The use of geomorphology as the basis of mining closure: a case study of Waste Rock Facility rehabilitation at the Santa Bárbara mine (Perú)

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Abstract

Compañía de Minas Buenaventura is custodian of the Santa Bárbara mine located in the Departament of Huancavelica in Peruvian central highlands. Santa Bárbara is – one of the first gold and silver mines exploited by the Spanish conquistadors upon their arrival in the Americas – In 2021 Compañía de Minas Bubenaventura commissioned Amphos 21 to conduct basic and engineering studies for the design of a closure project. This project is focused on three waste rock dumps and an open pit. A novel geomorphological restoration approach was proposed, unifying these deposits and shifting from a standard regulatory closure framework to one that is more harmonious with the natural environment. The open pit was not part of the geomorphological rehabilitation.

The most outstanding feature of this pioneering and innovative project is the elimination of the need for concrete channels for surface water management. Instead, an organic soil cover layer was designed, with varying thicknesses tailored to the various slopes of the terrain. This solution is complemented by the use of native high Andean species (stipa ichu), which enhance the ecological integration of the site. This approach not only reduces post-closure maintenance costs but also minimizes socio-environmental risks typically associated with traditional infrastructure components. By prioritizing natural solutions, the project demonstrates a commitment to both sustainability and environmental harmony, setting a new benchmark for mining closure practices.

Keywords: Environmental liabilities, innovation, geomorphology, rehabilitation, runoff

Photography 1: *View of typical closure of mining environmental liabilities*

Introduction

The regulations governing mine closure in Peru were established in 2003, followed by the guidelines for the closure of environmental liabilities in 2005. These regulations were accompanied by respective closure guides, which serve as reference documents providing guidelines, suggestions, and minimum directives proposed by the state. These documents are widely used by mining companies and, particularly, by the consulting firms responsible for designing mine closure plans.

However, Peruvian closure legislation tends to be static, emphasizing the development of component engineering over specific, site-specific studies. Specialized consultancies often treat the guidelines and standards as strict compliance requirements, adhering to them to the letter. This approach overlooks numerous variables and natural aspects that are not adequately evaluated or incorporated into rehabilitation and closure designs.

Over the past two decades of activities related to the closure of mining environmental liabilities, the industry has largely operated within the framework of these guidelines and the predefined parameters for the shape and structure of components, such as waste rock facilities (WRFs). Most of these facilities have been remediated according to the following criteria:

- Total or partial removal of rock material.
- Profiling and physical stability of slopes
  - Covering with natural waterproofing material (clays, gravels and topsoil).
  - Waterproofing with geosynthetics and topsoil.

Many of these projects remain under restricted access and continuous surveillance, as none have successfully achieved stable closure conditions that harmonize with the natural environment. Common issues include soil erosion, limited vegetative growth, failures in concrete channels, and the presence of acid rock drainage, among others. These challenges force mining companies to incur permanent maintenance costs for infrastructure and water treatment, undermining the long-term sustainability of the closures process.

In contrast, this project aims to rehabilitate the site by integrating the waste rock facilities (WRFs) with the natural slopes (geo-shapes) of the surrounding environment. This innovative approach involves the implementation of a natural cover composed solely of topsoil and native species, such as Stipa ichu, eliminating the need for concrete channels and other artificial water collection, management, and discharge systems. By prioritizing natural solutions, the project not only reduces maintenance costs but also fosters a more sustainable and ecologically integrated closure, setting a new standard for mining rehabilitation practices.

Background

Santa Bárbara holds a significant place in mining history as one of the first Spanish mines in the Americas, with operations beginning shortly after the arrival of Conquistadors in the 16th century (1532). Over the centuries, Santa Barbara has played a pivotal role in the history of Huancavelica and Peruvian mining, standing out as the only quicksilver (mercury) mine in Peru during the viceroyalty period.

