

## Using Soil Bioengineering to Recover a Gully in the Amazon Forest

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### Abstract

During the dam construction process, sites adjacent to the construction work are licensed and called Borrow Areas. Due to the intensification of anthropogenic actions, these areas are more susceptible to erosive processes that result in soil movement, silting of water resources, loss of natural habitat, alteration of water quality, loss of local fauna and flora and alteration of the natural environment. Traditionally, the control of erosion processes on slopes is carried out using conventional civil engineering techniques (gabion walls, slope reshaping, etc.). However, Hydro Bauxite & Alumina, which is driven by more sustainable and environmentally friendly actions, takes care of neighboring communities and future generations, and decided to implement techniques with a lower environmental impact. The aim of this case study was to demonstrate soil bioengineering techniques. The target area (borrow area) of the intervention project consists of a large gully with an area of approximately 575 m<sup>2</sup>, 35.5 m long at its central axis and 9.0 m deep at its highest point, with slopes of 77° there are also negative effects visible at various points. Soil bioengineering focuses on a set of techniques that combine living/inert constructive materials, which can be applied as constructive solutions to structural problems of geotechnical and hydraulic stabilization, control of surface erosion processes, and simultaneously design ecosystems in dynamic balance, environmentally friendly and with less damage to nature. In this way, the following techniques were implemented: 1- Earthworks; 2- Live wooden cribwall; 3- Live slope grid; 4- Vegetated coir logs; 5- Selection of suitable plants. This case study presents the techniques used to stabilize the gully. The results were totally effective in controlling erosion and stabilizing the slope, withstanding high volumes of precipitation (82.70mm). There is no need for decommissioning works, as the structures will be integrated into the environment and are more economically viable than traditional molds.

**Keywords:** Soil Bioengineering, Gully Control, Environmental Recovery, Nature Based Solutions, Slope Stabilization.

### 1. Introduction

According to data consolidated by Instituto Brasileiro de Mineração do Brasil (IBRAM – Brazilian Institute of Mining) [1], the mineral sector raised 58 billion USD in Brazil in 2021, playing a fundamental role in the balance of the economy, considering exports and imports for that reference year. More specifically, the export of bauxite from Brazil accounted for 184 million USD in 2021, equivalent to 1.48 million tonnes of the ore exported [1].

Bauxite is currently the main raw material used in the global aluminum production chain [2]. For the generation of bauxite slurry used in the production of alumina, the ore undergoes a physical

beneficiation process involving grinding and washing, which generates the product and a bauxite slurry that is not usable in the process (tailings material) [3]. Despite the emergence of new tailings material disposal technologies, according to the Brazilian Aluminum Association - ABAL [3], the main method of bauxite tailings material disposal in Brazil occurs in large reservoirs, where the tailings material undergoes a process of drying and settling over time until the end of the reservoir's useful life.

According to data from Integrated Mining Dam Management System/National Mining Agency (SIGBM/ANM) updated until July 2023, Brazil has 928 mining dams registered in the system, distributed across 20 Brazilian states, with 461 included in the National Dam Safety Policy - PNSB [4]. The state of Pará has the highest representation in the collection of the Financial Compensation for the Exploration of Mineral Resources (CFEM) in the country, equivalent to 45.6 % of the total collected [1]. According to ANM data (2017), Pará has 37 companies that explore metallic minerals, including 18 of medium or large size, with 3 large bauxite mining companies.

During the process of dam constructions, adjacent areas to the work are licensed and called Borrow Areas. These perimeters are used for the installation of construction sites, traffic, and parking of equipment, removal, transport, and deposit of substrates from soil horizons (laterite) among other utilities. These actions can lead to erosive processes resulting in soil movement, silting of water resources, loss of natural habitat, alteration of water quality, loss of local fauna and flora, and changes in the natural environment. Natural factors such as soil susceptibility to erosion, high rainfall levels, and undulating relief strongly influence the dynamics of erosive processes [5]. Although erosion is a continuous and natural process that contributes to the distribution of sediments on the Earth's surface, its acceleration due to human action results in environmental and economic losses.

