Reconnaissance of the Rio Coca Regressive Erosion and Building the Partnership

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Abstract

The Río Coca regressive erosion is an unprecedented event in non-geologic time scales. On February 2, 2020 the San Rafael waterfall on the Coca River in northern Ecuador collapsed. As of September 2022, the headcut has advanced approximately 11.1 km upstream and is only 7.9 km downstream from the intake structure associated with the Coca Codo Sinclair (CCS) hydropower complex – the largest hydropower facility in Ecuador. Following these events, the Government of Ecuador (GoE) through the Ministry of Energy and Non-Renewable Natural Resources and the Electrical Corporation of Ecuador (CELEC) began a dialog with the US Embassy and US Army Corps of Engineers (USACE) to develop a partnership with USACE. The purpose of the partnership is to provide technical assistance for the continual operations of the Coca Codo Sinclair hydropower complex within the context of the regressive erosion and progressive deposition.

USACE subject matter experts visited the Rio Coca through a US funded Water Resources Development Act (WRDA), Section 234 request and met with CELEC, Petroecuador, and the Ministry of Energy and Non-Renewable Natural Resources during a trip in July 2021. During the reconnaissance visit, several key observations were made that shaped the international partnership. The failure of the San Rafael lava dam and the processes that event initiated are unique globally, especially considering the potential impacts to infrastructure (hydropower production at the Coca Codo Sinclair hydropower complex). The team identified two potential modes of failure that could impact the CCS operations in the coming seasons: 1) Regressive Erosion (acute problem); and 2) Continual Progressive Deposition at the discharge tunnel (chronic problem). Based on these findings it was recommend to develop a team dedicated to understanding and developing measures for the regional progressive deposition trend at the discharge tunnel in addition to the team dedicated to the regressive erosion. USACE provided responses to charge questions associated with viable measures for arresting the regressive erosion, physical modeling recommendations, construction sequencing, and risk management.

Following the reconnaissance mission, a report of observations, findings, and considerations from the July 2021 visit was developed by the USACE team. In addition to the technical deliverable, the USACE project management team began discussions with CELEC on building an international partnership through the mechanism of a Foreign Military Sales (FMS) case, which was signed in December 2021. The primary tasks associated with the case included: 1) Physical Modeling of Proposed Regressive Erosion Solutions; 2) Collaborative Analysis and

Engineering Support to the regressive erosion and progressive deposition issues; 3) Technical Visits to the United States; and 4) Expert Elicitation.

Introduction

On February 2, 2020 the San Rafael waterfall on the Coca River in northern Ecuador failed catastrophically through a series of erosion processes including knickpoint erosion followed by a piping failure (see Figure 1 for a progression of the failure). The failure of the lava dam released over 200 million cubic meters of volcanic sediment downstream and resulted in a headcut that began to propagate upstream. Soon after the waterfall collapse, numerous oil pipelines, bridges, and structures failed as the regressive erosion propagated upstream in the valley. As of September 2021, the headcut has advanced approximately 11.1 km upstream and is only 7.9 km downstream from the intake structure associated with the Coca Codo Sinclair (CCS) hydropower complex – the largest hydropower facility in Ecuador. Additional description and context of the regressive erosion and overview of the event is described in Espinoza and Boyd (2023).

Figure 1. Evolution of the San Rafael Waterfall Failure from 2003 through 2020

Following these events, the Government of Ecuador (GoE) through the Ministry of Energy and Non-Renewable Natural Resources and the Electrical Corporation of Ecuador (CELEC) began a dialog with the US Embassy and US Army Corps of Engineers (USACE) to develop a partnership with USACE. The purpose of the partnership is to provide technical assistance for the continual operations of the Coca Codo Sinclair hydropower complex within the context of the regressive erosion and progressive deposition. USACE visited the Rio Coca and met with CELEC, Petroecuador, and the Ministry of Energy and Non-Renewable Natural Resources during a trip in July 2021. A report of observations, findings, and considerations from the July visit was developed by the USACE team. In addition to the technical deliverable, the USACE project management team began discussions with CELEC on building an international partnership through the mechanism of a Foreign Military Sales (FMS) case.

Reconnaissance Phase Findings

General Considerations

The primary motivation for the Reconnaissance trip was to develop a partnership to reduce risks of operations associated with the Coca Codo Sinclair Hydropower Facility. Based on the reconnaissance visit USACE observed two major processes of concern (Table 1) that may impact operations of the Coca Codo Sinclair (CCS) hydropower complex in the coming seasons. The regressive erosion and its potential to undermine the CCS intake dam is self-evident and deserves the attention it is receiving. The regressive erosion has been a major focus of many of the on-going efforts, and is the motivation for the development of many future measures. However, progressive deposition downstream of the former San Rafael waterfall is an equally concerning process that could impact the long-term operations of the CCS hydropower complex.

