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AN INTEGRATED DECISION-MAKING PROCESS IN EMERGENCY CONDITIONS DUE TO GEOHAZARDS – A STUDY CASE

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ABSTRACT

CENIT has implemented in its Rights of Way (ROW), an early warning system associated with rainfall and earthquake monitoring, through which it develops the management of ROW patrol and establishes the necessary action plans to maintain the integrity of the pipelines. At the end of July 2021, a condition of excess rainfall was identified that triggered the inspection of the ROW as a priority in a section of a hydrocarbon transport system owned by the company. On August 2, 2021, because of an exceptional rainfall, several landslides were activated on a regional scale; one of them interacted with a 170 m section of the pipeline causing loss of containment in a system that pumps 120000 barrel per day. The inspection and monitoring actions previously developed, as well as the activities carried out during and after the instability process are shown in this article. This includes, among others, a) the use of photointerpretation of images taken with a drone to identify the dimensions of the unstable mass and ground displacements, b) data of an inclinometers as part of a monitoring program in site, c) environmental and social restrictions in the area that do not allow build a by-pass outside of ROW, d), an alarm scheme for the operation based on the monitoring of triggers agents such as rain and earthquakes, considering a fault mass new conditions. An innovative temporal solution through flexible pipelines is also presented. Due to landslide wide (250 m), depth (around 30 m) and length (500 m) a possible by-pass should be built crossing the instable mass. This paper allows to demonstrate the relevance of an articulated management strategy and decision-making process in emergency condition to safely restore the operation in record time.

1. INTRODUCTION

Caño Limón Coveñas Pipeline allows evacuating 120 KBL per day from production fields of the Eastern Plains, taking them to the Coveñas terminal located in Caribbean Sea, due to its route it must cross Eastern Mountain range advancing in initial section through a sector occupied by young sedimentary rocks, affected by tectonism, a strong anthropic activity and an average annual rainfall that fluctuates between 5000 mm and 6000 mm.

As a result of these conditions that affect several of pipelines operated by CENIT, it was necessary to implement a real-time monitoring network of the main trigger agent of instability processes such as rain. From this monitoring, Right of Way (ROW) patrol are established, geohazards team and overflights with helicopters and drones with which new findings are identified and / or those previously identified are monitored.

As a result of monitoring plans are defined with geotechnical instrumentation or mitigation plans with maintenance and/or stabilization works to prevent pipeline from being affected by instability processes. Data obtained since the implementation of the strategy has generated a knowledge of environment that allows quick and accurate decision-making process to be made in the presence of unexpected natural phenomena.

2. GEOLOGICAL CHARACTERISTICS

In the area of interest, pipeline advances through the valley of the “La China” stream that follows the anticline of the same name, this forms a subsequent rope framed by the eroded escarpments of the geological layers present, in the background emerge older rocks folded partially covered by colluvial deposits detached from scarps.

Scarp slope is formed in the upper part by hard white sandstone quartz that are part of “El Diablo” Formation and give rise to “Cortinas de Samoré”, and in the lower zone by gray clay trees of “San Fernando” Formation covered by coluvions, this condition is key to understanding hydrogeological model of the area (Figure 1 and [2]).

The valley has a considerable amplitude that is reduced when reaching “El Caraño” stream very close to the event site.

Vegetation of the area has been cut down almost entirely, leaving relicts of forest in some drains and in the areas of greater slope. Additionally, the sector has a monsoon climate, according to the Köppen-Geiger classification [1], with a monomodal precipitation regime that reaches 5500 mm per year, distributed mainly between the months of March to September.

Conditions described above make the sector highly susceptible to mass removal processes.

