IPG 2023
INTERNATIONAL PIPELINE GEOTECHNICAL CONFERENCE
November 23rd - 24th. Bogotá D.C. - Colombia

Under the auspices of:
arpel
ASOCIACIÓN DE EMPRESAS DE PETRÓLEO, GAS Y ENERGÍA RENOVABLE DE AMÉRICA LATINA Y EL CARIBE

Organize:
C-IPG
ACIEM

6TH INTERNATIONAL PIPELINE GEOTECHNICAL CONFERENCE IPG 2023

IPG2023-0038

PRIORITIZATION CRITERIA FOR DEBRIS FLOW ENGINEERING WORKS TO PROTECT PIPELINES IN THE BRAZILIAN SERRA DO MAR REGION, SÃO PAULO

Pedro Victor Serra Mascarenhas[1], Wanderley Camargo Russo Jr.[1], Thiago da Costa Santos[1], João Duarte Guimarães Neto[1]

[1]Petrobras Transporte S.A – Transpetro, Rio de Janeiro, RJ, Brazil

ABSTRACT

In the state of São Paulo, Brazil, a crucial pipeline runs through the coastal region, connecting the country's largest marine oil terminal to a strategic refinery. This pipeline's route passes through the Serra do Mar region, a tropical mountainous area along the South and Southeast coast of Brazil. In February 2023, the region encountered the most extensive rainfall event ever recorded in Brazil, with rainfall reaching 684 mm within 11 hours. A total of 52 geotechnical events, ranging from low to high risk for the pipelines, were detected. Debris flows were identified as the primary cause of these incidents along the pipeline's right-of-way (ROW). Previously to this event, a study aimed to identify critical areas along the pipeline's route and establish a prioritization process for necessary engineering works to prevent pipeline failures due to debris flow. The prioritization process led to the identification of two regions requiring immediate mitigation measures to safeguard the pipelines from future damage. During the intense rainfall event in February, one of these regions experienced a debris flow incident that caused significant destruction to the surrounding community and the road crossing the river. However, due to the completion of engineering works a year prior to the rainfall event, the pipeline remained intact. This paper focuses on the prioritization process employed to identify critical hydraulic basins prone to debris flows, and provides details on the engineering works that effectively prevented pipeline failure due to the implementation of the prioritization process.

Keywords: Debris flow, stream erosion protection

1. INTRODUCTION

Pipeline failures can be classified by means of their causes in internal corrosion, external corrosion, natural causes, third party causes, material/construction defects, stress corrosion cracking (SCC), and others [1].

Geotechnical events are a subcategory of natural causes, and it often is the only natural cause that contains registries of pipeline failures. In Europe, 96,55%t of Gas pipeline natural causes failures are due to ground movement between 2010 and 2019 were due to landslides [2], and 33% of the spillages in cross-country oil pipelines due to natural causes were caused by landslides between 1971 and 2019 [3].

In Brazil, soil mass movements are frequent in the South and Southeast regions of the country due to the geological formation "Serra do Mar" (Sea Ridge), which circumscribe the coast of those regions. The Sea Ridge is a system of escarpments and mountains that ranges about 1500 km, with high lithological and structural complexity, and it has great economic importance due to its historical occupations, and due to the fact that it connects the largest city in the country to the sea [4]. The Sea Ridge is often stricken by heavy rainfalls, which trigger great mass movements that harm the local community and local infrastructure.

The Sea Ridge contains some of the most important facilities of the midstream oil market segment. The largest marine terminal of the country, with capacity around 2 million m³ for oil and byproducts storage, is located in the municipality of São Sebastião, at the Northeast coast of São Paulo [5]. Two major pipeline ROWs begin their routes in the terminal, crossing the Sea Ridge mountains in the direction of oil refineries.

The first ROW is named OSBAT, and it connects the terminal to the oil refinery at the city of Cubatão, the refinery Refinaria Presidente Bernades (RPBC). The second is named OSPLAN, and it connects the oil terminal to the São Paulo's highland, allowing for more intricate oil logistics. Both are especially prone to soil mass movements triggered by rainfall mechanism particular to the Sea Ridge. These pipelines and the oil marine terminal are operated by Transpetro.