Traditionally, the control of erosive processes on slopes is carried out with conventional civil engineering techniques, such as slope reshaping through cutting, which can even intensify existing erosive processes, or the application of gabion walls, soil cement bags, concrete linings, rockfill, among others. However, Hydro Bauxite & Alumina, driven by more sustainable and environmentally correct actions, as well as care for neighboring communities and future generations, decided to implement techniques with lower environmental impact.

Thus, to correct erosive processes on slopes, projects of soil bioengineering were developed. Soil bioengineering proves to be a viable solution compared to traditional techniques, as considers technical criteria in the design of works, and also values ecological and environmental factors [6, 7]. Moreover, the correction and/or mitigation of erosive processes through conventional engineering approaches can be more costly from a technical, economic, and especially ecological standpoint [8]. According to various authors, soil bioengineering presents more economical construction solutions than traditional engineering solutions [6, 9, 10].

Soil bioengineering primarily uses living construction materials (seeds, plants, plant parts, etc.) that may or may not be combined with inert materials. It can be used as a substitute, but mainly as a useful and sometimes necessary complement to classic civil engineering techniques [11]. Soil bioengineering techniques can be applied in the hydraulic field for stabilization and protection of slopes, as well as to increase the morphological diversity in stretches or sections of watercourses, or to increase biodiversity and connectivity of ecological networks [9]. They offer more flexible and permeable construction schemes, which can be more easily integrated into nature, do not suffer from soil settlements and movements, and also do not alter the soil's hydraulic conductivity. Furthermore, since these techniques use natural construction materials, there is no need for decommissioning of the works, as the structures will perfectly incorporate and integrate into nature. The lack of need for decommissioning also results in lower operation costs and mainly

in lesser environmental impact, as it will not be necessary to undertake new interventions for the removal of artificial structures implemented for stabilization and control of erosive processes and subsequent environmental recovery of the intervened area.

## 2. Materials and Methods

### 2.1 Study Area Description

The project area is located in a bauxite deposit owned by the Norwegian group Norsk Hydro ( $3^{\circ}15'38''\text{S}$  and  $47^{\circ}43'28''\text{W}$ ), 70 km from the headquarters of the municipality of Paragominas ( $2^{\circ}59'42''\text{S}$  and  $47^{\circ}21'10''\text{W}$ ), in the Northeast region of the State of Pará, located at a distance of 350 km from the state capital, Belém [12] and the map can be seen in the Figure 1. The climate of the region is classified as “Aw” according to the Köppen-Geiger [13] classification, characterized as warm and humid with well-defined rainy and dry seasons. The average annual temperature is  $26.3^{\circ}\text{C}$ , with an average annual relative humidity around 81 %.

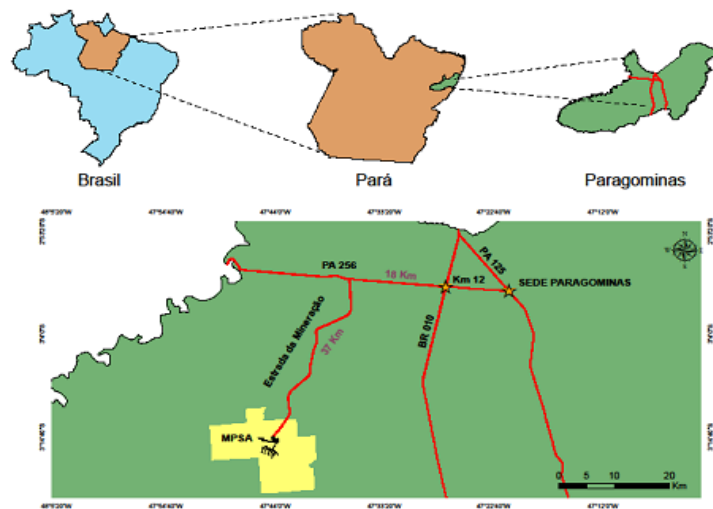


Figure 1. Location of the municipality of Paragominas-PA.