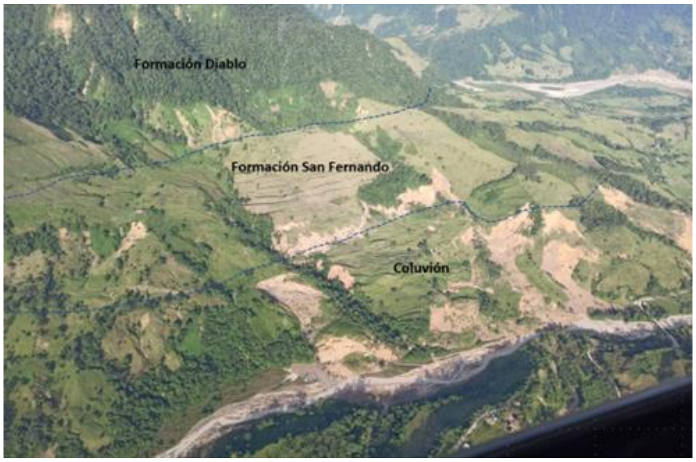

FIGURE 1: GEOLOGICAL ENVIRONMENT OF THE AREA (Photography by Lázaro Castillo).

3. BACKGROUND

In this area of "Caño Limón – Coveñas" Pipeline, there had been three landslides, one during construction in 1984 and two containment losses: one in 1988 and another in 1993.

80's processes were associated with wandering channel of stream that attacked the toe of colluvial deposit where both, pipeline and "La Soberania" road, are located. For this reason, after loss of containment on September 14, 1986, it was decided to make a variant, which began before site of the event, passed "La China" stream and advanced along the left bank in a flat area, until crossing "El Caraño" stream and joining with the initial alignment. On April 25, 1993, there was a high-speed landslide that overloaded alluvial deposit generating a lateral fault of this, causing the pipe to be uncovered and displaced laterally with total rupture.

Faced with this loss of containment, ECOPETROL decided to resume the initial route by building a large rockfill to protect the left bank of "La China" stream, accompanied by horizontal drains, French drains, metal piles, ditches for water management and terraced the front area of slipped area. Initially pipeline was left above-ground parallel to road but was later buried leaving a section inside a chamber formed by steel sheet to isolate pipeline from unstable ground.

At that time the design philosophy was to reduce the speed of the displacements so that through monitoring and analysis it could be determined the moment in which it was required to make a stress relief that would allow the pipeline to recover its deformation capacity.

FIGURE 2: LANDSLIDE OF 1984, NOTE HOW THE STREAM UNDERMINED COLLUVIUM'S TOE (Photography by José Vicente Amórtegui IGL).

FIGURA 3: LANDSLIDE OF 1993, NOTE HOW MATERIAL FLOWED OVER ALLUVIAL DEPOSIT CAUSING PIPELINE TO COME ABOVE GROUND DUE TO LATERAL DISPLACEMENT (Photography by José Vicente Amórtegui IGL).

4. MONITORING PLAN

Based on the design philosophy of 1997, the sector had installed geotechnical instrumentation consisting of 3 slope indicators and 14 topographic milestones that were read regularly. Prior to date of the event slope indicator located on the slope above ROW had shown displacements of about 9 mm in the last six months with a fault surface located at 13 m depth, the slope indicators located on the ROW showed no activity. The network of milestones indicated accumulated displacements less than 2 cm, a value that is within the precision of the methodology, so it is not considered conclusive to declare reactivation or hazard due to landslide. Monitoring carried out by the geohazards strategy indicated that there were some signs of movement due to cracking of some concrete channels and the presence of minor scarps.

Additionally, on June 26, 2020, an inertial geometric ILI was executed, which ratified the presence of bending strain to the left side of landslide. However, this information was compared with previous ILI, and it was determined that it was not necessary to advance a stresses release, since there had been no progress and did not exceed intervention thresholds defined by CENIT, as a strategy it was decided to continue with geotechnical monitoring and ROW Patrol waiting for a new ILI run.

FIGURA 4: STABILIZATION WORKS CARRIED OUT BETWEEN 1994 AND 1997 TO PLACE PIPELINE IN INITIAL ROW (Photography by José Vicente Amórtegui IGL).

To monitor rainfall in the area, CENIT has installed two rainfall stations located near to the event site that capture and transmit data in real time every 10 minutes. These meteorological stations cover the catchment area and are located at a distance around 5 km, each one. These meteorological stations have been climatologically referenced to nearest IDEAM stations (government office of meteorological analysis – “Santa María Abastos” and “Tunebia”). This network was installed in 1972 and have precipitation measurement on a daily scale.

