Landslide Control Program at the Panama Canal

by

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ABSTRACT

Since the beginning of its construction, the safety and reliability of the Panama Canal excavations and dam structures have been a challenge**,** due to the heterogeneous and complex geological setup, added to a highly variable rainfall regime comprising average daily precipitations of 140 mm. At the Panama Canal a program has been adopted for the detection of landslide activity in its early stages to mitigate the related consequences and maintain the Canal operation. This program has been named as the Landslide Control Program and was implemented in 1968.

The execution of improvement projects to the navigation channel, including the construction of containment dams, excavations for widening, straightening, and deepening the navigation channel, especially the recent Canal Expansion, represented new challenges in the surveillance process. To overcome the new challenges, the Panama Canal Authority has undertaken an improvement process to incorporate state-of-the-art robotic and real-time monitoring technology. This paper presents the importance of the Landslide Control Program, and describes the methodology used to identify instabilities using data from the different types of instruments installed along the waterway, and the Protocol set forth for their stabilization.

1. INTRODUCTION

Landslides were a prevailing aspect since the construction of the Panama Canal. They resulted in 40 million cubic meters of additional excavation. Indeed, the most difficult problem related to the building of the Panama Canal was the control of landslides in Gaillard Cut, the narrowest segment of the waterway, 12.6 km in length, where the Canal crosses the Continental Divide (see Figure 1). The slopes in Gaillard Cut were shaped from the deep excavation required to build the Canal and the occurrence of landslides during this construction period was mainly due to the unstable geometry of the over-steepened slopes.

The slopes of Gaillard Cut have evolved continuously throughout the history of the Canal, as a result of the excavation of the original construction, the Canal widening, the straightening and deepening, the removal of landslides debris, and more recently, of the Canal Expansion. All these events have imposed new challenges in the surveillance process and demanded the use of new techniques for data acquisition and detection of landslides, improving the process through the years, to become a more efficient tool for detecting and evaluating landslide-prone terrains.

In 1968, Dr. Arthur Casagrande, acting as a consultant for the Panama Canal Company (PCC), recommended an empirical observational method to detect incipient landslides in Gaillard Cut. The complex geological environment in Gaillard Cut precludes the use of analytical methods as a tool for reliable predictions of slope movements. This observational method has undergone several improvements in the subsequent years, becoming progressively more reliable. It evolved to what is known today as the Landslide Control Program that has helped to detect and stabilize numerous potential landslides.

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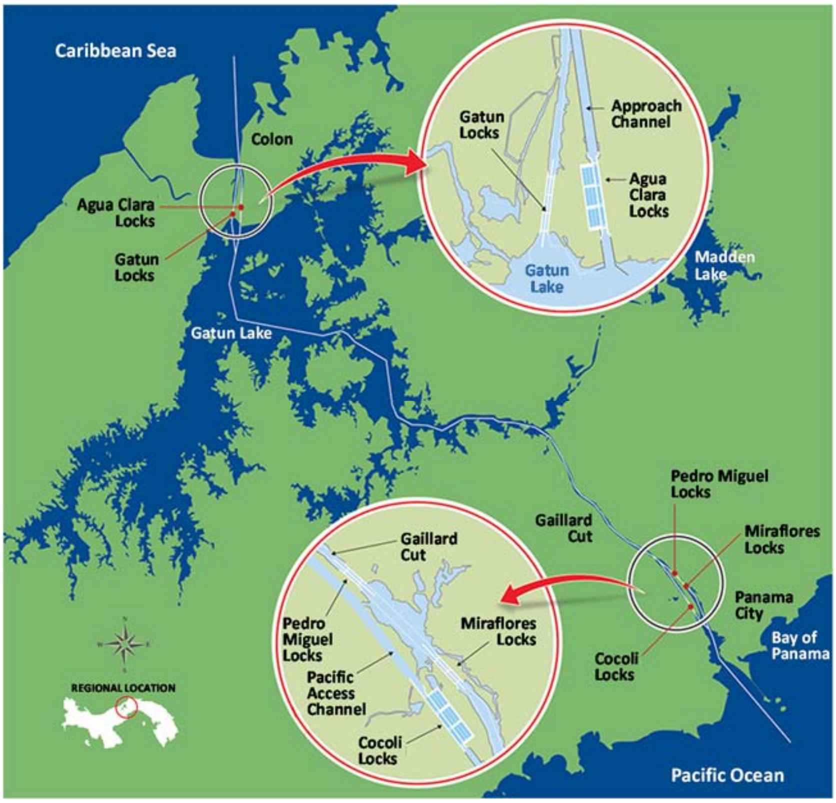

Figure 1: Gaillard Cut in the Panama Canal

Presently, the Landslide Control Program involves the surveillance of surface control points distributed along the banks, not only of the Gaillard Cut but also at the Pacific Access Channel (PAC). The observational method has demonstrated to be effective, particularly in areas with difficult geological conditions, as those present in Gaillard Cut. Also, the Landslide Control Program includes subsurface monitoring instrumentation installed in the excavated slopes and containment dams. It makes use of Casagrande and Multipoint Piezometers; traveler pipes for locating slip surfaces; open wells for ground water readings; among other instruments.

The Pacific Access Channel is a 6.2 km waterway, 218 m wide, derived from the south end of Gaillard Cut toward the new Cocoli Locks in the Pacific side (see Figure 1), that allows the transit of Post-Panamax vessels, at Gatun lake level of 25.91 m PLD (Precise Level Datum for the Panama Canal) and is separated from the Miraflores Lake (elevation 16.45 m PLD) by the East Borinquen Dams. This new access channel has cut slopes that have the potential to block the navigation channel in the event of a massive landslide.

In order to be more efficient and effective in detecting the potential risks of channel encroachment due to landslides in Gaillard Cut and the Pacific Access Channel, the Panama Canal Authority (ACP) allocates significant resources in state-of-the-art monitoring and data acquisition equipment to monitor different types of instruments installed along the banks of Gaillard Cut and the banks and containment dams along the Pacific Access Channel.

2. BRIEF HISTORY OF THE LANDSLIDE CONTROL PROGRAM

In May 1968, at the beginning of the rainy season, the Canal was threatened by a major incipient landslide. Hodges Hill, a Canal slope in Gaillard Cut, developed cracks about 2 meters across, just north of the Continental Divide and was in imminent danger of completely blocking Canal traffic for a month or more. A board of prominent consultants, among which was Arthur Casagrande, was convened to recommend a solution to the crisis. They recommended a stabilization plan consisting of nineteen horizontal drains drilled into the hill from the bank of the Canal, together with extensive drainage systems installed on the upper slopes to divert runoff from the ground cracks. This action was implemented at a cost of $400,000, much lower than the $10 million considered necessary initially for a massive remedial excavation.

Under the leadership of Dr. Arthur Casagrande (see Figure 2), the board also recommended that the Canal initiated a "systematic surveillance of the banks of Gaillard Cut… to cover all critical slopes on both sides", an empirical observational method to detect incipient landslides. This recommendation was given due to the complex geological conditions in Gaillard Cut, which invalidate the use of analytical methods as a tool for early detection and improved control of landslide activity. The Landslide Control Program was created in response to this recommendation the following year. The program was referred to as the "Bank Stability Surveillance Program" or BSSP, which is now referred to as the Landslide Control Program.

