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GEOLOGICAL GEOTECHNICAL INSPECTION ON 2.600 KM ON THE RIGHT OF WAY IN BRAZILIAN GAS PIPELINE

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ABSTRACT

This paper highlights the results of the geological-geotechnical inspection carried out in approximately 2.600 km on the ROW (right of way) managed by a Brazilian Gas Pipeline Transportation between 2023 and 2024. This type of inspection is a regulatory requirement in Brazil, according to the RTDT (Regulamento Técnico de Dutos Terrestre ANP, 2011) and is part of the integrity management program of pipeline transportation companies.

These inspections aim to identify, record, classify and monitor, on the ROW and adjacent areas, Geotechnical occurrences that could cause risk to the structural integrity of the pipelines, which crosses 5 states of Brazil, different geological features, more than 1000 river crossing, different types of slopes, hills and “serra do mar”.

At the end of the inspections the risk classification of 42 existing geotechnical occurrences was reassessed (21 were aggravated and 21 were mitigated), the risk of 31 new geotechnical occurrences were classified and 17 monitoring landslides were available.

In January 2024, a geological and geotechnical survey was conducted in the area, combining on-foot inspections and drone-based aerial imaging. This survey enabled the classification of geotechnical anomaly risks, focusing on the integrity of the gas pipeline. The most critical locations were identified and prioritized for the next phase of the project, which involves developing geotechnical solutions.

The field team and geotechnics designers determined 10 sites, based on risk analysis, to be developed studies and conceptual projects. Each case had at least 3 alternatives as a solution. Quantitative evaluation of materials, prices and

advantages and disadvantages of each alternative were included for each solution.

Between April and May 2024, the State of Rio Grande do Sul had experienced a catastrophic climatic event, with average rainfall reaching up to 500 mm and peaks exceeding 1,000 mm in certain areas. This extreme weather caused widespread flooding, erosion, and landslides, which motivated the decision to conduct a new inspection campaign.

The results of this new inspection revealed the existence of 5 new anomalies caused by the heavy rainfall (3 landslides, 1 riverside erosion and 1 soil fissure). The comparison of the inspections conducted before and after the event not only aids in guiding the development of preventive geological and geotechnical solutions but also enhances the understanding of local conditions. This understanding is crucial for defining the optimal frequency of geological-geotechnical inspection campaigns, which must account for extreme weather events within the context of current climate change scenarios.

Keywords: Geological, Geotechnical, Inspection, Right of way.

1. INTRODUCTION

The structural integrity of onshore gas pipelines is continuously challenged by geotechnical and environmental factors, especially in regions prone to extreme weather events. The Bolivia-Brazil Gas Pipeline (Gasbol), operated by Transportadora Brasileira Gasoduto Bolívia-Brasil (TBG), in its southern segment connects the city of Campinas (São Paulo) to the metropolitan region of Porto Alegre (Rio Grande do Sul). Historically, geological-geotechnical inspections have been carried out along the pipeline right-of-way (ROW), with major campaigns conducted in 2004, 2009, 2012, and 2014. These inspections aimed to identify geotechnical anomalies and classify pipeline segments according to risk levels, using

geotechnical zoning maps based on attributes such as erodibility, landslide susceptibility, and lithostructural features.

Geological knowledge gathered during these campaigns has shown that the northern portion of Rio Grande do Sul is characterized by rugged terrain highly susceptible to erosional processes and mass movements. This region also features a dense hydrographic network with steep valleys, which can generate flash floods in hilly areas and gradual inundation in lowland river valleys.

A routine hydrological and geotechnical inspection was carried out in December 2023 and January 2024. However, between April and May 2024, Rio Grande do Sul was affected by an extreme weather event, with average rainfall totals reaching 500 mm and local maxima exceeding 1,000 mm. The resulting widespread floods, erosions, and landslides exposed the urgent need to reassess geotechnical conditions along the pipeline, especially in critical segments.

Geotechnical risk management—whether of natural or anthropogenic origin—is a fundamental component of integrity strategies for linear infrastructures like gas pipelines. Aligned with the guidelines of the United Nations Office for Disaster Risk Reduction (UNDRR, 2019), disaster risk reduction (DRR) involves the continuous monitoring and systematic assessment of hazards and vulnerabilities, with a strong emphasis on failure prevention and impact mitigation. For the Gasbol pipeline, this approach entails identifying critical areas prone to erosion, landslides, and climate-induced instabilities, while also supporting the planning of preventive actions to ensure operational safety and regulatory compliance.