The failure mechanism of the mass movements triggered by heavy rainfalls on the Sea Ridge comprises shallow landslides in the upper, steeper, part of the slopes, rotational slides associated with some creep along the lower, less steep part of the slopes, and debris flow triggered by intense rains [6]. Shallow landslides.

The Sea Ridge region of the coast of the state of São Paulo mainly experiences shallow landslides and debris flows triggered by heavy, periodically occurring rainfalls. Examples of historical accidents that greatly affected the region are the Caraguatatuba incident in 1967 and the Cubatão incident in 1993 [7]. Recently, a heavy rainfall event occurred in the municipality of São Sebastião, summing up more than 680 mm in less than a day, the largest volume of a rain ever registered in the country [8].

This last rainfall event caused severe damage to the roads, buildings electric powerplants, and other facilities, also putting the ones that were not directly affected in hazard. It also caused integrity issues to the ROWs that crosses the areas, especially to the OSBAT. 52 geotechnical occurrences, ranging from low to high risk to the pipeline's integrity.

The situation rapidly prompted reaction to the risk rise. Field surveys, aerial surveys, field geotechnical instrumentation campaigns, inline-inspection, pipeline operation stop, and product were some of the immediate actions taken to avoid any further consequences arising from unknown leakages. Later, emergency engineering works were taken, granting safe pipeline operations.

During the field investigations a debris flow was found where the pipeline crosses a river, on the km 11+050 of the ROW. On that place, an engineering work completed in May 2022 avoided a drastic pipeline failure that would have been if it were not for preventive studies performed years ago with the goal of pinpointing places where debris flow was critical to the pipeline.

Figure 1 – Debris flow occurred due to the rainfall event of February 2023 in OSBAT, km 11+050, and the channel built an year earlier that protected it.

This engineering work was a result of a priorization process done over a study that aimed to find locations where there is a worrying probability of a debris flow striking the pipeline.

In 2004, a study was conducted along the OSBAT ROW. The study goal was to classify the ROW regarding its susceptibility to the most common mass movements the region: lansdlides, rock falls, debris flow and movements of talus. Regarding debris flows, 8 hydrological catchments were chosen for more refined studies by means of a distance from the pipeline criteria. From the 8 hydrological catchments, two were deemed as critical (basins 6 and 7) by the quantitative methodology employed [9]. The two critical hydraulic basins were localized in the kilometers 11+050 and 12+280 of the ROW.

This paper shows the prioritization process undertook, the engineering works built to mitigate debris flow risk, and their performance after the historical rainfall event that happened in February 2023 along the ROWs.

2. MATERIALS AND METHODS

2.1 Critical hydraulic catchments selection criteria

The potential of debris flow in the hydraulic catchments was studied through a quantitative and a qualitative method [9]. The qualitative method classified the catchments by means of a score that weights the triggering, geometric and geomorphological characteristic of the catchments into a single number. The quantitative method compared the debris volume transported against the available depositional volume, using empirical formulas to find the materials that was transported.

The qualitative method was employed to define a rank between the catchments. Its formula is:

$$FS = \sum PS_i . w_i$$

where FS is the final susceptibility score to debris flow for the catchment, PS_i is the partial score relative to each parameter that is associated to debris flow susceptibility, and w_i are their respective weights.

The parameters that compose the final score and thei possible partial values are shown in Table 1.

Table 1 – Parameter of the qualitative method employed to define debris flow potential for the studied catchments, class definitions, weight, parameter values' ranges and partial scores.

PARAMETER	CLASS	WEIGHT	PARAMATER VALUE	PARTIAL SCORE
RAINFALL (mm/h)	R1	3,0	>80	10
	R2		60 - 80	6,6
	R3		30 - 60	3,3
	R4		<30	0
SLOPE ANGLE (DEGREES)	S1	2,5	>45	10
	S2		45 - 30	6,6
	S3		15 - 30	3,3
	S4		<15	0
STREAM DECLIVITY (DEGREES)	D1	0,5	>25	10
	D2		15 - 25	6,6
	D3		10 - 15	3,3
	D4		<10	0
WATERSHED AREA (km²)	A1	1,0	<5	10
	A2		5 - 10	6,6
	A3		10 - 20	3,3
	A4		>20	0
WATERSHED HEIGHT (m)	H1	1,0	>750	10
	H2		500 - 750	6,6
	H3		200 - 500	3,3
	H4		<200	0
LAND USAGE AND OCCUPATION (%)	V1	0,5	90 - 100	10
	V2		50 - 90	6,6
	V3		30 - 50	3,3
	V4		<30	0
GEOMORPHOLOGY	G1	1,5	G1	10
	G2		G2	6,6
	G3		G3	3,3
	G4		G4	0