Figure 2: Inspection at Hodges Hill Landslide - Beginning of Modern Landslide Control Program (1968)

3. GEOLOGY

The Geology of Gaillard Cut and the Pacific Access Channel is complex. It is composed of a series of weathered tuffs and sedimentary deposits interspersed with strong igneous hills. This geological environment in combination with the average rainfall regime of the area, of about 2,000 mm per year, pose a high and continuous risk of landslides along the banks of these navigation channels. In fact, the evidence shows that rainfall is the single most important cause of landslides in Gaillard Cut.

Don C. Banks et al, from the U.S. Corps of Engineers (1975), observed that "Rock formations exposed at shallow depth in the banks of the Panama Canal through Gaillard Cut are believed to range in age from Eocene to Miocene. All the rocks have been derived through volcanic and/or sedimentary processes from volcanic sources. These processes, alone or together, can result in a multitude of rock types. Accordingly, the banks revealed coarse, thick breccia formed with the involvement of sedimentary processes; thick massive volcanic conglomerates formed by rapid accumulation in water-filled basins; air-fallen tuff and tuff breccia; tuffaceous varieties of sandstone, siltstone and shale; and a few intrusive igneous rocks" (see Figure 3).

The sedimentary rocks, derived from marine and terrestrial deposits of both alluvial and volcanic origin, are highly variable, and many of the recurring beds are extremely weak, sometimes slickensided, and often expansive. These rocks are the vehicle for most landslide activity in the Cut, and the Cucaracha formation was a prime factor in the development of the massive slides of the later construction years.

The much stronger volcanic rocks, mainly agglomerates and basalts, also play an important part in Gaillard Cut landslide activity. The unusual sequence of geologic events, caused these igneous rocks to form the peaks of many hills bordering the Canal, while the weaker sedimentary rocks support them, also forming the flatter lower slopes and the valleys between. The Canal was excavated through such valleys, resulting in basically unstable slopes. The intensive faulting in the Cut aggravates the problem by providing weakness planes to form the sides and "backscarps" of potential slides.

In addition, the bedding of the sedimentary formations generally dips downward from the east bank to the west in the Gaillard Cut, which has a mixed effect on landslide activity. Under this condition, east bank slopes tend to fail by traslatory motion along the inclined beds dipping toward the Canal, whereas on the west bank, where the bedding dips into the slope, slides are more likely to develop along circular failure surfaces.

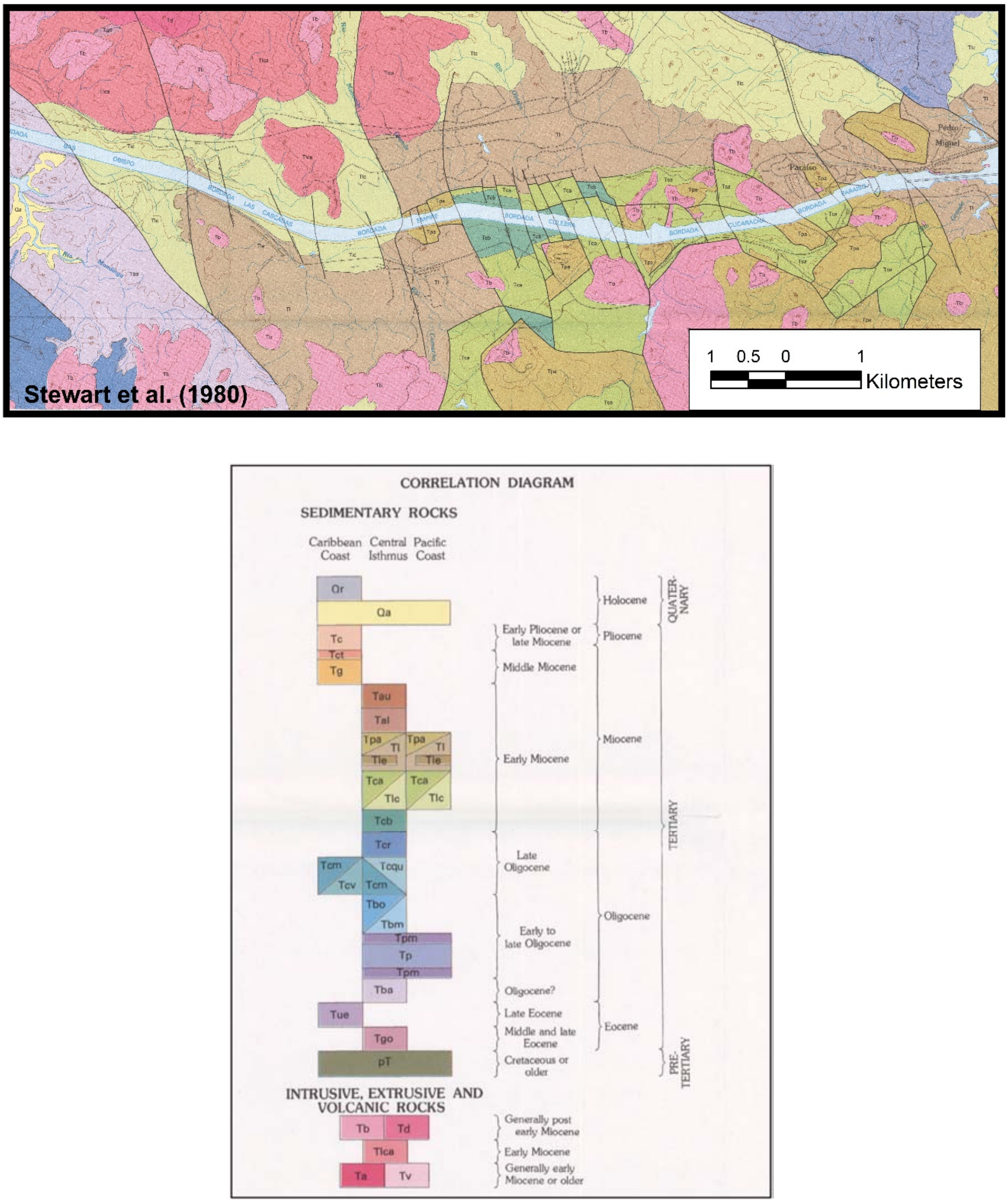

Figure 3: Geological Map of the Gaillard Cut

4. RAINFALL REGIME

Panama has a tropical rainy climate, hot all year round, with a dry season that usually commences at January and lasts until April, and a rainy season from May to December. The average annual rainfall in the Panama Canal is approximately 2000 mm and 2030 mm in Gaillard Cut. There are eleven meteorological stations located along Gaillard Cut and the Pacific Access Channel (see Figure 4): Gamboa, Cascadas, Sardinilla, Empire, Culebra, Gold Hill, Pedro Miguel, Miraflores, Cerro Cocoli, Victor Valdez and Cocoli 326. The data obtained from the meteorological stations is correlated with the pore pressure and surface deformations of the slopes, to analyze the soil behavior for managing and controlling landslides.

Figure 4: Location of meteorological stations along the Gaillard Cut and the Pacific Access Channel

When the sloped areas become entirely saturated, and the infiltration recharges the water table on the slopes, most of the time, landslides can occur. Heavy prolonged rainstorms, in the absence of some other external factor, trigger the majority of landslides in Gaillard Cut.