Table 1. Potential Failure Modes of the Coca Codo Sinclair Hydropower Facility

Upstream	Downstream
Regressive Erosion	Progressive Deposition
Threatens to undercut the intake	Threatens to bury the outlet

A site location and details of key site features is shown in Figure 2. The The Coca River flows to the northeast at the former San Rafael waterfall location (Station 19+000 km). The Coca Coda Sinclair (CCS) diversion intake is located 19km upstream of the former San Rafael waterfall, and the Outlet works of the CCS discharge at a location 45km downstream of the former San Rafael waterfall. The Reventador Volcano (the source of the lava dam that created the San Rafael waterfall) is located to the northwest of the former San Rafael site.

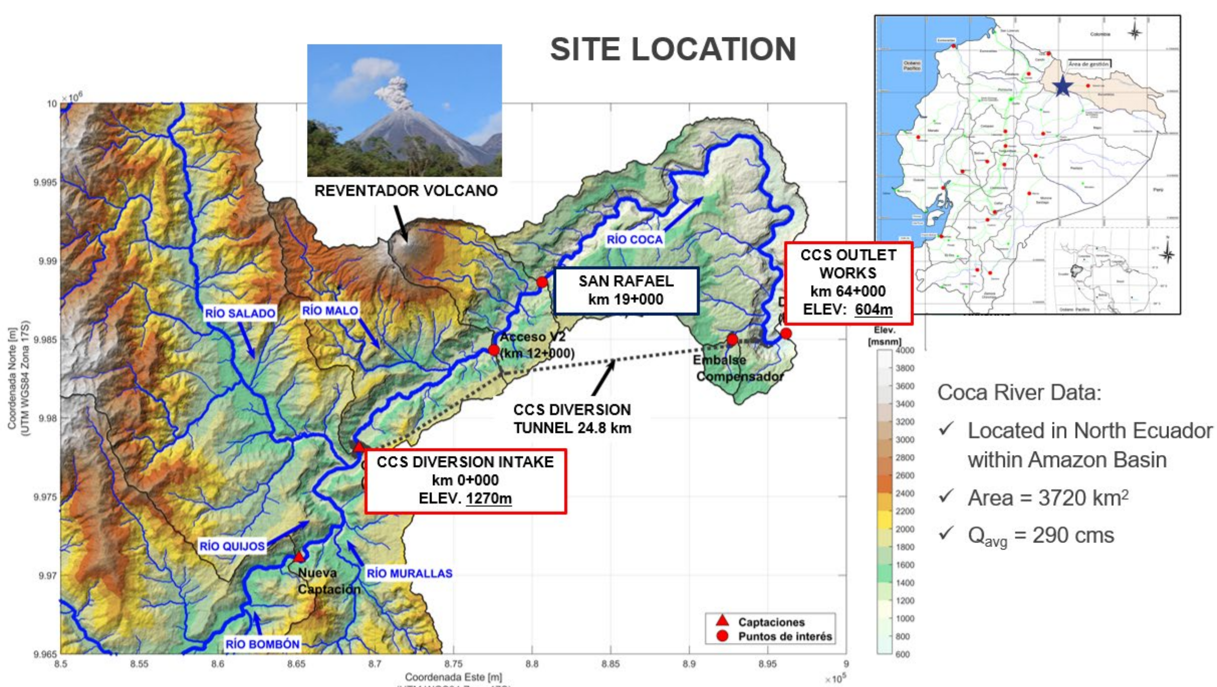

Figure 2. Site Location and Key Site Features.

Regressive Erosion (Upstream) Considerations

The potential future impacts of the regressive erosion are primarily related to the operations of energy infrastructure (hydropower and pipelines) as well as significant social-environmental impacts. The potential economic impacts associated with the loss of hydropower production are expected to be enormous. The majority of the environmental impacts are natural at the geologic scale, but significant and unique in the timescales of human development in the region. The primary environmental impact to plan for mitigation is any future unexpected ruptures of pipelines. The social impacts of continued regressive erosion are significant based on the potential impacts to hydropower production, relocation of villages and towns, loss of livelihood, etc. Life safety due to the continued regressive erosion should be accounted for and any structures at risk evacuated.