The rain factor is notably the most critical element when considering the triggering of debris flow events. It carries significant weight in the overall analysis, particularly in the context of such phenomena. In this specific case, the most crucial rain events are those with peak hourly measurements, expressed in millimeters per hour. The slope Inclination factor also holds pivotal importance in our evaluation, as the slope's incline plays a vital role in the contribution of material to the primary drainage systems, primarily through shallow planar landslides, which in turn feed the debris flows.

Conversely, the slope of the channels is fundamental as it serves as the surface upon which hyperconcentrated flows chart their course. There exists a direct proportionality between the steepness of slopes and the velocity of the flow. Additionally, understanding the watershed area is essential for sizing the collection and concentration of rainwater, as well as for defining the principal routes and dynamics of debris flow in the event of initiation. The height of the slopes is significant for measuring landslides.

Geological aspects encompass the identification of the prevailing lithology in the study area, as well as the fracture patterns in the rock formations, soil thickness, and the mapping of deposits that provide evidence of past debris flows. The factor of land use and occupancy pertains to the pattern of land use in the study area. It is crucial to observe whether exposed soil and at-risk infrastructure are present.

Table 2 shows the scores calculated for each of the catchments analyzed.

Table 2 – Susceptibility scores for each of the catchments studied.

Catchment	score	Rank
1	1.90	5
2	1;60	6
3	1.00	8
4	1.41	7
5	2.24	4
6	3.86	3
7	4.31	1
8	4.19	2

Out of the 8 hydraulic basins studied, the 3 most critical were selected for a more refined analyses, aiming to model the debris flow path, debris volume and whether the pipeline needs constructions for protecting it. The 3 catchments were selected as the quantitative ranking method also classified them accordingly. Hydraulic catchments 6, 7, and 8, located respectively at the positions pipeline ROW km 12+380, 11+010 e 9+600, were the 3 selected catchments. More information regarding declivity profile of the main drainage path and declivity range over the catchment are provided in Table 3

Table 3 – declivity overview of the catchments.

catchment	Area >30º	% of the total area >30º	Total area
6	132.8	35.2	26.6
7	117.8	45.6	38.7
9	96.6	30.1	31.2

The refinement studies were performed by modelling the debris flow path using the Rapid Mass Movement Simulation (RAMMS) software [10].

The RAMMS software simulates the debris flow volume, erosion depth, friction and other important parameters by numerically solving a depth-averaged equations of motion (shallow water equations) for granular flow.

For the debris flow rate analysis, the employed method was the Discharge Hydrograph Method. Four rain return periods were chosen: 25, 50, 100 and 200 years.

For the erosion process, the adopted value was a constant (0.025 m/s), proposed in the study published by Berger *et al.,* 2011 [11], for the Illgraben torrent (erosion rates measured by sensors buried in the channel bed). This is the rate used by the model for transport until the predicted erosion depth is reached (maximum thickness of 1.0m).

The friction parameters μ and ξ were assumed with the values $\mu = 0.2$, $\xi = 120$ m/s^2. These parameters should fall within the values suggested by the developer of the software based on the Voellmy model.

For the simulation of debris flow, the Area Release Method was also used, considering the occurrence of planar landslides on slopes with instability potential (in this case, young and mature residual soils), which make up the watershed. To do so, situations were simulated for landslides with 4 thicknesses (0.10, 0.50, 1.00, and 1.50 m), representative of historical occurrences on the slopes of the Serra do Mar.

The terrain model (domain) was expanded to allow visualization of the deposition of the debris flow. The areas of material release for the debris flow were taken from the Geological-Geotechnical Features map of the corresponding watershed.

2.2 Engineering solution and design considerations for the debris flow potential areas.

The engineering solutions to the debris flow potential consisted of concrete channels built over the pipeline. The channels were built with buried beams on the beginning of the channels to protect the pipeline from debris that might cause erosion along the river path, striking the buried pipelines; and with shorter beams at the end of the channel with the intention of avoiding erosion under the channel due to the water passage between the natural river channel and the concrete channel. The channels were firstly built for hydraulic catchments 6 and 7, as the prioritization quantitative method showed that these tow catchments are subject to debris volume that exceeds the catchment reservoir area, which does not occur for catchment 8.