In the 20th century, the mine transitioned into private ownership and was converted into an open-pit copper operation. It operated from 1960 until 1982, when activities ceased. By 1998, the site was officially declared an environmental liability. Due to its historical and cultural significance, the mine was designated as Cultural Heritage of the Nation by the Peruvian Institute of Culture in 2005.

Since 2009, closure works have been underway at the site. In 2021, Amphos 21 was commissioned to design and engineer the geomorphological rehabilitation of two waste rock facilities (WRFs), DSB-02 and DSB-14, covering an area of approximately 20 hectares. This project represents a groundbreaking effort to restore the site in a way that harmonizes it with its natural and historical context, setting a new benchmark for the closure of mining sites.

Design and Engineering

WRF DSB-14, was first "closed" in 2015, under the closure criteria mentioned in the introduction. However, the field works undertaken in 2015 presented the following problems:

- Soil erosion within the reservoir
- Low vegetative growth
- Clogging of concrete channels
- Discharge of water over the existing road
- Sediment entrainment on natural soils
- Permanent maintenance and control costs
- Constant supervision and nonconformities issued by the Peruvian Environmental Evaluation and Control Agency (OEFA).

Buenaventura, the custodian of Santa Bárbara, decided to incorporate this component as part of geomorphological rehabilitation, aiming to propose a comprehensive closure solution. This decision was driven by the recognition that previous design criteria had proven ineffective in achieving long-term stability and environmental integration.

The WRF DSB-02 was divided into two distinct sectors: DSB-02A and DSB-02B (Fig. 1). Sector A corresponded to a waste rock dump located on natural terrain without regular slope control or proper conformation, resulting in an irregular and unstable structure. In contrast, Sector B maintained a well-organized and managed waste rock dump, with a more controlled and stable configuration. This division allowed for a tailored rehabilitation approach, addressing the unique challenges of each sector while ensuring a cohesive and sustainable closure design.

The new design criteria for the geomorphological rehabilitation of these WRFs were as follows:

- Restore the functionality of the hydrological network and the promotion of biodiversity through the recovery of the natural hydrological regime.
- Avoid the use of terraces or banks
- Design a drainage network with hydrological criteria (incorporating maximum storn events and climate change).
- Use the surrounding natural area as a reference
- Generate concave or convex-concave slopes (Fig. 2).
- Avoid the use of anthropic or artificial elements such as pipes, ditches or concrete channels, etc.

In 2021, Amphos 21 conducted a comprehensive geochemical study of the entire Santa Bárbara mine site, including the two waste rock facilities (DSB-02 and DSB-14). The results revealed that the rock material contained in these facilities is not expected to generate acid rock drainage (ARD), results that are consistent with the site, since during more than 40 years of mine abandonment, there was never acid drainage. This condition significantly simplifies the rehabilitation

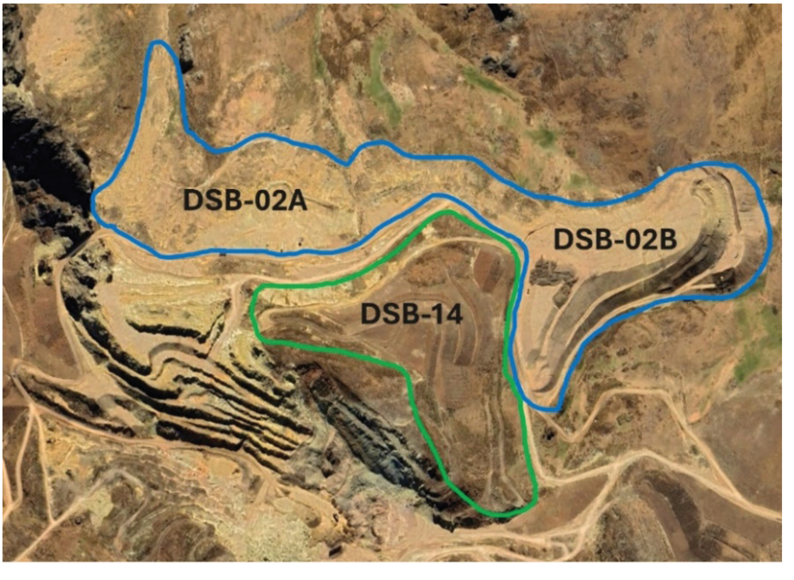


Figure 1: *Design sectors Santa Barbara waste rock facilities DSB-02A and DSB-02B*