5. NATURE AND HISTORY OF LANDSLIDE ACTIVITY IN GAILLARD CUT

Since the construction of the Panama Canal until the Canal Expansion, about 545 million cubic meters of soil and rock were excavated. During the initial construction period, several major landslides occurred as the excavation of the waterway across the Continental Divide progressed to form what today is known as the Gaillard Cut. The constructors selected an arbitrary slope of 3V:2H for the excavated slopes along the whole length of the cut, either side, despite the type of materials found or required depth of the cut. The materials being excavated were too weak to sustain the excavated slopes. In addition to the weak strength of the rock, the rainfall water infiltration, the heavy blasting used to fracture the material to be removed, and the surcharge of the slopes with spoil were contributing factors to the development of such landslides.

Furthermore, the mechanics of landslides were not completely understood at the time and it was considered more economical and faster to allow for the landslides to develop and just remove from the toe of the slopes the mass that had moved until a stable slope was attained. The fact that such slopes had to be much flatter than required for stability before initial failure, due to the progressive weakening of the constituting materials, was not realized until much later.

Once the canal started operations in 1914, many slides reactivated, moving gradually or intermittently, and new slides developed in over-steepened slopes that had not yet failed, closing the waterway in several occasions. Most of the slide reactivations, or extension landslides, in Gaillard Cut are generated by the strain softening effects in weak rocks, and by prolonged periods of high precipitation that causes pore water pressure build-up. Other important factors in the development of landslides is the swelling of the underlying sedimentary material due to the unloading caused by excavations and the presence of sedimentary strata dipping towards the canal and discontinuities.

Most of these slides have been active more than once. Also, some failures occurred as a consequence of the improvement and maintenance of the navigation channel. Since year 1915 until 2017, there have been a total of 175 landslides in Gaillard Cut. Figure 5 presents a chart indicating the number of landslides that have occurred per year.

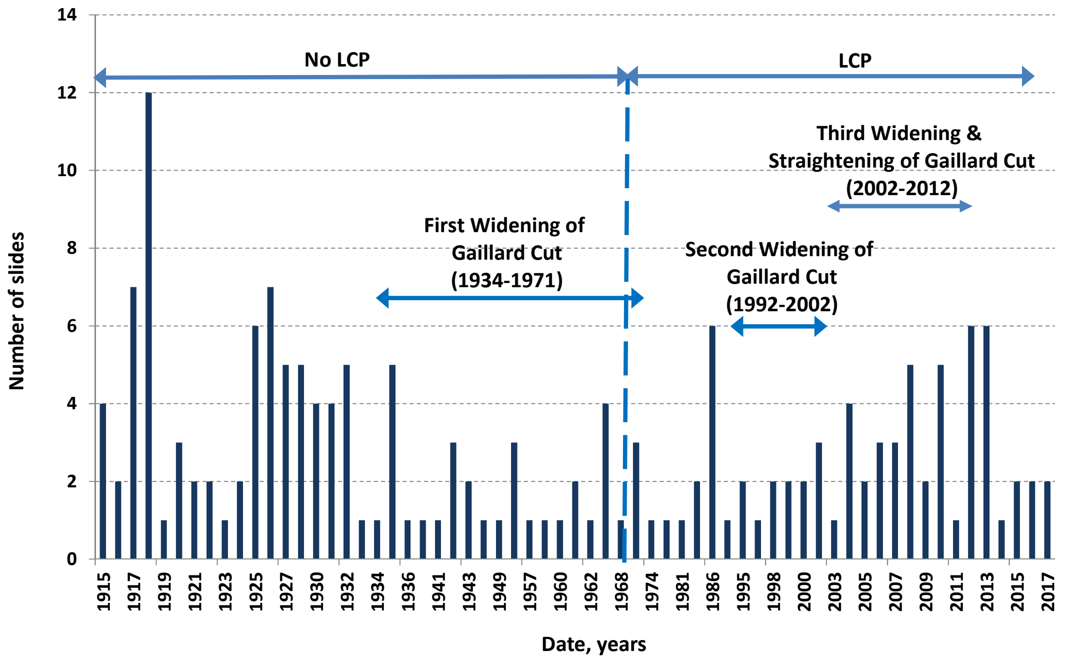

Figure 5: History of Landslide Activity (1915-2017)

6. CHANNEL IMPROVEMENTS

In addition to the internal factors already mentioned, the Gaillard Cut, being the narrowest section of the Canal, has undergone several improvement programs for its widening, deepening, and straightening:

- The Gaillard Cut Widening from 91.4 m to 152.4 m (300 feet to 500 feet), which was carried out completely on the west bank of the canal;
- The Second Gaillard Cut Widening from 152.4 m to 192 m (500 feet to 630 feet) at the straight segments and to 222 m (730 feet) at the curves, which affected both sides of the canal avoiding the most sensitive areas, such as the Cucaracha sector;
- The Third Widening & Straightening Program, from 192 m to 218 m (630 feet to 715 feet) at the straight segments;
- And the Canal Expansion Program, that included:
  - Further widening and straightening of the Gaillard Cut,
  - The construction of a new third set of locks, both at the Atlantic and Pacific sides of the Canal,
  - The excavation of a new access channel, with a length of 6 km, constructed to connect the Gaillard Cut with the Pacific Third Set of Locks, which required about 50 million cubic meters of unclassified excavation and the construction of four new earth fill dams, normally referred to as Borinquen Dams.
  - The widening and deepening of the canal entrances at the Pacific Ocean and the Caribbean Sea, and
  - The deepening and widening of the navigational channel through Gatun Lake.

A consequence of these improvement projects is the removal of all existing instrumentation in the areas affected by excavations. This is also true for any earthwork project that is performed for the remedial of instabilities. New instruments are installed following project completion. The amount, type, and location of the instruments is defined depending on final cut slope geometry, properties of constituent materials, known geologic structures, past landslide activity, and remaining failure planes: The greater the landslide hazard is, the more instruments are installed.

7. IMPLEMENTATION OF THE LANDSLIDE CONTROL PROGRAM

The objective of the Landslide Control Program is to identify and remediate potential instabilities along the banks of the Panama Canal. The main benefit of the program is to reduce the risk of blockage or serious encroachment in the navigation channel.

7.1. Management

The Geotechnical Branch of ACP's Engineering Division is in charge of the management of this program; carries out all engineering work under this program, interprets and analyzes all data, performs all instrument installations, and develops any stabilization plans needed.

Also, the Geotechnical Branch issues an annual report which comprises: the history of landslide activities in Gaillard Cut from 1915 to the present; a description of the stabilization projects and other remedial works executed on the reporting year; projects to be executed the following year; the new surface and subsurface instrumentation to be installed; the location of all existing instrumentation, per type and sector; and the rainfall data and location of meteorological stations.

Other ACP branches support the program, such as Surveys Branch, which is responsible of the instrumentation readings; Maintenance Division, which performs the construction and maintenance of all access roads and drainage works, and the Dredging Division, in charge of removing any material that falls into the navigational channel.