5. LANDSLIDE EVENT

By monitoring the rainfall with CENIT’s network, it had been identified that in the two months prior to the event there had been rainfall above historical records (Table 1), considering historical monthly average rainfall from nearest IDEAM reference stations (Table 2).

TABLE 1. PERCENTAGE OF RAINFALL WITH RESPECT TO AVERAGE HISTORICAL VALUE.

Meteorological Station	May	June	July
Troya	111.4%	140.1%	133.1%
Samoré	88.3%	108.2%	130.9%
Alto de La Virgen	118.4%	107.6%	151.6%

TABLE 2. HISTORICAL MONTHLY AVERAGE RAINFALL FROM NEAREST IDEAM REFERENCE STATIONS (mm).

IDEAM Station	May	June	July
Santa María de Los Ángeles	605,2	793,7	699,4
Tunebia	554,2	651,2	643,9

During August 2 and 3, there were extreme rains that exceeded the daily extreme upper limits recorded since 1972 by the IDEAM meteorological network, (Figures 5 and 6). In conclusion, it is identified that the event of August 2 reached the second highest rainfall recorded in the Santa Maria station and the fourth highest in the Tunebia station.

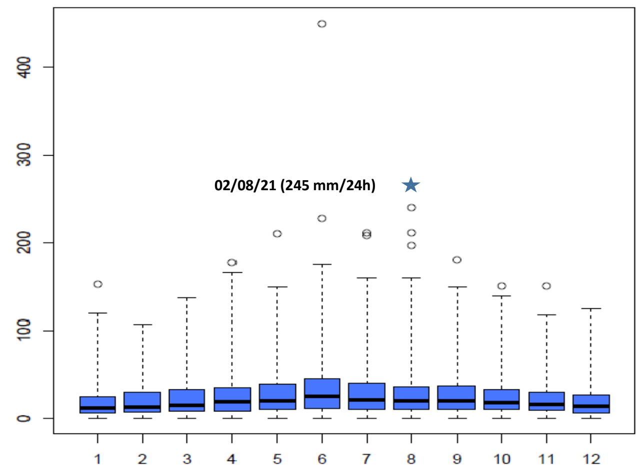

FIGURA 5: BOX PLOT FOR EXTREME DAILY ATYPICAL PRECIPITATION - SANTA MARÍA ABASTOS STATION (COMPARED WITH SAMORÉ STATION).

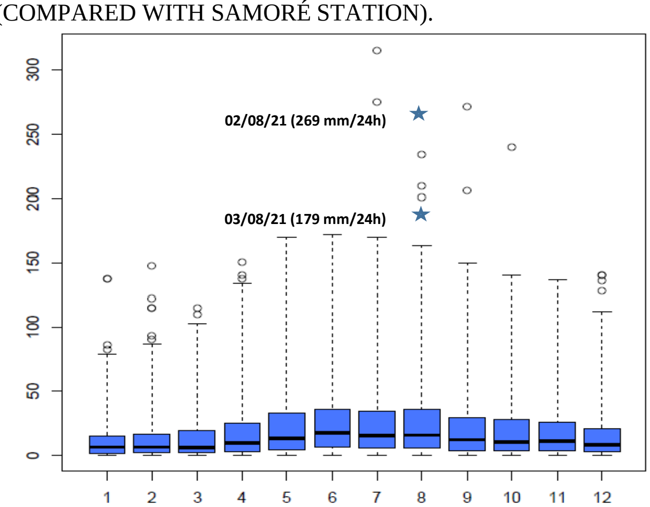

FIGURA 6: BOX PLOT FOR EXTREME DAILY ATYPICAL PRECIPITATION - TUNEBIA STATION (COMPARED WITH TROYA STATION).

Reviewing in greater detail data collected at the Samoré station, it is identified that the rainfall event began on August 1, 2023, at 11 am and ended on August 3 at 1 am, for a total rainfall of 314 mm (Figure 7) with hourly intensities that reached 34 mm. The event affected several villages in the Sarare area, impacting several towers of the 230-kW power line of the Toledo – Samoré – Banadía systems, the La Soberanía road at least in 8 points with total or partial closure and the Gibraltar – Bucaramanga gas pipeline affected in about 4 km. Additionally, there were dams and later avalanches in the La China and El Caraño streams (Figure 8).