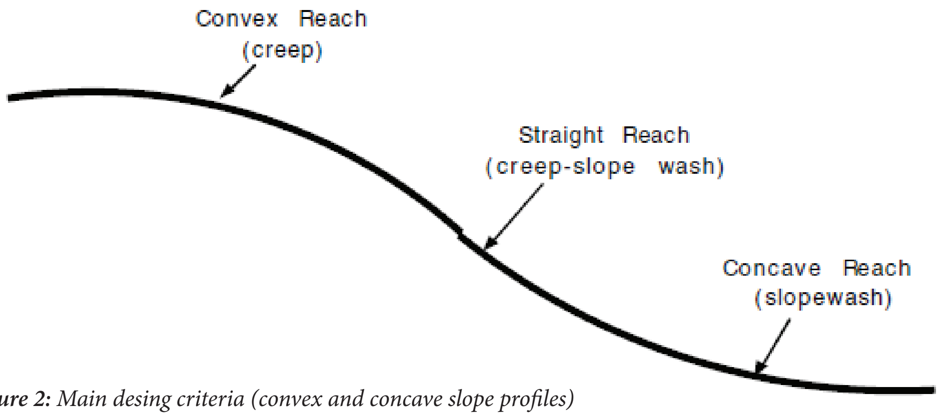


***Figure 2:** Main desing criteria (convex and concave slope profiles)*

challenge, as the focus shifts from designing a complex cover system to restoring the water and landscape functionality of the environment.

However, the tools available in the market for modeling and designing such an alternative are limited, often tied to patents and licenses from specific suppliers. Faced with this constraint, Amphos 21's project management decided to take an innovative approach by conducting the design modeling exclusively using Civil 3D (Autodesk), leveraging the expertise of Peruvian civil engineers. This decision not only demonstrates adaptability but also highlights the commitment to developing locally-driven solutions for sustainable mine closure.

The integration of these waste rock facilities (WRFs) required the removal of the access road that previously divided the two components. This road was identified as a key factor contributing to erosion and sediment drag, exacerbating the environmental challenges at the site. Its removal was a critical step in ensuring the long-term stability and ecological integration of the area.

Between 2023 and 2024, extensive engineering and earthmoving works were carried out under the supervision of Amphos 21. A total of approximately 314,000 m^3 of waste material was moved, balancing cut and fill operations during this period (Table 1). The process resulted in a surplus of 18,700 m^3, which was repurposed as fill material in the open pit of the unit being closed. This approach not only optimized the use of available materials but also contributed to the overall geomorphological restoration of the site.

***Photography 2:** Front view of the WRFs*

Table 1 *Earthwork for geomorphologic conformation (Buenaventura. Dec. 2024).*

Earthwork Activity	Year 2023 m^3	Year 2024 m^3	Total m^3
Cut	43 982.28	122 518.14	166 500.42
Backfill	25 271.61	122 530.95	147 802.56
Total	69 253.89	245 049.09	**314 302.98**

By the end of December 2024, all earthmoving activities, including cutting, filling, and surface shaping, were successfully completed. These tasks were carried out with contracted heavy machinery, such as motor graders, tractors, rollers, excavators, and dump trucks. The remaining task for 2025 involves the final shaping of the topsoil layer and the establishment of native herbaceous vegetation, as illustrated in Photograph 3. This step will mark the culmination of the geomorphological rehabilitation efforts, ensuring the site's seamless integration with the natural environment.