7.2. Zonation Scheme of Gaillard Cut

A zonation scheme was developed for Gaillard Cut, resulting in 22 sectors that contain segments of the Cut characterized by similar topographic and geologic conditions Likewise, the Pacific Access Channel was divided into 4 sectors for monitoring purposes (see Figure 6). All sectors with existing or potential landslide activity in Gaillard Cut and the Pacific Access Channel are periodically monitored.

Figure 6: Surveyed Sectors in Gaillard Cut and Pacific Access Channel

7.3. Drainage Networks

Due to the significant effect rainfall has on the stability of the slopes, a series of drainage networks have been constructed along the banks to intercept the rainwater runoff and conduct it before it infiltrates the soil. The program also contemplates the regular maintenance of these networks.

7.4. Landslide Remedial Costs

The mitigation of landslides in the Canal represents savings in that the earthworks performed are far more economical than the losses resulting from the blockage of the navigation channel caused by a landslide and the subsequent removal of debris by dredging operations.

Figure 7 shows the number of landslides that have occurred in Gaillard Cut and the costs of the corresponding maintenance or remedial works, per year, from 1968 to 2014. It is a collection of historical failures due to rainfall.

The information was taken from the Panama Canal Company annual reports (1952-1980), the Panama Canal Commission annual reports (1980-2000), the LCP annual reports, the Risk of Landslides in Gaillard Cut Report (1988), and from the estimation of landslide shapes shown on published maps. Costs were not available for all of the events. Therefore, costs were estimated multiplying the excavation and dredging volumes by the corresponding unit costs in US dollars for the year 2014. For those remedial projects having cost information, costs were brought to their value in year 2014 by applying an annual increment of 2.5%.

In Figure 7, the year 1986 stands out from the rest with a total cost of 41.7 million dollars due mostly to the historical reactivation of East Cucaracha Slide on October 13th. The total volume of the stabilization works was about 3.5 million cubic meters. Of this volume, approximately 400,000 cubic meters fell into the navigation channel and were dredged (see Figure 8).

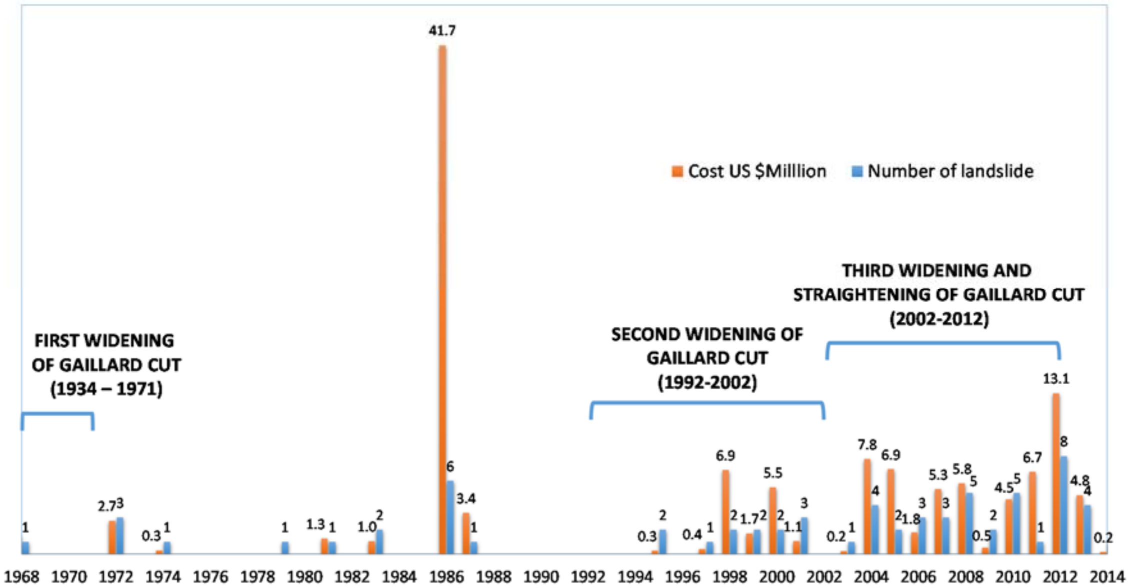

Figure 7: Landslides & Costs of Remedial Works (1968-2014)

Figure 8: East Cucaracha Slide Reactivation of October 13, 1986

8. INSTRUMENTATION

Due to the existence of many slide-prone areas along the Gaillard Cut and the threat they represent to the continued traffic of vessels along the canal, continued surveillance of slopes is performed by means of superficial and subsurface instruments. The instrumentation installed along Gaillard Cut is the main component of the monitoring program to obtain a picture of the slope behavior. The primary purposes of the instruments are to locate the slide surfaces, and to monitor the rate of movement and the variation of water pore pressures which could affect slopes stability. These measurements are used for detecting and forecasting landslide events and for issuing alerts. The different types and quantities of instruments installed in Gaillard Cut and the Pacific Access Channel are listed in Table 1.

Table 1. Landslide Control Program instruments

Instrument	Description	Quantity
Casagrande piezometers	Measurement of pore pressure at specific depth.	40
Multipoint piezometers	Measurement of pore pressure at different elevations in the same borehole.	33
Observation Wells	Measurement of the water table.	41
Traveler pipes	Measurement of depth of slide surfaces.	35
Real-time vibration wire piezometers	Real-time measurement of pore pressure at different elevations in the same borehole.	37
Real-time settlement cells	Real-time measurement of settlement and heave in soils.	2
Inclinometers	Measurement of subsurface movements and deformation.	4
Post-processing Superficial Monuments	Measurement of surface movements.	725
Real-time Superficial Monuments	Real-time measurement of surface movements.	165

8.1. Superficial Instrumentation

Superficial monitoring of movement is carried out on a continued basis for the early detection of slide activity and the timely execution of the corresponding remedial works. For this purpose, a series of control points or monuments comprised of a steel pipe 955 mm tall, embedded in concrete and extending down 600 mm into the ground, with a pedestal at the top end to fix a reflecting device, are placed within the limits of each area to be monitored. In the Gaillard Cut, there are currently more than 700 active monuments being monitored. The position of each monument is periodically surveyed, normally on a monthly basis.

Although the monthly collection of data have proven sufficient for the confident detection of incipient movement, the frequency of surveys is increased for sectors where movement patterns are detected, especially when field works are conducted at such areas, to secure the safety of the personnel.

Surveying of monument positions is performed using Total Stations. A Total Station integrates an Electronic Distance Measurement (EDM) device with an electronic theodolite, and is capable of determining the distance and angles from the instrument to a particular point. The measurement is accomplished by the emission of a modulated infrared carrier signal which is redirected to its origin by a prism reflector at the target location. The signal is modulated at multiple frequencies, and the distance is obtained from the count of the integer number of wavelengths for each frequency.

The Total Station is placed on a fixed location with known coordinates at the bank of the Canal opposite to that where the monument to be surveyed is found. The monument position is recorded, along with the date of the reading, as displacements in the northing, easting, and elevation axes. With these data, the position coordinates of each surveyed monument are obtained and recorded.