The project took into consideration the excavation profile predicted in the RAMMS numerical modeling for the protection of the pipeline. This was done while considering the peak discharge for a 60-minute rain intensity with a return period (TR) of 100 years. Under these conditions, the estimated flow velocity was 5 meters per second. The reaction forces take into account the confinement/passive effort of the protection channel within the limits of the pipeline's right-of-way on both sides of the channel.

3. RESULTS AND DISCUSSION

3.1 Numerical modelling of the hydraulic catchments

The application of the RAMMS software can be seen in Figure 2 and Figure 3. Numerical modeling of the debris flow for the most susceptible watersheds indicated that the debris flow crosses the pipeline right of way up to 300 m and 90 m downstream, respectively in catchments 6 and 7, for the return period of 100 years. The simulation of the debris flow reaches velocities of 2 m/s and 5 m/s in watersheds 6 and 7, recommending protecting the pipeline against drainage channel erosion.

The empirical formulations and the simulations of the RAMMS software proved to be adherent for the determination of the deposition of the flow of debris, showing the total distance and the volume of mobilized material, necessary for delimitation of the intervention area and definition of the pipeline protection works.

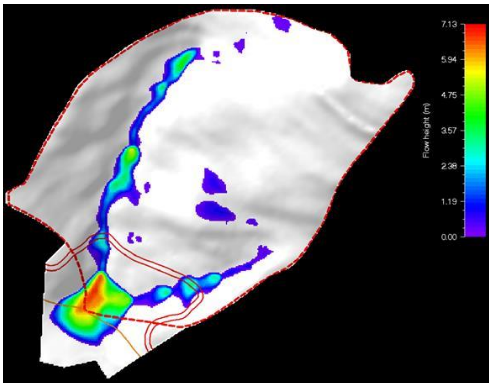


Figure 2 – Numerical modelling of the hydraulic catchment 6 (OSBAT km 12+380).

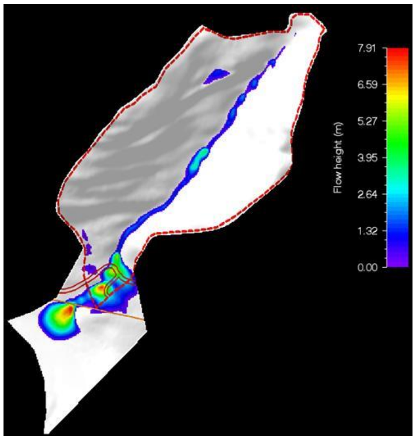


Figure 3 – Numerical modelling of the hydraulic catchment 7 (OSBAT km 11+010).

3.2 Concrete channels for stream erosion protection

The works started om December/2021, and they finished by March/2022. Figure 4 and Figure 5 show the rivers path before and after the channel construction. Figure 6 and Figure 7 show some details of the channel projects, such as the 3D modelling and profile.

(a)

(b)

Figure 4 – Hydraulic Catchment 6 (OSBAT km 10+600). (a) river path before the channel construction; (b) river path after the channel construction.

(a)

(b)

Figure 5– Hydraulic Catchment 7 (OSBAT km 12+100). (a) river path before the channel construction; (b) river path after the channel construction

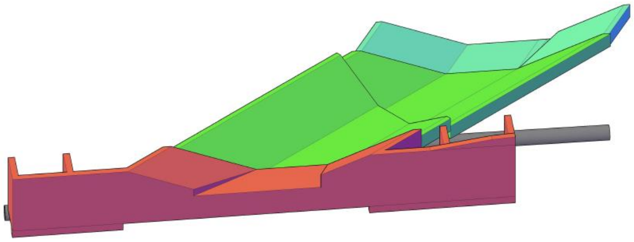


Figure 6 – 3D model of the concrete channel of the hydraulic catchment 6.