Regressive Erosion Timeline: The headcut has traveled 12 km in the first 18 months following the failure event, but modeling performed by the CELEC teams suggests it will slow considerably over the next 8 km, before it reaches the intake dam (CELEC, 2021). This is because the materials are more resistant in the upstream section and it is also closer to the equilibrium slope. In particular, the model attributes the headuct or knickpoint slowing due to a breccia outcrop at station 12+000 (12 km downstream of the dam intake) and an alluvial armor layer that protects the erodible lacustrine deposits upstream of this outcrop.

The model (CELEC, 2021; Barerra, 2023) attributes much of the headcut slowing to alluvial armoring in the last (upper) 8 km. Monitoring of the rate of regressive erosion has been continual, and the CELEC and USACE team have been observing armoring processes and have identified that there is a process of exposure and attack of the softer lacustrine layer beneath the armor layer, which could undermine the large alluvial material and reduce or negate the benefits of the armor layer. This process is already active at the Río Malo confluence (Figure 3). An empirical headcut analysis may provide additional estimates of headcut migration through the armored-lacustrine reach. USACE would consider analyses like Wu and Wang (2005) and Stein and Julian (1993) to supplement the numerical modeling.

Figure 3. The headcut at the mouth of the Río Malo (which developed mostly during the July 19, 2021 event) illustrating the conceptual model of the plunge pool driving the lacustrine headuct.

The most promising evidence of the slowing was the modest headcut migration during the July 2021 event (largest flow since the mid-1970s with an estimated 5% annual exceedance probability). Although the regressive erosion rate was relatively modest, the vertical downcutting of 4 meters during the event is concerning. The regressive erosion has been propagating in an episodic fashion since February 2020. Regressive erosion occurs when a discharge threshold is exceeded. Therefore, the rate of regressive erosion may be more a function of the amount of time that the threshold discharge is exceeded, instead of a function of the discharge value alone.

Progressive Deposition (Downstream) Considerations

Most analysis and studies to date have focused more attention and effort on the upstream failure mode, but the downstream process – progressive deposition –also threatens the hydropower project capacity and, eventually, failure. Figure 4 and Figure 5 show the progressive deposition 7 km downstream of the site of the lava dam, about 15 months after the initial lava dam failure. The center of mass of the sediment-wave is still in this reach. The sediment-wave will move downstream as a slow moving sedigraph. The bed elevation at the CCS outlet structure will raise as the center of mass approaches. Near the former San Rafael waterfall there has been deposition of approximately 40m. The maximum deposition will attenuate downstream, so the deposition at the outlet will be less than the 40 m at the former San Rafael waterfall. However, it will be more than the initial 2m observed after the July 2021 event.

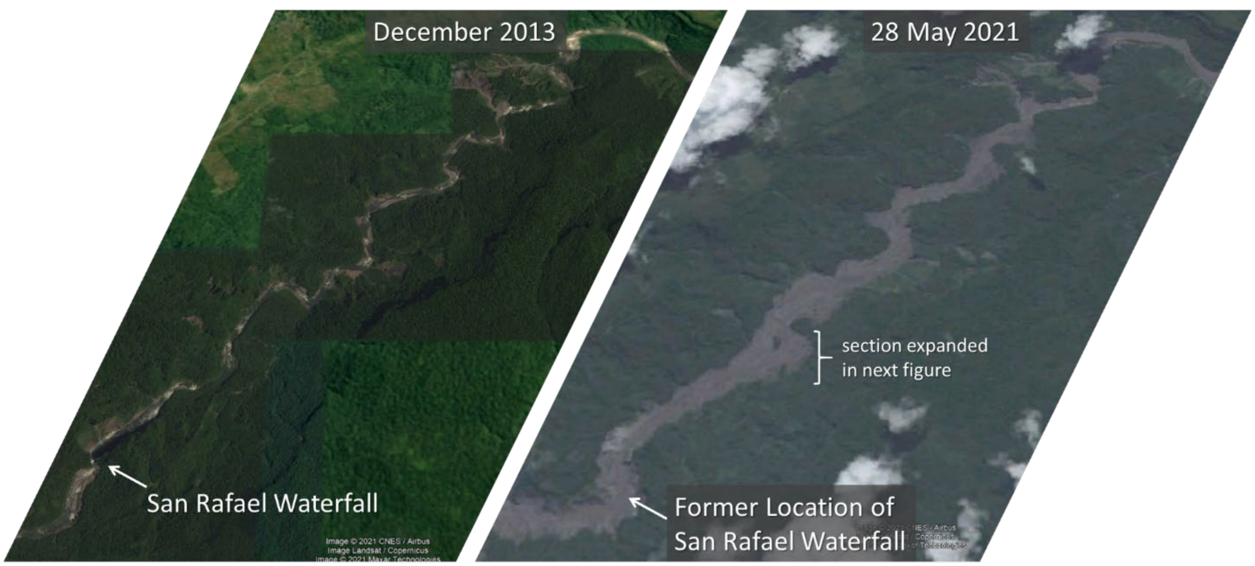

Figure 4. Approximately seven kilometers downstream of the San Rafael waterfall site before (2013) and after (May 2021) the collapse. The image on the right provides some insight on the scale of deposition downstream of the dam and the center of mass of the downstream sediment that must transport past the outlet structure. (May 2021, photographs from the Unclassified Digital Globe database).