Moreover, the increasing intensity of extreme events—such as concentrated rainfall and mass movements—has raised concerns about their growing impact on gas transport infrastructure, particularly in geotechnically and hydrologically sensitive regions. The IPCC Synthesis Report (2023), along with national studies (PBM, 2021; Marengo et al., 2020), indicates that the effects of climate change are already observable in Brazil, marked by more frequent climate anomalies. This context requires careful evaluation of rising geotechnical and hydrological risks for oil and gas infrastructure. Climate variables must therefore be incorporated into the definition of inspection frequencies and the prioritization criteria for high-risk sections, reinforcing the resilience of pipeline networks to changing environmental demands.

Considering these scenarios, TBG's technical team, following best practices and upholding the principles of precaution and safety, decided to conduct a second geotechnical inspection between August and September 2024. This post-event campaign, led by the same team responsible for the pre-event inspection, focused on areas with steep terrain. It is also worth noting that TBG's operational integrity team had already surveyed the pipeline shortly after the peak rainfall period.

This study presents the results of the post-event geological-geotechnical inspection along the Gasbol ROW in Rio Grande do Sul, emphasizing the consequences of the 2024 extreme rainfall event. The analysis compares pre- and post-event conditions, identifies new geotechnical anomalies, and assesses

the worsening of previously mapped occurrences. In addition, it discusses the importance of establishing an optimal inspection frequency that considers the increasing recurrence of extreme weather events under current climate change scenarios. Defining such frequency remains a relevant topic across oil and gas transmission companies and other linear infrastructure operators, aiming to balance safety-driven practices with economically viable decision-making.

2. LOCAL CONTEXT AND GEODYNAMIC HAZARD CONDITIONS

The study area extends from the municipality of São José dos Ausentes to Canoas, following an approximately northeast-southwest (NE–SW) orientation (Figure 1), and intersects multiple geological domains in the northeastern portion of the state of Rio Grande do Sul. Starting from the northernmost sector, the gas pipeline traverses the elevated plateaus and tablelands underlain by the Caxias Unit, composed predominantly of rhyodacitic and andesitic lava flows. Further south, it continues across basaltic plateau areas sustained by the Gramado Unit (Serra Geral Formation), which marks the beginning of the Escarpas Serranas (Serra Escarpment zone).

Along this escarpment zone, the pipeline cuts through sedimentary rocks of the Paraná Basin, notably the Botucatu Formation, and transitions into lower relief domains characterized by dissected hills and rolling terrain. These southern sections are composed mainly of Pirambóia and Rio do Rastro formations, often mantled by unconsolidated materials such as alluvial, colluvial, and eluvial deposits. The pipeline continues through these units until reaching the urbanized zone of Canoas (Figure 2).

This regional setting reflects a complex interplay between volcanic and sedimentary stratigraphy, varying geomorphological contexts, and differentiated geomechanically behaviors that influence the susceptibility of the terrain to mass movements and hydrological hazards.

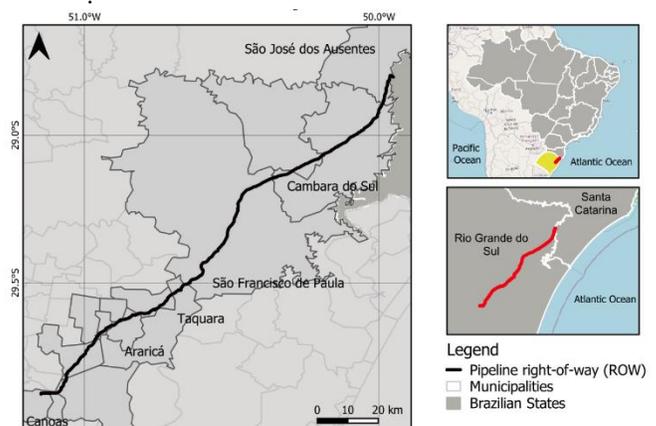


FIGURE 1 – Location of the study area along the Bolivia-Brazil gas pipeline corridor, northeastern Rio Grande do Sul, Brazil.