For the storage of bauxite residue, reservoirs were constructed using earth structures, taking advantage of the terrain’s topographical features. The reservoirs are designed for the planned disposal of the residue in a slurry form. During the construction period, adjacent areas were duly licensed, serving as support for the construction.

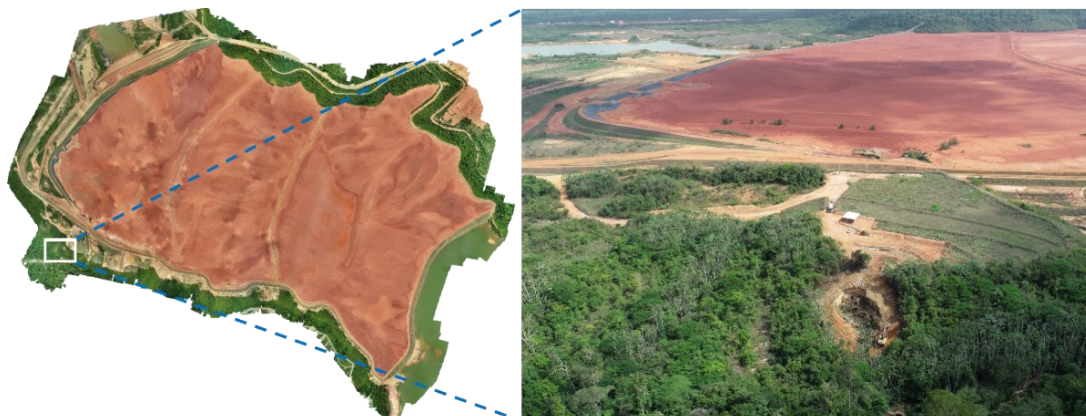


Figure 2. Left: Location of the soil bioengineering work relative to the residue dam, Right: borrow area.

The target area (borrow area) of the intervention project consists of a large gully approximately 575 m<sup>2</sup> in area, 35.5 m in length along the central axis, and 9.0 m in depth at the highest point (Figures 2 and 3). The gully originated due to the absence of a drainage system that adequately directed water from the contributing basin at the top of the slope. The gully features high, very steep slopes, with a 77° incline at its highest point at the head and visible negative grades at several points (slope > 90°), as observed in Figure 3.



**Figure 3. Geometric and geotechnical characteristics of the gully before intervention.**

## 2.2 Hydrological and Hydraulic Study

To design the construction typologies, a hydrological and hydraulic study of the basin was conducted to determine the project's precipitation and flow rates, providing technical criteria and support for the basic-executive project design. The hydrographic basin was characterized by delimiting the contributing area and determining its cover features. The adopted data refer to a conservative (most critical) scenario. It was considered that water flow from the plateau located upstream of the gully would be diverted by a specific drainage system installed on-site through protective berms/dikes directing the flow into a dissipation gabion and into a 315 mm diameter in High-density polyethylene (HDPE) pipe installed on the slope. This system prevents the flow from being directed to the intervention area. The contributing basin has an area of 0.00158 km<sup>2</sup> (0.158 ha) and a perimeter of 0.1636 km (163.6 m).

The length and drop of the thalweg are 33.0 m and 16.1 m, respectively. The basin's slope is 0.482 m/m, and the adopted runoff coefficient is 0.40, considering a region with low vegetation [14]. The time of concentration calculated by the Ven Te Chow formula was 1.75 minutes. Rain intensity data for the project were obtained from [15], for a minimum recommended concentration time of 5 minutes for mining area works for this type of intervention in small basins, with a return period (TR) of 100 years. The obtained pluviometric intensity was 228.3 mm/h. Peak flow estimation for the basin was conducted using the rational method. This indirect method is widely spread and suitable for use in small basins ( $\leq 3$  km<sup>2</sup>). For a return period of 100 years and a project rain, the expected project flow at the control section was approximately 0.04 m<sup>3</sup>/s, or 40 L/s.