Figure 5. Imagery from one river bend (location indicated in previous figure) about one kilometer downstream of the former site of the San Rafael dam before and after the collapse.

Long-Term Progress Deposition Threats: The downstream threat has impacted operations first – before any impacts have been realized to CCS operations due to the regressive erosion. With the upstream regression slowing, and the July 2021 event accelerating the downstream progression of the sediment wave, it is possible that the downstream process could shut down operations before the headcut reaches the intake.

While the project team currently understands upstream regression more than downstream progression on the Río Coca, large scale sand-wave diffusion will be easier to understand and predict using standard scientific tools that are currently available. There are several reasons for this. First, deposition is almost always easier to model than erosion. Depositional physics are more predictable (gravity dominates the process) and depositional models do not suffer from subsurface material uncertainty or the parametric uncertainty surrounding the erodibility of cohesive and consolidated materials. Finally, while the Río Coca's progressive erosion is almost unprecedented (outside of geologic timeframes) at this scale, there are a number of analogous, large scale, downstream progression processes that could guide this study (for example, volcanic eruptions, and dam removals).

The USACE team recommended that CELEC form a team to forecast the timing and magnitude of the sand wave at the CCS outlet structure (and other critical downstream infrastructure). A regional sediment model could route the sediment wave downstream and distinguish between the representative possible future scenarios illustrated in the conceptual model in Figure 6. This downstream study will have a larger model domain and will run for multiple years (or decades). A simplified one-dimensional model would likely be sufficient to address initial operational questions downstream.

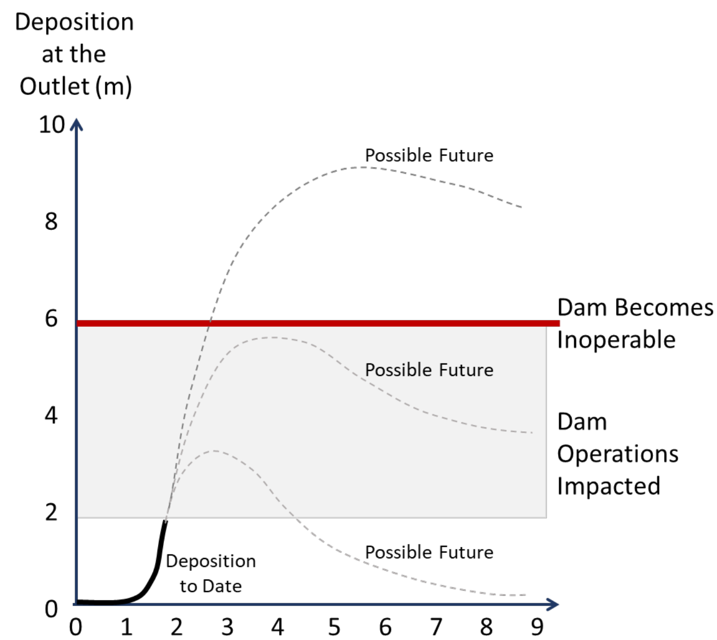

Figure 6. Schematic of the deposition at the downstream outlet (KM65). The black line is the deposition to date (total = 2m) and the dotted lines represent several possible futures. The dam becomes inoperable at 6m and will have to go offline more often as deposition increases.

Short-Term Issues and Operations at the Downstream Outlet: The left-bank deposition at the CCS outlet structure pushed the flow to the right side of the channel, scouring the right bank, removing riprap and undermining the outlet structure. CELEC plan to build hydraulic structures (groynes) to redirect flow away from the localized erosion is promising.

Dredging could temporarily reduce the hydraulic pressure on the CCS outlet structure. However, dredging is not a sustainable solution at this location. With 220 million tons in the system, dredging and disposal operations will quickly be overwhelmed. Additionally, it will not be sufficient to just dredge the immediate location of the structure to decrease water levels. CELEC would have to dredge a reach downstream to mitigate backwater effects from deposition downstream of the outlet.