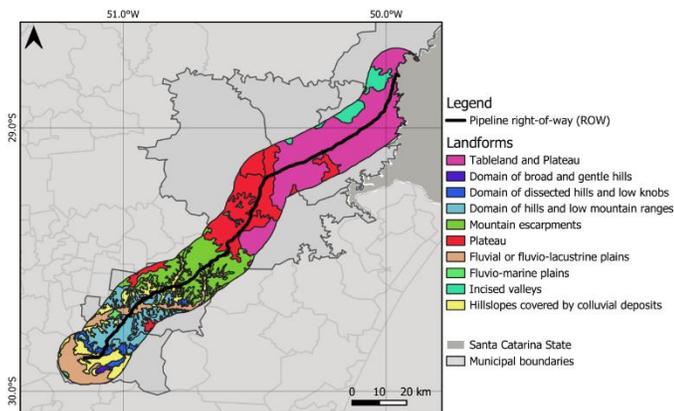


FIGURE 2 – Geological domains crossed by the Bolivia-Brazil gas pipeline in northeastern Rio Grande do Sul.

The natural hazards identified along the pipeline route are intrinsically linked to the regional geological and geomorphological context. In the northern sector, encompassing plateaus and high plains (tablelands), slope instabilities such as erosion, shallow landslides, and creep were observed, particularly near watercourse crossings where riverbank undercutting is prevalent. In the escarpment region, processes such as debris flows, landslides, and flash floods are predominant, while in the domains of dissected hills and low mountain ranges, the main processes include sheet erosion, localized slope failures, and bank erosion.

The regional context was also characterized by geotechnical products previously developed by TBG between 2004 and 2014. Of particular importance is the 2012 campaign, which included the preparation of geotechnical mapping. That study incorporated base maps and thematic maps at regional scales, such as erodibility maps, landslide susceptibility maps, and lithostructural maps. Based on this integrated analysis, a set of Geotechnical Zoning Maps, that classified the pipeline according to its geotechnical risk level: Low, Moderate-Controlled, Moderate, High, and Critical (Eminent).

According to the zoning maps, the SID-CAN section — corresponding to the entire pipeline corridor in Rio Grande do Sul — was classified as follows: 5% Low risk, 37% Moderate-Controlled, 23% Moderate, 13% High, and 22% Critical. Therefore, over 35% of the analysed area falls into categories equal to or greater than Moderate risk, based on the available cartographic datasets at regional scale.

Complementing this contextualization, the 2014 inspection campaign included aerial reconnaissance by helicopter. This activity aimed at an expedited survey of the right-of-way, supporting real-time monitoring and allowing for targeted recommendations for in situ verification of critical geotechnical features.

3. METHODOLOGICAL FRAMEWORK

The geological-geotechnical inspection primarily consists of identifying anomalies affecting the soil or subsoil cover, whether of natural origin or anthropogenic, with particular attention to destabilizing processes that may compromise pipeline integrity (Varnes, 1968). The inspection methodology is based on systematic field surveys conducted along the pipeline right-of-way, focusing on detecting geotechnical manifestations such as landslides, erosional features, creep, ground fissures, and slope deformations.

Field data are recorded using standardized digital forms via a mobile application, allowing for georeferenced logging of kilometer markers and the characterization of pre-existing geotechnical occurrences, newly identified anomalies, intact containment structures, and damaged containment structures.

All geotechnical occurrences are assessed through a qualitative risk classification methodology developed by TBG. This classification considers both the severity of the anomaly and the likelihood of it compromising pipeline functionality or safety. The applied risk matrix, summarized in Table 1, combines geotechnical severity with the estimated probability of failure, resulting in five risk categories.

Geotechnical Risk Degree		Probability of Pipeline Failure				
		Unlikely	Occasional	Possible	Probable	Highly Probable
Geotechnical Severity	Extreme	TOL	MED	MED	HIGH	HIGH
	High	TOL	TOL	MED	MED	HIGH
	Moderate	ACE	TOL	TOL	MED	MED
	Low	MON	ACE	ACE	TOL	TOL
	Insignificant	MON	MON	ACE	ACE	ACE

MON (Monitorable), ACE (Acceptable), TOL (Tolerable), MED (Medium), and ALTO (High)
Source: produced by the author.

TABLE 1 – Qualitative Matrix of Geotechnical Risk Classification.