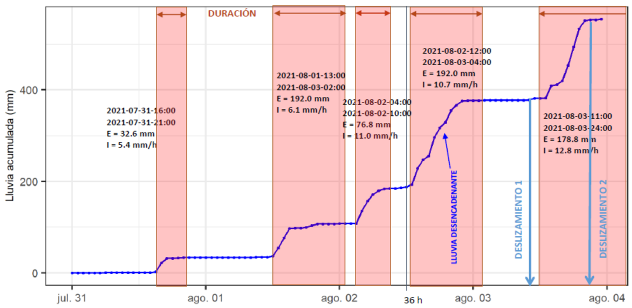

FIGURE 7: RAIN EPISODES IN THE 96 HOURS PRIOR TO LANDSLIDE EVENT

FIGURE 8: LANDSLIDE PROCESSES LOCATED IN LA CHINA BASIN.

6. LANDSLIDE EVOLUTION

Before the day of landslide a precipitation warning (thanks to applied meteorological monitoring predictive schemes – IPG2019-5343 [3], IPG2021-65003 [4] and IPG2023-0045 [5]) had been generated that specified the need to advance ROW patrol; as a result of that patrol it is identified, in the early hours of the morning, that in the zone there is a retrogression of the main scarp of the 1986 event. Towards noon began a flow of land on the left flank that closes “La Soberanía” road, and this advance lasted about an hour until completely closing the road, (Figure 9). Figure 10 shows the appearance of the hillside according to the photo, taken with a drone from CENIT's Geohazards Management Strategy, on August 3 at 4 pm. It is possible to see the earth flow completely covering “La Soberanía” road and how ROW was not yet affected by the process. Also, in the upper part a main scarp was observed with a height that by that time already exceeded 10 m; this scarp followed alignment of a slope change that did not slide located on the right side.

According to data collected towards early hours of the night, general fault was presented, impacting ROW, which generated the loss of containment. Landslide mass has a width of 250 m, an approximate length of 500 m, main scarp reaches 45 m so the volume exceeds 3 million cubic meters, according to the classification of Fell (1994) [6] is considered as very large.

FIGURE 9: LANDSLIDE SEQUENCE THAT COVERS “LA SOBERANÍA” ROAD (Photographs by road Operator).

FIGURE 10: HILLSIDE CONDITION ON AFTERNOON OF AUGUST 03, 2021.

7. MITIGATION PLAN

Based on drone orthophotos monitoring, a multitemporal analysis of images was carried out to determine the probability of having a retrogressive or successive process as well as displacement vectors of the slipped mass. From this, it was determined that middle and upper parts of the landslide largely retain their shape, despite the displacements evidenced of about 45 m (Figure 11). From this displacement, and time it took to reach it was calculated that landslide speed exceeded 4 m per hour, so it is considered "fast" according to the classification of Cruden and Varnes (1996) [7]. With these speed characteristics and magnitude, it is defined that process has a very high destructive power where escape is possible for people, but structures were destroyed.

FIGURE 11: LANDSLIDE OVERVIEW ON THE AFTERNOON OF AUGUST 04, 2021, (Photography by Lázaro Castillo).

Once the main event was over, monitoring continued through orthophotos taken with drone to evaluate behavior of landslide, in this way it was ruled out that process advanced uphill or the advance of the accumulation zone was presented. However, landslide toe was completely saturated and had a very soft consistency that prevented transit of people and / or equipment. For this reason, it was necessary to build a palisade to allow pipeline detection and identify section affected; at the end of this process, it was determined that pipeline presented a double break leaving a central section of 173 m that moved about 45 m, confirming the magnitude of the displacement vector (Figure 12). Additionally, the slope located on the right flank that did not slide, presented multiple families of cracks whose length exceeded 600 m with widths and depths reaching 30 cm and 90 cm respectively. These cracks were sealed manually immediately to prevent rainwater from percolating further reducing the precarious stability conditions of the slope.