Building the Intergovernmental Partnership

Following the reconnaissance visit funded by WRDA 234, USACE and the CELEC developed a scope for a long-term partnership in technical support to the Government of Ecuador in the interdisciplinary field of river engineering. This partnership is through a Foreign Military Sales (FMS) case. Under this case, USACE has been directly supporting CELEC and its Executive Commission for the Rio Coca (Commission), who is tasked with developing engineering solutions to prevent operational impacts of the Coca Codo Sinclair (CCS) Hydropower Complex. Since the San Rafael waterfall failure in February 2020, the Commission has completed significant analysis, studies, investigations, and has contracted design and construction measures aimed to mitigate the regressive erosion and downstream deposition of sediment. The role of USACE in the current partnership is support of on-going efforts for mitigating impacts associated with the San Rafael waterfall collapse. Based on the initial observations from the

USACE team during the reconnaissance phase, there are two relevant modes of failure that could impact operations of the CCS Complex. These include:

1. Regressive erosion that could reach the diversion intake of the CCS Complex and undermine the diversion weir at the structure.
2. Progressive deposition of sediments that increase the elevation at the discharge canal of the CCS Complex

Either process could impact the operations of the CCS Complex and are being investigated through a series of studies and designs by the Commission. The following sections describe the proposed tasks that are aimed to support the Commission's investigations, studies, and design of mitigation measures against regressive erosion and progressive deposition of sediments in the Rio Coca.

Task 1 – Expert Elicitation: USACE will gather two interagency teams of Subject Matter Experts (SMEs) to provide geomorphic assessments and review the project designs. SMEs for these teams have come from the USACE laboratories and districts, US Geological Survey, the US Bureau of Reclamation (BoR), and the US Department of Agriculture – Agricultural Research Service (ARS). Design charrettes have been organized with the experts involved in order to develop mitigation alternatives and to review proposals for engineering solutions.

Task 2 – Physical Modeling of Proposed Regressive Erosion Solutions: One of the primary alternatives being considered for implementation by CELEC is the design of a series of grade control structures using sub-surface jet-grouting. Due to a number of concerns over the proposed design, several international experts have recommended to develop physical models of the design to possibly modify or enhance the project features and reduce the probability of failure of the structure. Due to time constraints and the on-going regressive erosion, USACE supported CELEC and developed physical models of the system and proposed design in parallel to the construction of the cofferdam associated with the project.

USACE also recommended to construct a localized, section model in a flume. This model was used to investigate piping and seepage concerns associated with the proposed design. The recommended localized model consisted approximately 3 grade control structures. Information regarding the details and findings of the physical modeling are described in Sharp et al. (2023). Additional physical modeling of proposed solutions, including the construction of a grade control bridge are also described in Sharp et al. (2023).

Task 3 – Numerical Model Support: The first two tasks of this FMS support are focused on the conditions upstream of the San Rafael waterfall and the mitigation of regressive erosion. In Task 3, USACE provides technical support in sediment transport modeling. One of the identified modeling tasks include the development of a one-dimensional (1D), reach-scale, long-term sediment transport model of the Rio Coca downstream of the San Rafael waterfall in order to estimate timing and magnitude of deposition rates at the Coca Codo Sinclair outlet works and other infrastructure in downstream reaches.

USACE sedimentation subject mater experts will develop the one-dimensional hydraulic and sediment transport model in the Hydrologic Engineering Center – River Analysis System (HEC-RAS). A literature review of existing sediment and hydraulic data will be completed, and a data gap analysis will be performed. USACE will identify recommended additional data to be used for input and calibration for the sediment transport model.

Numerical sediment transport modeling will be also be used to support the evaluation of proposed measures. These sediment transport modeling analysis may include measures associated with mitigating the regressive erosion impacts or the progressive deposition impacts.

Task 4 – Technical Visits: USACE proposes two technical visits to the United States to interact with US Agency SME's, see some of our related sites, and interact with the physical modeling team. The two proposed site visits include:

- A Major Morphological Disturbance Technical Tour of the Pacific Northwest
- A Visit to the Coastal Hydraulics Laboratory Physical Model

Conclusions

The USACE team performed a rapid assessment of the current regressive erosion and progressive deposition of sediment in the Río Coca, Ecuador. The failure of the San Rafael lava dam and the processes that event initiated are unique in the world, especially considering the potential impacts to infrastructure (hydropower production at the Coca Codo Sinclair hydropower complex). The rapid assessment provided several considerations for CELEC, Petroecuador, and the Ministry of Energy and Non-Renewable Natural Resources, and served as the basis for the development of the intergovernmental partnership between USACE and the Government of Ecuador.

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