4. FIELDWORK SURVEYS

The present study initially comprised a geotechnical inspection by walkover across 45 km (29% of the segment) of the pipeline right-of-way and surrounding areas in the state of Rio Grande do Sul, as well as an additional 59.5 km in the southern region of Santa Catarina, totalling 187 km. During this phase, four new geotechnical occurrences were identified in Rio Grande do Sul, associated with mass movements and erosion processes on land and within watercourses. Of these, three were classified as “acceptable risk,” and one as “monitoring required.” The field investigations were conducted between December 2023 and January 2024. In this same campaign, a total of 152 previously registered occurrences were re-inspected across both states, with only two showing risk evolution—both transitioning from “aggravated monitoring” to “medium risk.”

Between April and May 2024, the state of Rio Grande do Sul was severely affected by an extreme weather event, impacting approximately 96% of its territory. This event resulted in widespread flooding and mass movement occurrences. In Porto Alegre, for instance, water levels in the Guaíba Lake

reached a record-breaking 5.35 meters, causing extensive damage throughout the region.

Given the magnitude of the impacts, it was deemed necessary to reassess the entire affected region. Accordingly, an additional 100 km of right-of-way and adjacent terrain within the state of Rio Grande do Sul—equivalent to 53% of the total 187 km pipeline section—was selected for detailed walkover inspection between kilometer posts 1083 and 1183. This second round of geotechnical fieldwork was conducted between August and September 2024, with a focus on areas characterized by steeper terrain and known geomechanically sensitivity.

During this post-event field campaign, five new geotechnical occurrences were identified that were not recorded in TBG’s previous inspection records. These events are directly associated with mass movement processes, including soil creep, landslides, tension cracks, and erosion of streambanks and channel crossings (Table 2). Notably, these features had no historical record before the extreme rainfall event, highlighting their recent genesis.

It is important to emphasize that the geological framework of the inspected region, composed of layered volcanic flows (predominantly basalts and rhyodacites), presents natural predisposition to creep-type mass movements. The heavy rainfall concentrated over short durations likely contributed to the acceleration of these creep processes, which are often difficult to detect during routine inspections due to their subtle and progressive nature.

Chainage (km)	Type of Occurrence	Location	Current Risk Level	Municipality
1117+187S	Creep / Landslide	ROW and Left Flank	Medium	São Francisco de Paula
1119+813S	Landslide	East Flank	Acceptable	Taquara
1120+210S	Creep / Landslide	West Flank	Acceptable	Taquara
1120+670S	Tension Crack	ROW	Acceptable	Taquara
1156+066S	Streambank Erosion	Channel Margins	Acceptable	Araricá

Table 2 – Newly Identified Geotechnical Occurrences.

The subsequent sections describe the geotechnical occurrences identified during the inspection:

- I. The occurrence at km 1117+187S (Figure 3) consists of a landslide accompanied by fissures along the pipeline right-of-way, primarily on the left side and extending laterally toward a nearby road (approximately 20 meters from the right-of-way). The fissures are predominantly aligned longitudinally with the pipeline, although some transverse fissures are also observed. The fissure system exhibited progressive displacement, forming subsidence steps ranging from centimeters to decimeters in height. Initially, the area showed signs of incipient creep; however, following the extreme weather event, the movement rate reached levels consistent with landslide conditions, according to the classification proposed by Varnes (1978).
- II. The geotechnical occurrence at km 1119+813S (Figure 4) consists of a landslide located outside the pipeline right-of-way, on its eastern side, approximately 10 to 15

meters from the right-of-way boundary. Due to the local geology, characterized by volcanic flow deposits, only a thin soil layer (ranging from centimeters to decimeters) overlies the bedrock, forming a sharp contact that favours the development of this type of sliding feature. Interflow sedimentary layers between the volcanic flows typically facilitate strong horizontal groundwater movement, resulting in a water emergence at the slip surface that further contributes to the landslide process. As observed previously, this configuration indicates the evolution of pre-existing creep processes, whose velocities increased significantly due to the abnormal infiltration of rainfall into the rock mass.