Such data is transferred using ASCII text files to a software extension for ESRI ArcGIS developed by ACP personnel. The software extension reads the input files and thoroughly validates each position reading against a set of rules:

- Monument ID not found - new Monument ID
- More recent reading than current one found in database
- Displacement distance larger than threshold
- Displacement distance of zero
- Monument Location outside defined sectors
- Duplicate Monument ID & Date combination found in input
- Reading Date more recent than System Date
- Reading with coordinate values that are Null, Zero, or Outside valid ranges
- Duplicate coordinates & different Monument IDs found in input
- Existing Monument ID having no previous Readings
- Duplicate Monument ID & Date combination found in database
- Duplicate coordinates & different Monument IDs found in database

The software extension then computes increments along the three dimension axes, velocity, and acceleration; also, effective distance, direction, and inclination with reference to the original position. The calculated values are compared to certain established criteria to issue Movement Warnings when required. The criteria relate to displacement increment length and acceleration, and also to effective displacement length and consistency. For each monument, a warning is issued when any of the following is true:

- Successive position readings show displacement consistency with the total effective displacement. This is quantified as the result of dividing Effective Displacement by the sum of Displacement Increments. If the value obtained is equal or greater than 80%, the monument is considered to be moving in a given direction and sense.
- The monthly displacement increment is larger than 30 mm.
- The total effective displacement is larger than 100 mm.
- More than three successive movement acceleration increments are observed.

After this process, the software extension generates three geometric object datasets that represent the location of monuments, their displacement paths, and the effective displacement vectors. It also creates one raster image dataset, which is the outcome of an Inverse Distance Weighted Interpolation of the effective displacement distance of the superficial monuments considering only the positions surveyed during the time period of analysis which, by default, is the year (365 days period) ending the day the extension is executed. The resulting raster grid can be displayed using a color classification of the displacement magnitude, obtaining an image that provides clear indications of potential landslides occurrence and extent of affected areas (see Figure 9), mostly when compared to grids generated for previous time periods.

New monitoring systems are available in the market that make use of the new technologies developed in recent years and the advancements in their application to surveying and data processing. The ACP has acquired such a monitoring solution comprised of robotic total stations that automatically scan for and locate the specified monument targets, communication equipment required for data transmission, and software for data processing and storage in a database, issuing warnings when displacements exceed threshold values established. This system is used to monitor more than 160 control points located on the new earth fill dams. Data is collected three times per day by fully automated equipment and processed in real time automatically be specialized software.

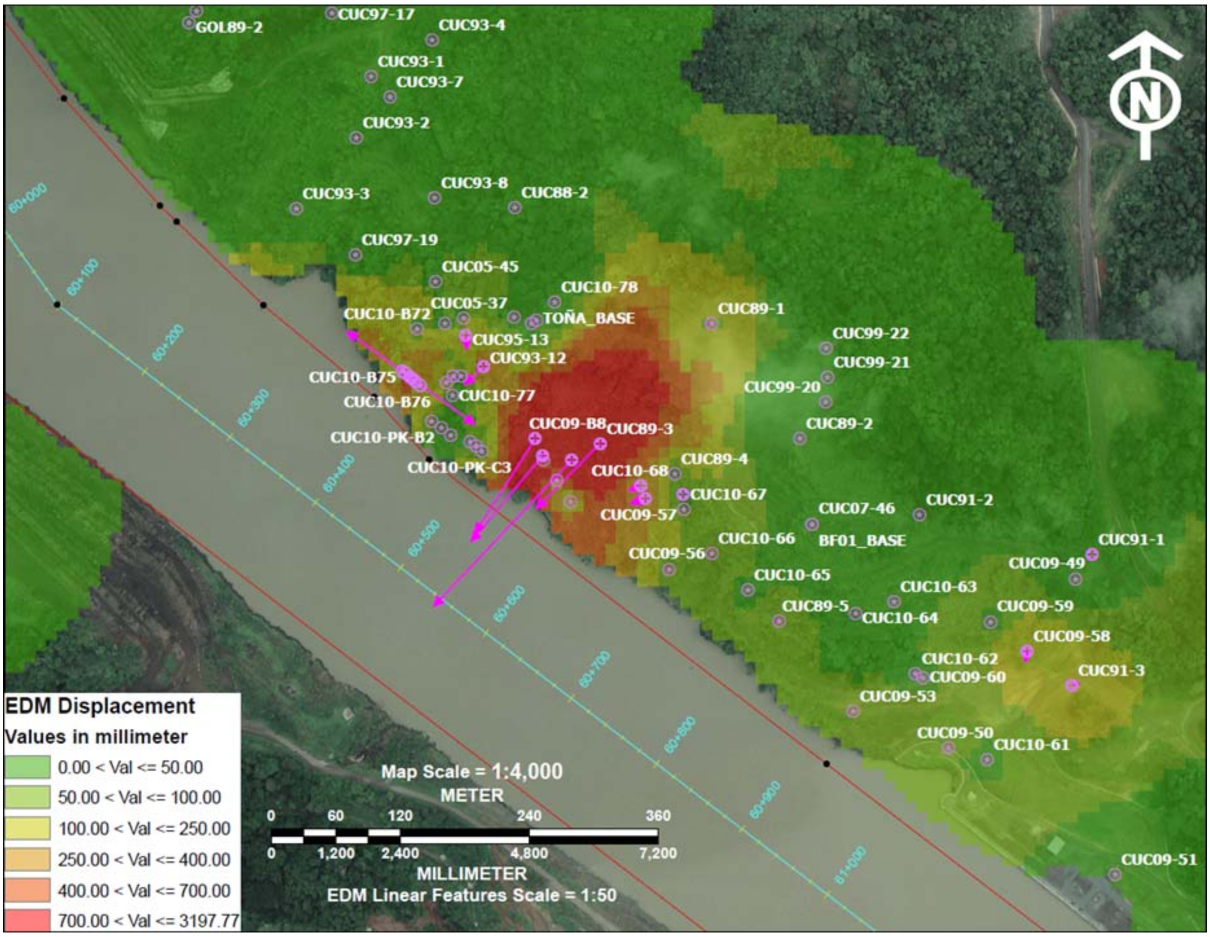

Figure 9: Superficial monuments location, displacement vectors, and color-classified representation of horizontal displacement

8.2. Subsurface Instrumentation

The instruments installed in the Gaillard Cut and the Pacific Access Channel include piezometers, observation wells, and traveler pipes, used to monitor pore water pressure and lateral deformations. The measurements are collected manually every month, and extraordinary readings are made when the daily accumulated rainfall is 90 mm or more.

In recent years, the amount of monitored monuments has increased significantly because of the increase in the extent of the areas disturbed as a result of the execution of the different improvement projects, especially those related to the Canal Expansion Program. The new earth fill dams are critical to the operation of the canal and the preservation of water in the Gatun Lake, so constant monitoring is required to secure and preserve their safety

Because the Borinquen Dams are critical elements of the Panama Canal, a new Automated Data Acquisition System (ADAS) has been implemented to automatically read, store, and transmit the measurements from piezometers and settlement cells installed on the earth fill dams. The system uses a combination of dataloggers and vibrating wire interfaces integrated with multiplexers and radio communication devices which send the data via radio waves from the dam to Cerro Luisa, and then to the office in West Corozal. Additionally, there are some inclinometers installed at the dams, but they are read manually every 15 days, and additional readings are made when the daily accumulated rainfall is 90 mm or more.