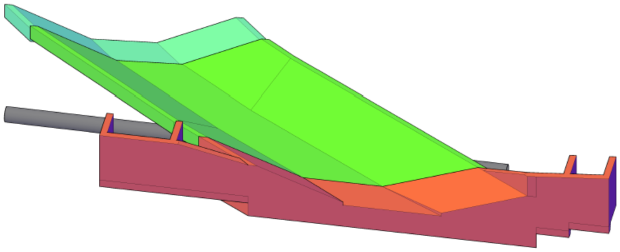


Figure 7 – 3D model of the concrete channel of the hydraulic catchment 7.

The channel section designed for the catchments 6 and 7 have the same dimensions and it is shown in Figure 8

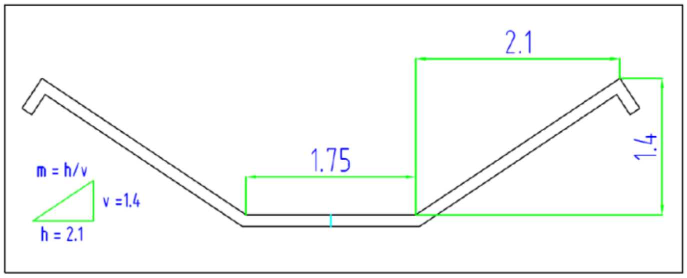
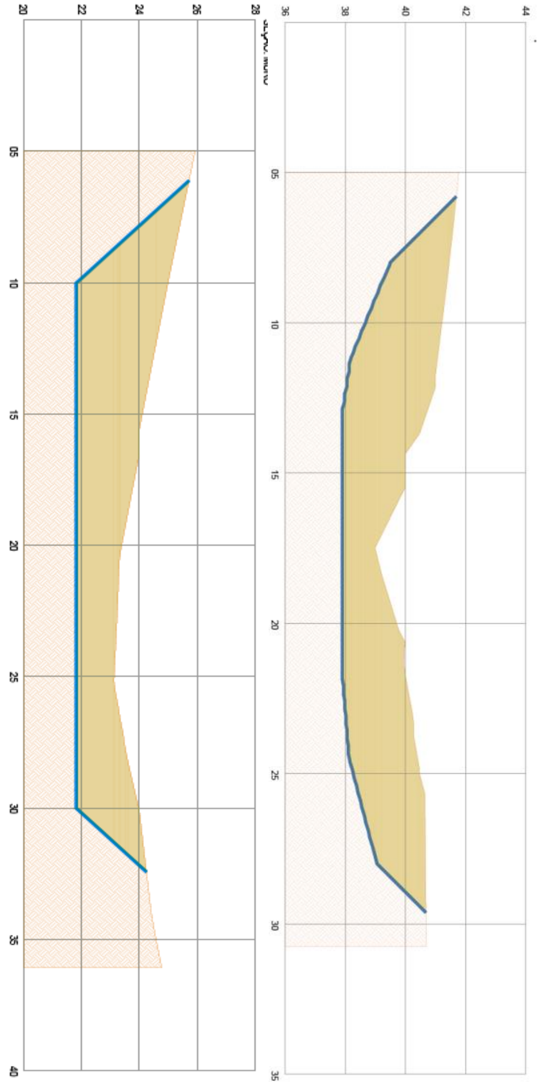


Figure 8 – Channel section designed for catchment 7.

The excavation profile that resulted from the numerical studies for catchments 6 and 7 are in shown in Figure 9.



(a) (b)

Figure 9 – Excavation profiles for catchments 6 (a) and 7 (b).

In February 2023, the region encountered the most extensive rainfall event ever recorded in Brazil, with rainfall reaching 684 mm within 11 hours. A total of 52 geotechnical events, ranging from low to high risk for the pipelines, were detected. One of these events consisted of a debris flow that impacted the catchment 8, causing wreckage along the river path and to the surrounding community. A 24" oil pipeline buried with 1,5 m depth passes under the mentioned river. The debris flow excavated around 2 m of the river's bottom after the channel, which shows that the channel had significant influence over the erosion profile along the river's path, since the erosion did not change the river's bottom immediately before the channel along the river's path. The concrete channel guaranteed the protection of the pipeline, avoiding a clear failure, as can be seen in Figure 10. Catchment was not affected by any debris flow.

Although the pipeline ROW was indeed affected by the debris flow, the pipeline remained intact, showing that the completion of the channel was crucial to the integrity of the pipeline. The outcome of the debris flow showed that the prioritization process was successful in defining areas that needed immediate mitigation.