- III. The geotechnical occurrence at km 1120+210S (Figure 5) refers to a landslide/creep process located outside the pipeline right-of-way, on the western slope, approximately 80 meters away. The landslide scar is approximately 100 meters long, subparallel to the pipeline corridor, and exhibits a scarp with a vertical displacement of up to 1 meter in the most downstream sections. The exposed layer reveals a predominantly colluvial soil composition. Such heterogeneous and poorly consolidated soils are highly susceptible to mass movements. Once again, the percolation of rainfall into the rock mass contributed to increased velocities in the creeping process, ultimately leading to a landslide.
- IV. The newly identified occurrence at km 1120+670S (Figure 6) refers to a midslope landslide that resulted in a surface crack approximately 15 meters in length, transversely crossing the pipeline right-of-way, with a vertical displacement (scarp) of up to 0.2 meters.
- V. The occurrence at km 1156+066S (Figure 7) refers to erosion affecting both banks of a watercourse, including its channel and the western edge of the pipeline right-of-way. It is recommended to monitor the progression of this feature and, in case of worsening erosional processes, assess the conditions and develop a containment project for the crossing, focusing on stabilizing both banks, restoring the right-of-way slopes—especially the right bank—and rehabilitating the channel. The erosion was intensified due to the abnormal water flow in the area.



FIGURE 3 – Km 1117+187S – The base of the image corresponds to the left side of the right-of-way. On the right, detail of the subsidence step and erosional rills.

View from the pipeline right-of-way toward the right hillside. B) Downstream view on the right hillside. C) Upstream view on the right hillside. D) Aerial image obtained by drone, view toward the right.



FIGURE 6 – A) Aerial image of the study area. The crack is represented by the yellow dashed line. Downstream is at the top and upstream at the bottom of the image. B) Detail of the crack.



FIGURE 4 – Geotechnical occurrence at km 1119+813S, classified as having an aggravated risk level. A) Downstream view. B) Upstream view. C) Detail of the slip surface with water emergence. D) Downstream view.



FIGURE 7 – Geotechnical occurrence at km 1156+066S with aggravated risk classification. A) Downstream view from the upstream bank and left side of the pipeline. B) View of the right side from the crossing point. C) Downstream bank view towards the right side. D) Upstream view from the downstream bank and right margin.

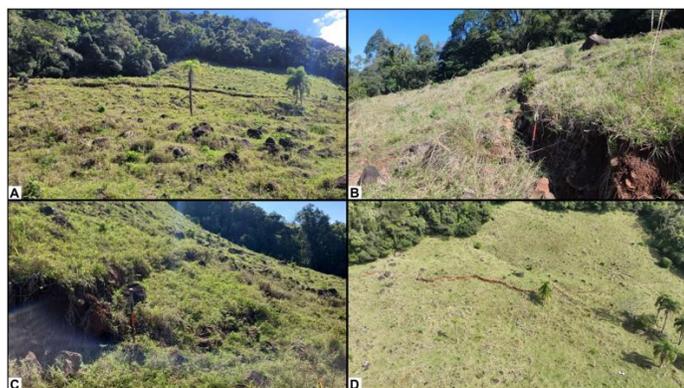


FIGURE 5 – Geotechnical occurrence at km 1120+210S, classified with an aggravated geotechnical risk level. A)

5. RESULTS AND DISCUSSION

Historical rainfall assessments for southern Brazil indicate that, although localized precipitation events exceeding 300 mm are relatively rare, they are not unprecedented. Catastrophic events such as those in Blumenau (1983), Joinville (1995), and the Itajaí Valley and Luís Alves (SC) in 2008, which resulted in widespread landslides and hundreds of fatalities, demonstrate that high-magnitude rainfall events tend to recur every one to two decades. However, climate models have increasingly indicated a trend toward more frequent extreme

events (Marengo et al., 2021). This observation underscores the importance of establishing a consolidated pluviometry database, integrated with time series of geotechnical occurrences, to assess the recurrence of such phenomena and support early preventive actions.

According to the Brazilian National Institute of Meteorology (INMET), between April 27 and May 2, 2024, several municipalities in the state recorded precipitation totals ranging from 300 mm to 400 mm within just six days—values equivalent to nearly three times the historical monthly average for May. In the municipality of Soledade, for instance, total precipitation between April 27 and May 31 reached 884.0 mm, with 773.8 mm recorded in May alone. As illustrated in Figure 8, the northeastern region of Rio Grande do Sul—crossed by part of the Bolivia–Brazil pipeline corridor—was among the areas most severely affected by the intense rainfall during April and May 2024.