Based on this flow rate and the designed channel geometry, the hydraulic behavior of the flow at the bottom of the gully was studied, considering the implementation of the project and stabilization techniques on the slopes and bottom. The adopted Manning's coefficient ( $n$ ) was 0.070, typical for channels with little vegetation and regular flow conditions [16]. The bottom slope was set at 1° (0.0175 m/m). It was verified that for a TR of 100 years, the flow velocities obtained for the project flow after the construction were very low, capable of transporting particles up to 2 mm in size. The obtained velocities (0.21 m/s) are below the necessary speed to transport a very fine sand particle whose admissible average flow speed is 0.23 to 0.30 m/s [16].

## 2.3 Designed Construction Typologies

The soil bioengineering solutions proposed for the site must meet the demands imposed by the dynamics and characteristics of the site, namely stabilizing the slopes and the bottom of the gully, preventing the progression of the erosive process. Even with the redirection of water flow from the contributing basin, through the implementation of a drainage system, which initially originated the formation of the gully, due to the existence of very high slopes, with high steepness combined with the low mechanical resistance of the soil, the area does not have resilience to stabilize and recover without intervention measures.

To control and mitigate the existing erosive processes, various soil bioengineering solutions were specified. Soil bioengineering consists of a set of techniques that combine living construction materials with inert ones, and which can be applied as construction solutions in structural stabilization, geotechnical and hydraulic problems, control of superficial erosive processes, and simultaneously designing dynamic equilibrium ecosystems [7, 18]. Given the erosive typologies found at MPSA/Hydro, and as per their proposals for more sustainable activities, environmentally correct and with less damage to nature, soil bioengineering presents itself as an appropriate tool to stabilize and recover unstable and degraded areas, since it considers technical criteria for project design, besides presenting low environmental impact. Moreover, it also considers the effects and technical contributions of the plants produced in the mining nursery, autochthonous for solving problems related to erosive processes. Soil bioengineering is fully aligned with the concepts of nature-based solutions (NBS), which value biodiversity and reduce anthropogenic pressure on natural ecosystems, whose aspects are increasingly valued worldwide.

### 2.3.1 Earthworks

Earthworks involves the reconfiguration of the gully, i.e., cutting to reduce the slope gradient and subsequent filling inside and behind the designed structures (Figure 5).



**Figure 4. Planialtimetric topography and earthworks (12/08/2023).**

The slopes must be reconfigured to inclinations lower than the current ones, which increased the geotechnical stability of the slopes. In this regard, an estimate of the cut volume (480 m<sup>3</sup>) and fill (377 m<sup>3</sup>) was made. Since the soil will not support loads, the material should be compacted only using the bucket of the machine used for cutting, without the need for a soil compactor. Thus, the soil compaction should allow the development of the vegetation implemented in the interventions.

### 2.3.2 Live Wooden Cribwall

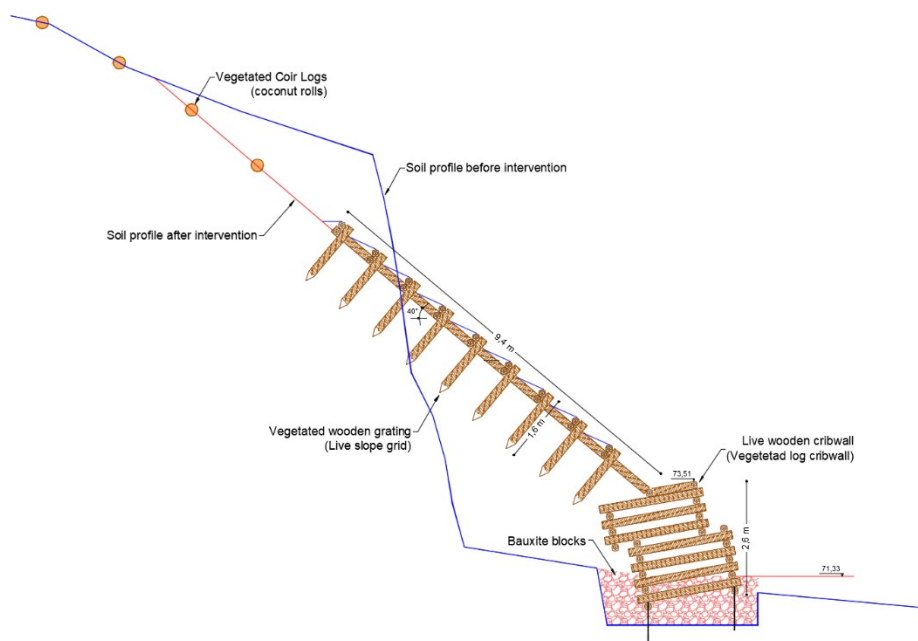
The live wooden cribwall will be used to stabilize the highest and steepest part of the slope located at the head of the gully, in addition to serving as support for the live slope grid. The live wooden cribwall consists of a structure where layers of longitudinal and transverse logs are arranged and fixed alternately, forming a gravitational box-shaped structure. The structure will be executed linearly with a length of 6.2 m at the base, a length of 10.20 m at the top, and a height of 2.60 m (measured vertically), consisting of 2 levels. Firstly, the terrain modeling should be carried out for the implementation of the structure, and excavation on the slopes for the lateral fittings. The structure will be filled with soil, and planting of autochthonous species from the region will be conducted on its face. Figure 5 shows some construction details of the structure.