9. ACTIVATION OF LANDSLIDE RESPONSE PROTOCOL

The Landslide Response Protocol implements procedures for identifying probable, imminent or current landslide emergencies which can affect the operation and safety of the Panama Canal Authority facilities and personnel. The early identification of existing or potential landslide is essential to opportunely initiate remedial measures with the objective of maintaining the waterway operational.

The protocol establishes three different risk conditions: Code blue, Code Yellow and Code Red (see Figure 10). Code Blue, or probable landslide threat warning, is activated when any signs of incipient movement are detected. Code Yellow, or imminent landslide threat warning, is applied when there is clear evidence of the occurrence of a landslide, such as cracks, but not foreseen as critical. Code Red, or existing landslide warning, corresponds to an Emergency condition, and is started when an existing landslide jeopardizes lives, the transit of vessels, or property.

Depending on the Code, different notifications are issued, and the support of different ACP Departments is requested immediately. The works comprise clearing tall grass and brush, surveying and mapping of the movements registered on-site and underwater, the use of construction equipment and personnel to initiate preventive or remediation measures, and dredging equipment to remove encroachment material if necessary.

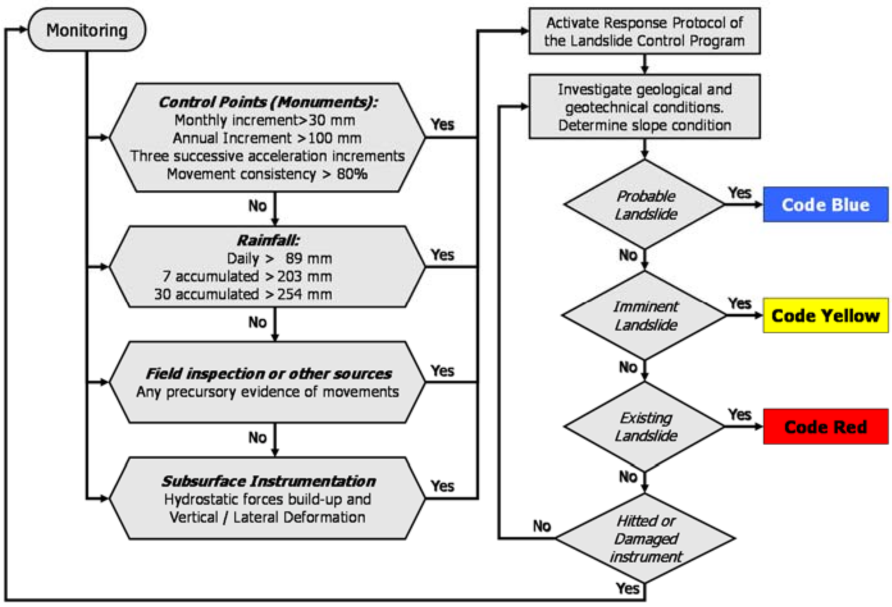

Figure 10: Landslide Response Protocol

9.1. Data Analyses

All collected data from the surveillance instruments are processed and analyzed to identify any sign of instability in the different areas. All instability features encountered are then evaluated in order to determine if there is a consistent displacement trend that might represent any threat to the general stability of the area. Also, rainfall data from the corresponding meteorological station is correlated with the instrument readings. The end result is the identification of the landslide risk condition. The analysis covers the following criteria:

- Control Points: The data of each monument issuing a warning is reviewed, first independently of the rest, and then, in the context of the surrounding area, as the degree of correspondence between the movements of all monuments within such area is evaluated. When a movement trend is identified in a given sector, further actions are performed as explained below.

- Rainfall: Given a potential instability is identified, rainfall records are reviewed. Also, rainfall intensity is constantly monitored by the Water Division, which is responsible for issuing notifications when the 24-hour rainfall average exceeds the 89 mm threshold for any of the meteorological stations.

- Field inspections: If either the rainfall intensity or the movement trend of a sector is above established criteria, a field inspection is conducted to the areas of concern, searching for other signs of movement, such as cracks, and tilting of trees and electric poles, and additional special data collection is performed for all existing instruments.

- Subsurface Instrumentation: The accumulated rainfall average is compared with the subsurface instrumentation data to detect if there is a direct correlation between rainfall intensity and variations of the phreatic level. Figure 11 shows the behavior of the pore pressure in a section of Dam 1E, the water elevation of Gatun Lake and the accumulated rainfall from the meteorological station of Cocoli. Data from groundwater measurements help to understand the flow regime present in the majority of potential slide areas in Gaillard Cut, many of the cut slopes are affected by water, because the shear resistance reduces as the pore pressure increases, causing instability.

The real-time data from the Automated Data Acquisition System is used to evaluate the performance of the dam relative to the expected performance or dam safety performance standards. The historical piezometric levels are used in the design of remedial excavation solutions.

Upon this evaluation, further actions may be necessary. Additional instruments may be installed to define the extent of the moving mass. Remedial measures are devised and implemented as required to stabilize the affected areas. In general, if the condition is critical, the stabilization works are executed either partially or entirely by internal forces, depending on the scope and magnitude of the works. Otherwise, the works are performed by contract.

This methodology has provided the means to recognize many instabilities in the early stages with sufficient anticipation to correct them before they would fail producing blockage or encroachment in the waterway. However, the behavior of slopes with similar initial patterns of movement may differ from one another depending on a variety of factors, such as geology, geomorphology, water table conditions, stress state of soil/rock materials, and failure mechanism of the area being monitored, among others. Therefore, the corrective measures to be adopted for instability remediation shall depend upon engineering judgment supported on site reconnaissance, supplementary geological investigations, history of slide activity and previous remedial works, and additional instrumentation when required.