Figure 8 illustrates that the Bolivia–Brazil gas pipeline segment within Rio Grande do Sul intersects one of the areas with the highest recorded precipitation during the April–May 2024 extreme weather event. The region near km 1120, which includes four newly identified geotechnical occurrences between kilometers 1117 and 1120 (in the municipalities of São Francisco de Paula and Taquara), is located within the geomorphological transition zone from the tablelands and plateau uplands to the range escarpments (Figure 2). In contrast, the occurrence at km 1156, in the municipality of Araricá, marks the lower boundary of the escarpments and the transition to the domain of dissected hills and lower ranges. In this location, the main impact was channel margin erosion, a process compatible with the hydrological dynamics of the base of these geomorphological units, where steep talwegs favour rapid flooding.

The analysis of the geotechnical occurrences indicates that creep processes, defined by very slow slope movements, were significantly exacerbated by the anomalous precipitation. This resulted in the triggering of landslides and the formation of settlement steps—clear evidence of increased instability. The local geology, dominated by basaltic flows of the Serra Geral Formation, favours lateral groundwater movement along interflow layers, which promotes saturation and spring emergence in specific zones, thereby accelerating downslope mass movements. This behaviour reinforces the importance of mapping and monitoring areas prone to creep, particularly in the aftermath of extreme precipitation events.

The decision to conduct a new inspection campaign just four months after the previous one—prompted by the 2024 weather event, enabled the identification of five previously undocumented critical occurrences. This finding highlights that geotechnical inspection intervals should not rely solely on fixed schedules but rather be informed by regional hydrological behaviours and the recurrence of extreme rainfall. Rigid inspection timetables may fail to detect the cumulative or sudden effects of intense rainfall on slope stability.

Despite the significance of this issue, there is currently no technical standard or regulatory guideline that mandates a fixed frequency for geotechnical inspections of linear infrastructure such as pipelines. International literature suggests that such periodicity should be determined by a range of factors, including local geotechnical characteristics, exposure to extreme weather, failure history, and the operational criticality of the asset. Silva et al. (2024) analysing historical failure data in U.S. pipelines using artificial neural networks, concluded that most mandatory inspections focus on corrosion risks, often at intervals of up to 10 years. However, this focus inadequately addresses geotechnical risks, which tend to manifest abruptly and unpredictably under conditions of climatic vulnerability.

In line with this, Wang et al. (2021) advocate for a risk-based integrity management framework, where inspection frequency is guided by continuous risk assessment, accounting for mass movement susceptibility, expansive soils, seismic activity, and evolving climate patterns. In the case of the Gasbol pipeline, the most critical occurrences were concentrated in geomorphological transition zones between the plateau uplands and range escarpments, even though other regions also recorded rainfall accumulations exceeding 800 mm. Classical studies on rainfall–landslide correlation (Guidicini & Iwasa, 1976) and more recent research on Critical Precipitation Coefficients (CPC) (Tatizana et al., 1987; Fernandez et al., 2018; Fernandez et al., 2022) emphasize that early warning thresholds should not rely solely on total rainfall but must consider peak intensities as well. This is particularly relevant for linear infrastructure, where pluviography data can inform more sensitive and effective monitoring protocols attuned to local rainfall dynamics and associated geotechnical responses.

It is recommended that pipeline operators adopt a risk-based geotechnical inspection strategy, informed by spatial zoning of susceptibility. This approach should include a systematic understanding of terrain predisposition to different failure mechanisms and their interactions with environmental triggers, such as rainfall thresholds and flood stages. From such zoning, segment-specific inspection frequencies can be established, optimizing monitoring efforts according to the geotechnical and hydrological characteristics of each section of the pipeline.

Furthermore, cost-benefit assessments comparing early-stage detection and intervention against responses to fully developed geotechnical failures should be integrated into inspection planning. This economic perspective supports the adoption of continuous monitoring technologies, including remote sensing (e.g., InSAR), drone-based imaging, rainfall intensity analysis from pluviography, and predictive modelling. These tools enhance the ability to detect early warning signs of instability, thereby improving the resilience and operational safety of pipeline infrastructure.

6. CONCLUSION

The findings of this study demonstrate that extreme weather events can trigger geotechnical risks either by intensifying incipient processes already present, such as early-stage creep or incipient erosion, or by initiating instabilities in areas that previously showed no observable signs of movement. However, such occurrences were observed exclusively in zones with higher susceptibility. In contrast, segments located on geomorphological units with low susceptibility, such as plateaus and tablelands, did not exhibit any new geotechnical pathologies, even under intense cumulative rainfall.

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