### 2.3.3 Live Slope Grid

The live slope grid is a widely used technique to support and contain very steep terrains, both on riverbanks and on slopes, to systematize landslides and to requalify gullied slopes. The live grid is a structure consisting of the application of vertical and longitudinal logs anchored by vertical posts fixed between them, forming a grid-shaped structure. Subsequently, the structure must be filled with soil, and in the soil grids, planting of autochthonous species from the region will be carried out. Figure 5 shows some construction details of the structure.

### 2.3.4 Vegetated Coconut Rolls

On the remaining slopes and on top of the live slope grid (Figure 5), vegetated coconut rolls will be used, arranged transversely on the slopes to reduce the slope length and consequently the water velocity and its erosive capacity. The coconut rolls dissipate the kinetic energy of the surface runoff, also acting in retaining soil particles and organic matter transported by the runoff, promoting improved fertility conditions for the establishment and development of vegetation. Transverse barriers composed of coconut rolls with a diameter of 30 cm combined with the application of shrub seedlings will be executed.

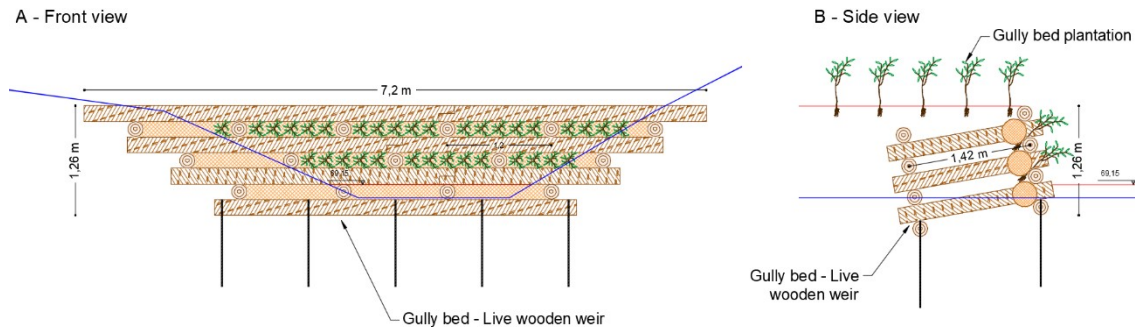


**Figure 5. Cross-sectional profile of the soil Bioengineering interventions. The drawing does not represent the plantings with autochthonous species in the designed structures.**

### 2.3.5 Live Wooden Weir and Gully Bed Plantation

The live wooden weirs will be constructed with a wooden cribwall, using logs arranged in overlapping levels, perpendicular to each other, to form a containment structure for inert material (Figure 6). Two structures will be executed transversely to the direction of water flow at the bottom of the gully. They should be combined with the application of shrub seedlings.