Given the impossibility of building a variant that would avoid landslide due to environmental and social restrictions, precarious stability conditions of the slope located on the right flank and consistency of material slid on ROW, it was necessary to implement a system of flexible pipes, located on the ROW, that would allow to comply with the minimum operating flow of the system. Once the hydraulic analysis was carried out by the CENIT team, it was determined that four flexible pipes of six inches connected to two multiple ones were required working at a pressure of the order of 750 psi. Additionally due to maintenance needs required in this sector, it was necessary to install a trap to capture stopper backs that are used in repairs arising from actions of illegal third parties. As one of the risks that existed was that the process of instability was reactivated or new material slipped from the upper slope, it was decided to install flexible pipe giving it a sinusoidal shape so that it could move up to 50 m before entering tension, in this way it was possible to rearrange flexible pipes in case of movements in the ground and the risk of breakage was reduced. in the face of a new process of instability (Figure 13).

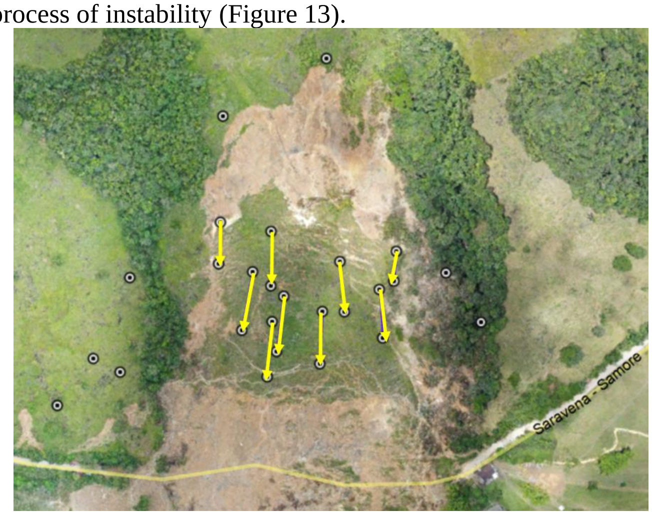

FIGURE 12: LANDSLIDE DISPLACEMENT VECTORS OBTAINED FROM MULTITEMPORAL ANALYSIS OF ORTHOPHOTOS TAKEN WITH DRONE.

FIGURE 13: FLEXIBLE PIPE FINAL DISPOSITION.

Additionally, a drainage network was built through channels on land covered with geomembrane in such a way as to avoid the percolation of water when cracks occur due to landslide rearrangement or by drying during the dry season. Indeed, based on the monitoring carried out and review of aerial photographs of 1982 – 1998 period (Figure 14), an interrupted drainage was identified in the wooded area located at main scarp, which had to be continued by means of concrete and stone channel that delivers to the stream that descends on the left flank of the landslide. In this way, the contribution of water that emerges in the transition rock-soil located on the main scarp was reduced.

FIGURE 14: AERIAL IMAGE - IGAC 1982.

8. MONITORING DURING OPERATION

Based on recollected data values of atypical precipitation obtained with the historical series of rainfall, thresholds were defined that allowed generating a decision tree to define rainfall alert levels (Figure 15). To real-time monitoring, a weather station was installed less than 200 m from the left flank of the landslide.

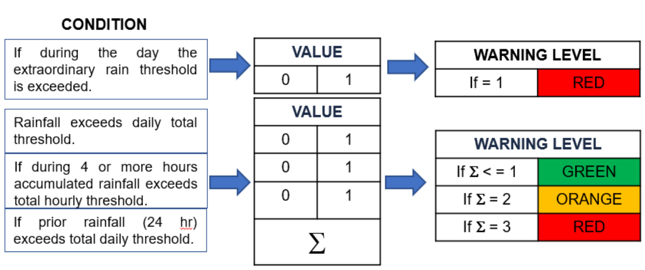

FIGURE 15: DECISION TREE TO DEFINE THE RAIN ALERT LEVEL.

In the case of earthquakes, which are another of the main triggers of landslides, it was defined to use the monitoring network of the Colombian Geological Service and the alert threshold defined in Figure 16 will be handled, which uses as a basis the proposal made by Keefer (1984) [8] applying a reduction factor to consider residual resistance parameters. In case of an event that is below this threshold, the red alert will be declared.

