.

According to the findings presented in section 2.1, ground cover can mitigate the potential for block movement. In this case, it was established that dense vegetation can prevent block displacement, thereby eliminating the risk of impact on the pipelines.

To select an appropriate mitigation alternative, it is essential to conduct a prior review of the following criteria: 1) Slope geometry (topography/gradient) – which directly affects the kinetic energy and velocity of the blocks, 2)

Slope cover material or restitution coefficient, as referenced by some authors – which helps determine the energy loss of the blocks during rebound, 3) Trajectory analysis using a probabilistic approach. These combined criteria will support the selection of a mitigation alternative that satisfies the cost-benefit condition.

It is also advisable to conduct right-of-way (ROW) inspections specifically aimed at identifying this type of threat in segments where the applied methodology indicates pipeline vulnerability to rockfall impact.

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