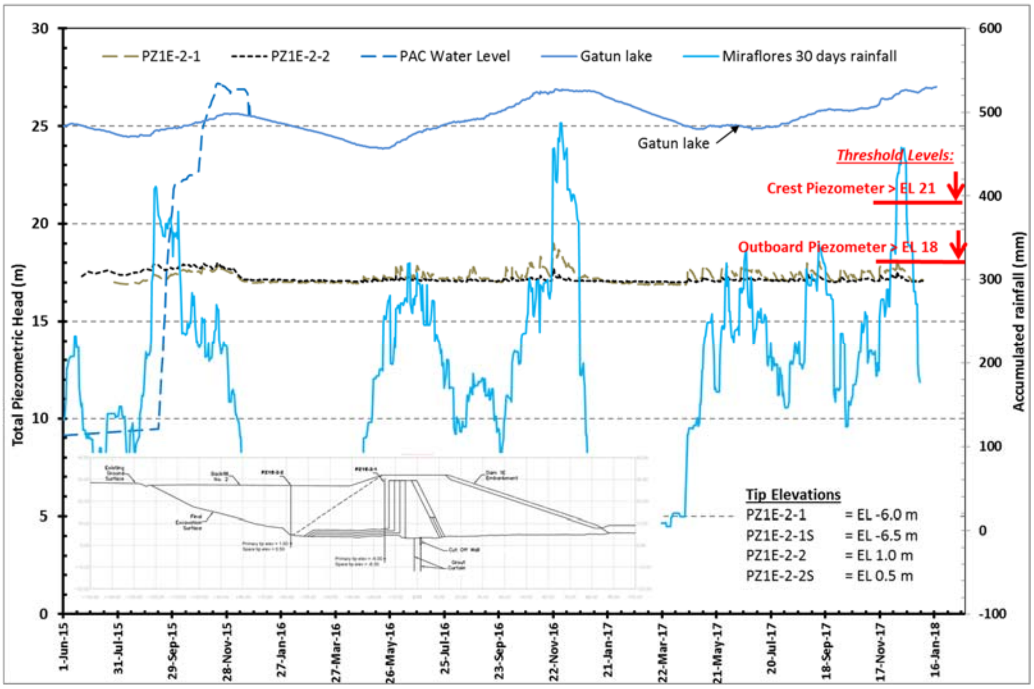

Figure 11: Vibrating wire piezometer Pacific Access Channel, Dam 1E

9.2. Geological and Geotechnical Investigation

After collection and review of all existing data on the slope, and a field reconnaissance of geologic and terrain conditions, further investigations are performed in areas of existing or potential landslide. The area is geologically explored by core drilling, using some of the drilled holes to install subsurface instrumentation. Along with the drilling, access roads are built, additional surface instrumentation is installed, drainage networks at the area are rehabilitated, improved, or built as required; and complete monitoring of the slopes is carried out.

9.3. Case Study: Monitoring and Remediation of Old Lirio Slide (2015)

The Old Lirio Slide area is located in Lirio Sector, at the central portion of the Gaillard Cut, on the west bank of Culebra Reach, from Canal station 58K+100 to station 58K+620. Elevation ranges between 27.5 meters and 60 meters PLD (Precise Level Datum used at the Panama Canal area).

In the past, several instabilities have occurred in this area, during and after the Canal construction. The most recent event before year 2015 occurred in June 17, 2013. Such event was located in the same area, between Canal stations 58K+250 and 58K+550.

The slide being studied occurred on December 7th, 2015. Several cracks were reported in the area (see Figure 12). Two days later, on December 9th, the Manager of the Geotechnical Branch activated the Landslide Response Protocol issuing an "imminent landslide" (Code Yellow) alert for this area.

The unstable mass was estimated to be 500 meter long and 200 meter wide, comprising approximately 2 million cubic meters. The potential encroachment was estimated to reach 50 meters into the west lane of the navigational channel.

In both, the June 2013 and the December 2015 events, the failure mechanisms were considered to be rotational, with a slip surface extending through layers of fill, clay shale, sandstone, conglomerate, and carbonaceous sandstone (see Figure 13).

Figure 12: Tension Cracks at Old Lirio Slide Area

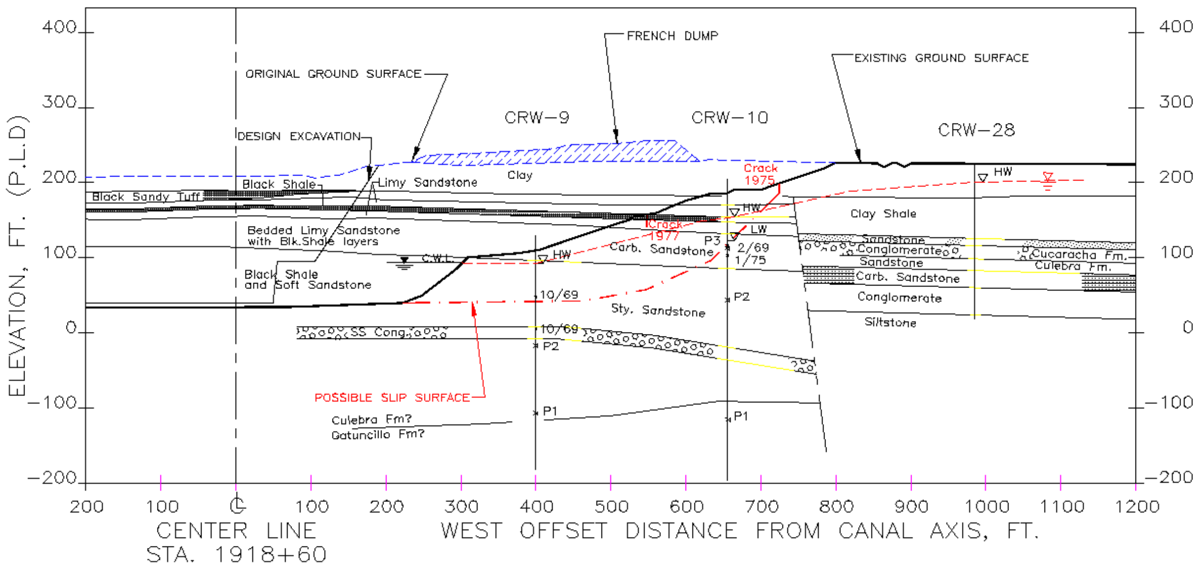

Figure 13: Geological Cross Section at Station 58K+479 m (1918+60 feet)

According to the Landslide Response Protocol guidelines, the instrument data was further analyzed. No additional geological or geotechnical investigations were required in this case. The remedial works were designed and implemented to stabilize the area. The works initiated on January 4, 2016. They were performed by ACP internal forces under the direction of the Geotechnical Branch and were completed by February 2017, after a 5-months interruption due to rainfall between July 2016 and January 2017. The works comprised the excavation of 204,000 cubic meters of unclassified material, the construction of a set of drainages with a total length of 170 meters, an inverted filter covering approximately 1825 square meters, and a french drain of about 168 meters long. No dredging works were required. Figure 14 shows the final excavation layout of the stabilized area in yellow, the excavation perimeter is shown in cyan, and the mapped cracks are shown in white.

Figure 14: Excavation Layout at Old Lirio Slide

Figure 15 presents a set of plan views showing color-classified raster images representing superficial displacements at the Old Lirio Slide area, and the corresponding vectors representing effective displacement in magenta. The first plan view shows data for the period beginning on January 1, 2010 and ending on June 30, 2013; some days after the June 2013 instability. The second plan view covers the period between July 1, 2013 and December 30, 2015, less than a month after the December 2015 landslide. The third raster shows the data indicating recorded displacements since January 1, 2016 up to March 15, 2018.