Subsequently, the gully bed plantation will be executed, which consists of planting seedlings in the areas formed between the live cribwall at the head of the gully and the weirs, after the filling and modeling of the soil. The planted area has a total dimension of 152 m<sup>2</sup>.



**Figure 6. Specified interventions for the bottom of the gully.**

Other Soil bioengineering interventions will be carried out complementarily to stabilize and superficially protect the slopes, namely the application of seedling planting and hydroseeding.

In all the described construction solutions, plant species selected from the Study of Native Vegetation for Soil Bioengineering Interventions at MPSA – Amazon Biome [17, 18] and from the list of species produced in the MPSA nursery were used, which will serve as the basis for all soil bioengineering executive projects. Considering the ecological characteristics of the intervention site, the following species should be used: *Allamanda cathartica* L.; *Adenocalymma magnificum* Mart. Ex DC.; *Banara guianensis* Aubl.; *Byrsonima crispera* A. Juss.; *Calliandra surinamensis* Benth. *Davilla kunthii* A. St.Hil.; *Macrolobium microcalyx* Ducke.; *Miconia gratissima* Benth.; *Senna chrysocarpa* (Desv.) Irwin & Barneby; *Senna multijuga* (Rich.) H.S.Irwin & Barneby, *Solanum stramonifolium* Jacq., among others. These species were chosen because they are autochthonous to the region, occurring naturally in preserved areas and are adapted to the edaphoclimatic conditions of the intervention area. Furthermore, they are low to medium in height, suitable for use on steep slopes.

### 3. Results and Discussion

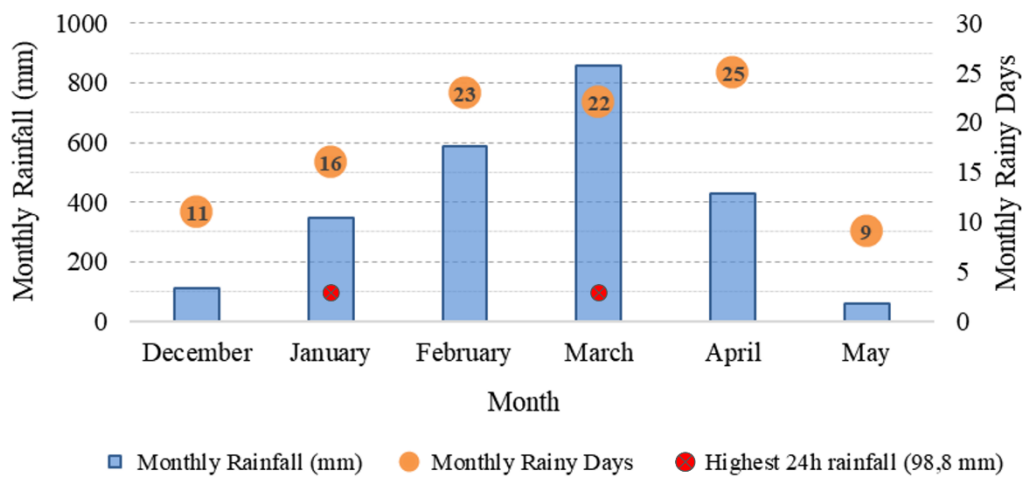
The soil bioengineering work took place between December 2023 and May 2024, lasting approximately 6 months. The work began with the reformation of the terrain, with earthworks carried out using a hydraulic excavator that enabled the cutting of slopes with heights of up to 9.0 m under adequate safety conditions. During the earthworks, cleaning and removal of all vegetative debris, such as fallen trees and logs, were performed at the bottom of the gully (Figure 7 on the right), to enable the proper implementation and execution of the designed soil bioengineering techniques.

The live cribwall was constructed with wooden logs, where rows of longitudinal logs were alternated with rows of transverse logs, forming a box-like structure. Notches and fixations between longitudinal and transverse logs were made with ribbed steel bars. During construction, the structure was filled with soil, which was slightly compacted to allow vegetation growth. The soil bioengineering work was carried out during the Amazonian winter (December to May). In

January, high rainfall totals reached 347.8 mm for the month, notably on January 10<sup>th</sup> (98.8 mm), as shown in Figure 8. Since the work was being conducted in a depression (gully), at the top of the slope, a temporary soil ridge was constructed to divert the water flow from the contributing basin, preventing water from flowing into the gully and the occurrence of erosive processes on the slopes.