Next steps

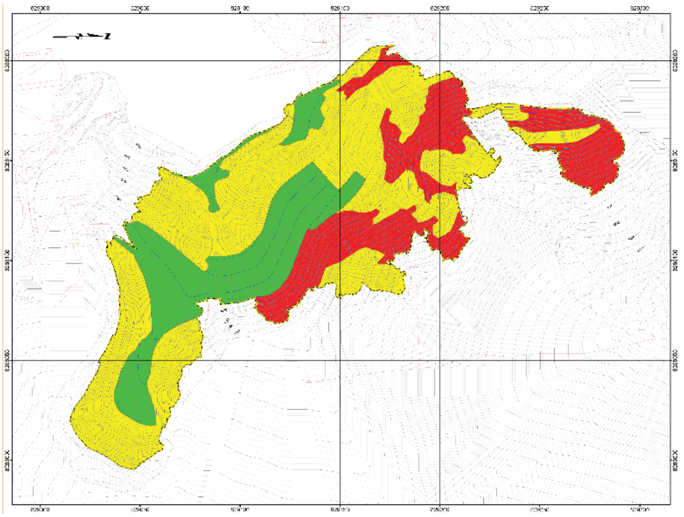
By the end of 2025, the project is expected to be fully completed with the final formation of the topsoil layer and the subsequent revegetation using native species. To ensure the success of this phase, Amphos 21 conducted a comprehensive soil characterization study of the surrounding soils. This study aimed to identify and understand the limiting factors of the soils, particularly considering the challenging environmental conditions of the area, which is located at an altitude of over 4,200 meters above sea level.

The study also had two additional objectives: first, to determine the characteristics and properties of the soils intended for use as cover material, and second, to evaluate the limitations of these soils from both a geochemical and productivity perspective. From a geochemical standpoint, the study assessed the soils ability to control underlying materials, while from a productivity perspective, it focused on their suitability to support vegetation growth. These insights are critical for ensuring that the topsoil layer not only stabilizes the site but also fosters the successful establishment of native vegetation, contributing to the long-term ecological restoration of the area.

To achieve this, 17 nearby points in the Santa Bárbara near area were evaluated. The results of these evaluations provided critical data to establish the final design of the soil cover composition, tailored to the specific requirements of different areas based on both the slopes and elevation of the sites.

According to the final design (Fig. 2), a total of 16,320 m^3 of topsoil will be required to complete the project. The project is

Photography 3: *View of the WRF (DSB-02B and DSB-14)*



Coverage				
Class	Height (m)	Area (m²)	Volume (m³)	Color
Class 1 - 4 S < 25%	0.15	42,450	6,368	
Class 5 S < 25% - 55%	0.70	105,570	7,390	
Class 6 S > 55%	0.20 a 0.50	50,870	2,544	

Figure 2: *Design of the surface to be covered with topsoil*

scheduled to resume in July 2025, with the goal of completing the revegetation process using Stipa ichu by November and December of 2025. This timeline ensures that the vegetation will be well-established before the onset of the rainy season in the area.

Conclusions

Geomorphological rehabilitation represents a groundbreaking and sustainability-focused approach that eliminates the need for traditional concrete structures and water management ponds, which are commonly used in the post-closure control. This innovative method not only reduces long-term maintenance costs but also promotes a more harmonious integration with the natural environment.

The implementation of this project in Peruvian mining marks a significant milestone in the design and closure planning of waste rock facilities (WRFs). After many years of remediation and closure activities in Perú, there has yet to be a fully successful case of WRF closure. This project aims to establish a new standard for sustainable and effective mine closure practices.

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References

El Peruano Official Newspaper (2017) Approval of Environmental Quality Standards (EQS) for Soil

FAO (2009) Guide for the description of soils. Fourth edition. Rome

Ministry of Energy and Mines of Peru (2009) Approved the Closure Plan of Mining Environmental Liabilities of the “Santa Barbara” mining unit.

National Institute of Culture of Peru (2005) Declares the Santa Barbara mine installations a National Cultural Heritage.

Buenaventura Mining Company SAA (2008), Closure Plan for Environmental Mining Liabilities of the former Santa Barbara mining unit.