Figure 10 – picture of the concrete channel of hydraulic catchment 8 after the debris flow event of February 2023.

4. CONCLUSION

A prioritization process following a qualitative method that considered a score that weights the geomorphological characteristic of the catchments into a single number was applied to the OSBAT ROW, which is maintained by Transpetro in the coast of São Paulo. Following, numerical modelling of debris flow along was performed by using the RAMMS software. The results showed significant hazard to the pipeline in case of a debris flow over two locations.

Concrete channels were designed and built over the river crossings that were deemed critical. During the historical rainfall event of February 2023, the engineering solutions were put to test. A debris flow occurred in one of the locations. The channel built over the pipeline successfully protected it.

One limitation that I recognize is the choice of the selected return period (TR), as opting for higher TR values could potentially lead to deeper excavation profiles. Another limitation lies in the assumptions made during the calculations and the accuracy of input parameters within the software, such as the topographical survey of the hydrographic basin - a highly sensitive parameter. On the other hand it primarily entails protecting the pipeline against the excavation caused by drainage channel formation during debris flows.

After the debris flow events triggered by rainfall events that stroke the ROW, new studies are being performed over the possibility of new debris flow occurrences, using refined input data and widening the study scope over new regions.

ACKNOWLEDGEMENTS

The authors would like to thank Transpetro for its support on disclosing the information about the debris flow and its support for the authors. We would also like to thank the Instituto de Pesquisas Tecnológicas (IPT) for the collaboration over the first studies done with the scope of finding regions of the pipeline ROW susceptible to debris flow.

REFERENCES

[1] Cunha, S. B. *A review of quantitative risk assessment of onshore pipelines*. Journal of Loss Prevention in the Process Industries, 44: 282-298, 2019.

[2] EGIG. *11th Report of the european gas pipeline incident data group, 1970-2019*. European Gas Pipeline Data Incident Group. Document number VA 20.0432, available at: https://www.egig.eu/, 2020.

[3] Cech M., Davis P., Gambardella F., Haskamp A., Gonzales P. H. *Performance of European cross-country oil pipelines*. Statistical summary of reported spillages in 2019 and since 1971. CONCAWE. Report 4/21, available at http://www.concawe.be, 2022.

[4] Vieira, B. C. & Gramani, M. F. *Serra do mar: the most "tormented" relief in Brazil. Landscapes and Landforms of Brazil*. Vieira, B. C., Salgado, A. A. & Santos, L. J. C. (eds.), Springer, London, England, pp. 285-297, 2015.

[5] Transpetro. *Terminal Aquaviário de São Sebastião*, available at https://petrobras.com.br/pt/nossas-atividades/principais-operacoes/terminais-e-oleodutos/terminal-sao-sebastiao.htm, 2023.

[6] Kanji, M. A. Cruz, P. T. & Massad, F. *Debris Flow Affection the Cubatão Oil Refinery Brazil*, Landslides, 5(1): 71-82, 2008.

[7] Furian, S., Barbiéro, L., & Boulet, R. *Organisation of the soil mantle in tropical southeastern Brazil (Serra do Mar) in relation to landslides processes*. Catena, 38(1), 65-83, 1999.

[8] Empresa Brasileira de Comunicação. *Litoral Paulista Teve Maior Volume de Chuva Registrado no Brasil*, available at https://agenciabrasil.ebc.com.br/geral/noticia/2023-02/litoral-paulista-teve-maior-volume-de-chuva-registrado-no-brasil, 2023.

[9] Magalhães, F. S., Corsi, A. C., Gramani, M. F., Barbosa, T. T. A., Augusto Filho, O. *Avaliação da potencialidade a movimentos de massa na Serra do Mar, entre São Sebastião-Cubatão, com vistas ao duto OSBAT*. Anais do IV Congresso Brasileiro de Encostas, 227-240, 2005.

[10] WSL Institut für Schnee- und Lawinenforschung . *RAMMS::DEBRISFLOW. User Manual v1.7.0 – Debris Flow. A numerical model for debris flows in research and practice*, 116 p, 2017.

[11] Berger C, McArdell BW, Schlunegger F. *Direct measurement of channel erosion by debris flows, Illgraben, Switzerland*. Journal of Geophysical Research: Earth Surface. 116(F01002): 1-18, 2011.