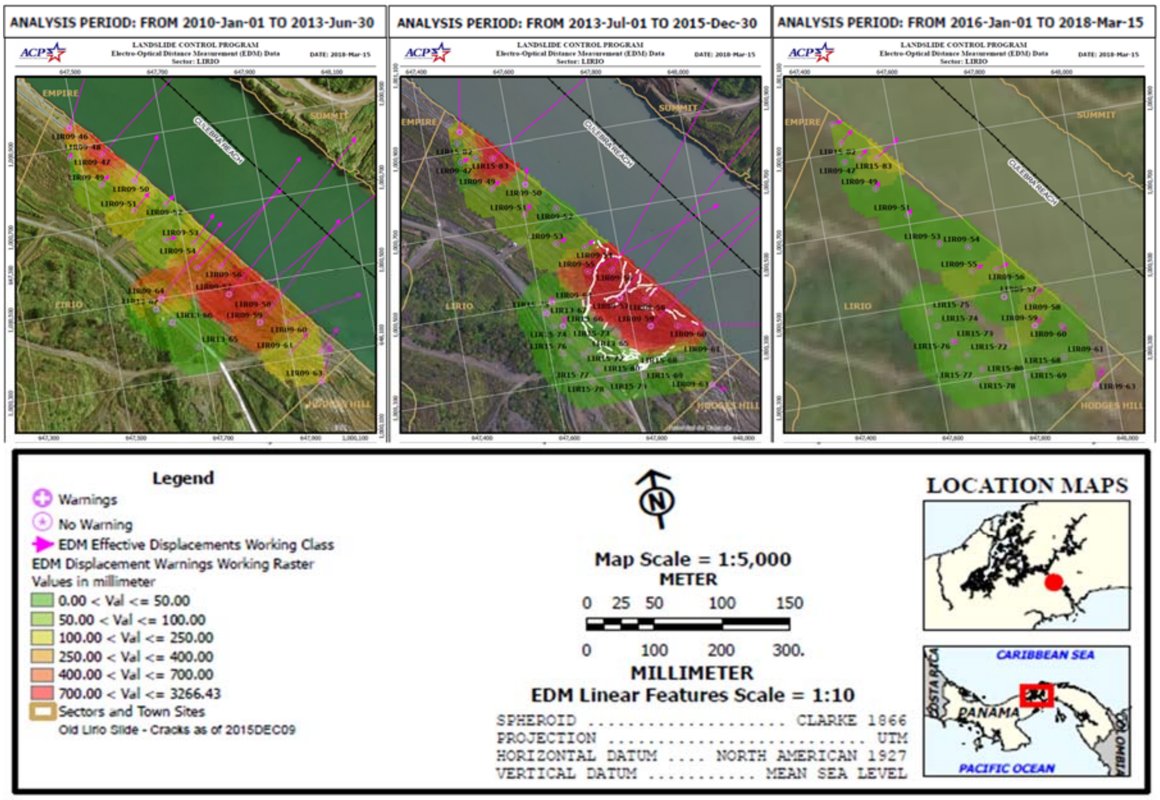

Figure 15: Displacement Vectors and Raster Images at Old Lirio Slide

Displacement vectors for the different monuments shown in the first plan view of Figure 15 indicate an average movement of about 1 meter that had accumulated for over three years before the June 2013 landslide occurred. Remedial works were performed for the next six months to stabilize the moving mass, including the removal of the material at the top of the moving mass and the construction and rehabilitation of drainages in the area. Even after the stabilization works were completed, movement towards the canal continued, and the new tension cracks developed by December 2015, shown on the second plan view in white, time at which the Landslide Response Protocol was reactivated and Code Yellow notifications were issued. New remedial works were executed as described previously, preventing any channel encroachment. The third plan view shows displacements smaller than 50 millimeters for most of the area, corroborating the landslide hazard has been mitigated.

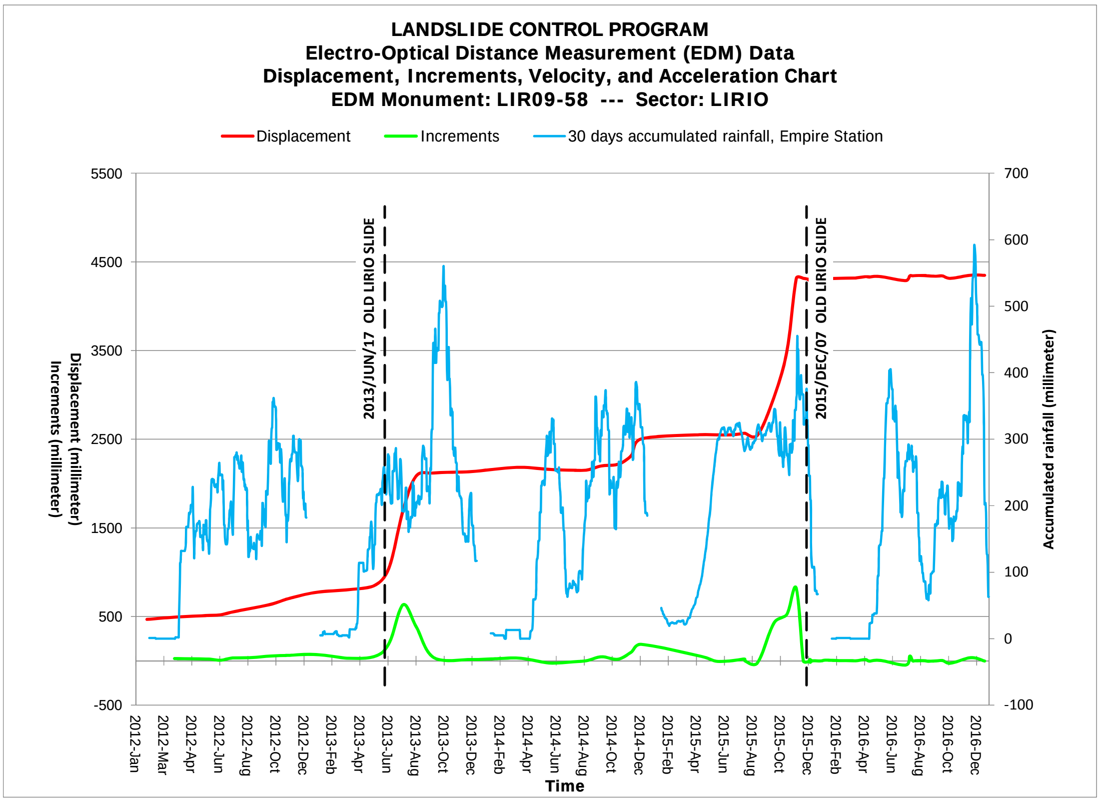

Figure 16: Effective and Incremental Displacement vs. 30-Day Accumulated Rainfall

Figure 16 shows a comparison between data for the effective and incremental displacements of Monument LIR09-58 and the 30-day accumulated rainfall, as recorded at the nearest meteorological station (Empire). The chart shows that the landslides mentioned above occurred during periods of heavy rainfall. Worth noting, the larger movements developed during the sustained periods of rain, which favor water infiltration and the consequent increase in water table and pore pressure, and not necessarily during the peaks of rain intensity, as shown.

10. CONCLUSIONS AND REMARKS

The occurrence of landslides in the Gaillard Cut is mostly due to the complex geological conditions combined with a high precipitation regime:

- Soft rock strata characterized by long-term loss of strength due to natural geological processes.
- Presence of discontinuities and weak planes, resulting from geological processes, that drive the geometry of failures.
- A direct relationship between the rainfall regime and the increase of hydrostatic forces and pore water pressure which largely affect the behavior of the soft rocks, such that rains are the main factor triggering Landslides in the Gaillard Cut.
- The progressive swelling/rebound of soft rocks due to the unloading caused by earthworks in the bank slopes.

The Landslide Control Program constitutes a risk reduction activity that supports the main business activity of the Panama Canal: The safe, efficient, and reliable transit of vessels through the Isthmus of Panama.

The Landslide Control Program does provide savings because:

- Any encroachment or blockage of the navigational channel that interrupts normal traffic through the canal represents a millionaire reduction of income.
- The removal of material from the navigational channel by dredging is far more costly than earthworks performed in the dry for the stabilization of a moving mass.

The Landslide Control Program has proceeded mostly as planned. To the present, the slopes of Gaillard Cut and the Pacific Access Channel are geologically explored and adequately instrumented, and are being effectively monitored for detection of incipient landslide activity.

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