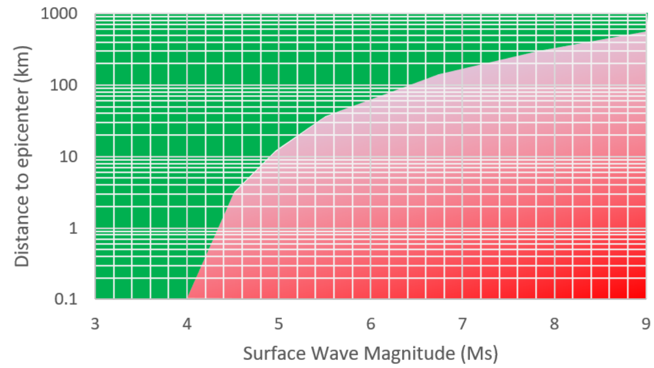

FIGURE 16: EARTHQUAKE-INDUCED LANDSLIDE ALERT THRESHOLD.

Depending on warning level, several actions must be executed, ranging from normal operation to pumping stop, as described below. For this purpose, a flowchart was defined where actions depending on the warning level (Figure 17) are stablished.

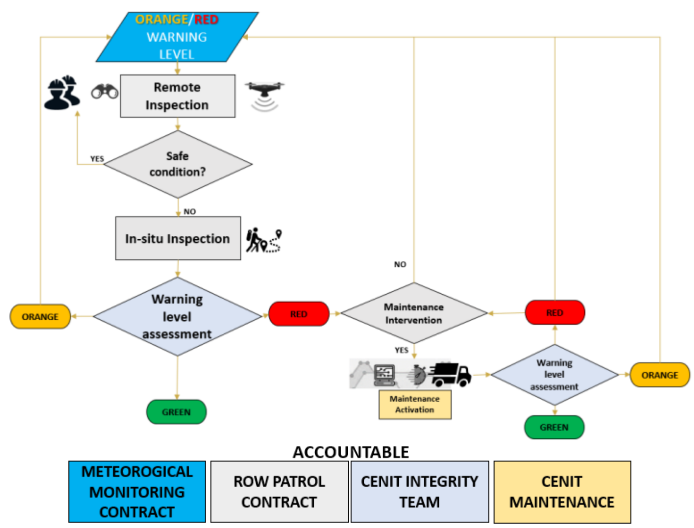

FIGURE 17: WARNING LEVEL ASSESSMENT FLOWCHART.

For a green warning level, the system is operated normally, and meteorological monitoring and right-of-way inspections continue without altering its periodicity.

When the orange warning is activated, detailed monitoring is made to the operational variables of the system. Drone inspection is done if weather conditions allow it or inspections from observation points away from the landslide. If this alert occurs during the night, pumping is suspended, but the pipeline is not drained.

For a red warning level, system operation is suspended, and the pipeline is drained into the flexible pipe zone including valve closure. Drone inspection is done if weather conditions allow it or evaluation from observation points away from the landslide.

Additionally, in orange and red warning level, a ROW Patrol inspection around the landslide is developed in a time not exceeding 12 hours, as well as on-site inspection by a geotechnical engineer and for a red warning, a mitigation plans with immediate implementation is defined, accompanied by assessment by the CENIT expert.

Based on this operational monitoring, it has been possible to safely operation from October 13, 2021, to date without incidents, in that period ten orange and two red alerts have been presented that have required ROW patrol and additional monitoring without identifying effects on flexible pipes or on the hillside.

9. CONCLUSIONS

Although there are multiple intrinsic and extrinsic factors that generate instability processes, monitoring rainfall condition in real time is easy and economical, which allows to identify in a timely manner the occurrence of landslides and their impact along linear infrastructures, to propose preventive or corrective actions.

Having an inspection plan that depends on rainfall conditions that occur in ROWs where linear infrastructure is installed generates great efficiency in use of resources.

The use of orthophotos taken with drone is an economical scheme and of great help to monitor processes of instability. It also allows to obtain data on displacements and evolution of processes in a fast and timely manner.

Flexible pipes have great versatility to meet instability processes that, due to their magnitude and/or location, do not allow traditional maintenance actions to be carried out.

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