**Figure 7. Earthworks (12/08/2023) and slope reshaping (09/01/2024).**



**Figure 8. Monthly precipitation and number of rainy days during the project execution period.**

The high volume of precipitation on January 11<sup>th</sup> (75.9 mm) caused the breach of the temporary ridge, leading to water inflow into the gully and consequently exacerbating the erosive process and transporting material from the slope. Thus, some damage to the work was observed, with the emptying of the cribwall structure which was in the initial phase of implementation (Figure 9).

During the intense precipitation events, the execution of the work was suspended for safety and operational reasons. After the decrease in precipitation, on January 13<sup>th</sup>, 2024, the construction activities were resumed (living support wall). Figure 10 on the left shows some details of the execution activities.



**Figure 9. Exacerbation of the erosive process after high rainfall on 11/01/24.**



**Figure 10. Execution of the activities of the double living support wall live wooden cribwall on 18/01/24 (left) and the live slope grid on 14/03/24 (right).**

After completing the live wooden cribwall, the execution of the live slope grid over the wall and on its left wing began (Figure 10 on the right). Vertical and longitudinal logs were placed, anchored in vertical posts. All logs were fixed together with ribbed steel bars, and then the structure was filled with soil. In the soil quadrants, planting of native species of the region was carried out. Subsequently, the live wooden weirs at the bottom of the gully, the application of vegetated coir rolls on the slopes, and the planting of the gully bed were executed. At the end, hydroseeding was performed throughout the intervention area with native herbaceous species. All soil bioengineering interventions involved planting seedlings of native species from the region, always alternating between species. During the planting, fertilization, and application of hydrogel were carried out. Figure 11 shows the project in the final stage of its execution, before finishing with hydroseeding.

During the project execution period, between 01/12/2023 and 17/05/2024, a total of 169 days elapsed, of which 63 % (106 days) experienced rainfall events. Notably, the days 11/01 and 22/03 recorded the highest daily accumulated precipitation of 98.8 mm. The total accumulated precipitation during the work was 2 389.3 mm. Figure 8 represents the accumulated volumes and number of rainy days monthly during the activities. However, despite the high rainfall events recorded, no soil losses were observed in the intervened areas, neither damage to the Soil bioengineering structures that were under construction. This denotes and confirms the viability of Soil bioengineering structures to mitigate and correct erosive processes, despite them not yet being completed and fully functional (vegetation is still in the initial establishment stage) during the precipitation events. With the development and full establishment of the vegetation over the years, the intervention tends to increase its technical and environmental efficacy.



**Figure 11. General aspect of the soil bioengineering project at the conclusion phase on 03/05/24 (above) and 15/07/2024 (under).**

#### **4. Conclusions**

Based on the information presented in this case study, where Hydro Bauxite & Alumina implemented more sustainable solutions with lower environmental impact compared to traditional interventions, through soil bioengineering techniques, it was observed that the interventions implemented to date are performing the technical functions for which they were designed, namely the control of erosive processes and stabilization of slopes and the bottom of the gully.

The applied vegetation shows good survival and field development rates. In the coming months, maintenance tasks necessary to aid the initial development of the vegetation will be carried out. With the development and full establishment of the vegetation, the intervention is expected to increase its technical and environmental efficacy in the coming years. Monitoring of the project with an assessment of the integrity of the structures and the development of the vegetation in the coming years should be conducted to obtain data about the technical and ecological efficacy of the soil bioengineering, as these interventions are innovative in the Amazon Biome.

The soil bioengineering solutions designed are suitable for controlling and mitigating active erosive processes, as they recreate an environment closer to the ecosystem that existed on the site, integrating into the natural landscape. Moreover, by using only natural construction materials that incorporate into the ecosystem, there is no need for decommissioning interventions, which can be considered an advantage for the mining sector.

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