

# Mine Rehabilitation of Sulphide-rich Ore Deposits Based on Geomorphic Solutions Coupled with AMD Chemical Stabilization: A Pioneering Project at the Lousal Mine, Portugal

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**Abstract.** The rehabilitation of the sulphide-rich Lousal mine in Portugal is the first case in Europe to combine geomorphic methodologies with geochemical solutions. A new rehabilitation topography was designed and built using the GeoFluv method; a chemical buffering blanket made up of mineral and organic soil layers was extended over a highly contaminated, 1.7 hectares pilot drainage basin, associated with open limestone channels and a widespread endemic vegetation cover was established in the intervening area. The project sought to create synergies between the beneficial effects of each of the rehabilitation actions implemented. Early results strongly suggest sustainability of the created ecosystem, which is fundamental to the economic viability of this solution in future mine reclamation projects. The insights obtained provide new knowledge and methodological innovations that can be extremely useful in current and future green mining scenarios.

## 1 Introduction

To comply with modern regulations, mining companies need to design closure plans that account for the rehabilitation of the disturbed land. Conventional approaches in mine rehabilitation such as outslope/berm systems, rectilinear slopes, and drainage ditches, aim to maximize the material storage volume with a minimum footprint, convey water away from the disturbed areas, and attain geotechnical stability for the unconsolidated spoils. However, during the last few decades, studies on mine waste erosion have demonstrated that these conventional rehabilitation practices do not guarantee long-term stability of mine wastes and are not self-sustainable. Without constant maintenance, conventional mine rehabilitation landforms usually end up with severe slope erosion problems that can increase the cost of the total mine operation and become a potential environmental hazard.

A paradigm shift is therefore needed to move away from mine management and rehabilitation techniques which are not capable of sustaining ecosystem functionality of degraded areas towards the adoption of new methodologies and approaches based on ecological and geomorphic principles.

Here we describe the design and construction process of the Lousal mine (Portugal) rehabilitation

project within the LIFE funding program framework of the European Union (LIFE RIBERMINE). The LIFE RIBERMINE project is the first mine rehabilitation project in Europe in which geomorphic rehabilitation solutions have been jointly applied with soil reconstruction techniques and chemical neutralization of Acid Mine Drainage (AMD; Sánchez-Donoso et al. 2024).

## 2 The Lousal Mine

The Lousal polymetallic massive sulphide deposit is located at the NW section of the Iberian Pyrite Belt. The mine operated between 1900 and 1988 for pyrite, to extract sulphur for the fertiliser industry. With the closure of the mine, several social and environmental rehabilitation projects were undertaken. Today the old mine facilities house various initiatives, including a Mining Museum, a Science Centre (Portuguese “Ciência Viva” network), and a visitable underground mining gallery, the Waldemar Gallery, operated by an on-site team at the Science Centre (Relvas et al. 2014; 2015).

The Lousal mine bears the scars left by decades of exploitation with very little environmental management. Most soils on the mine site can be considered as Technosols, composed by mixtures of acid soil with very coarse texture and poor organic matter content, rock fragments, and tailings material (Ferreira da Silva et al. 2005).

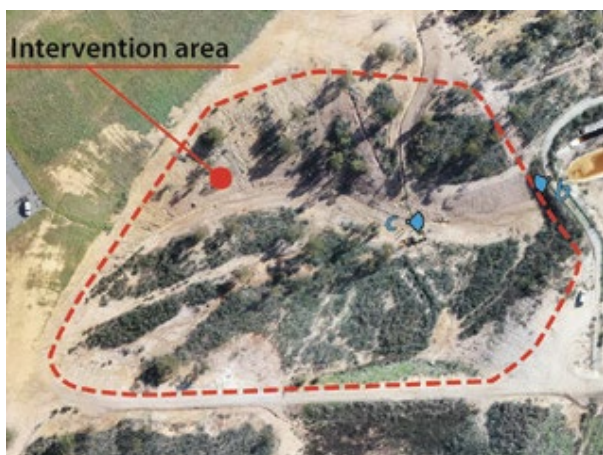


**Figure 1.** General view of some surface facilities, open-pit and tailing deposits at the Lousal mine.

Mining activity at Lousal resulted in a large volume of wastes, ranging from overburden materials to various types of mine waste deposits and tailing impoundments, estimated to be greater than 1 Mt. During the lifetime of the mine, the waste deposits were left exposed to weathering, and no effective environmental measures were taken to reduce tailings erosion and avoid the generation of AMD. As part of the rehabilitation program of the old mine, promoted by the mining company and the town council (Grândola Municipality), a system of artificial wetlands and open limestone channels was constructed in the north-eastern area of the mining complex to reduce potentially toxic element (PTE) content and increase the pH of surficial waters that drained into the nearby stream. Additionally, a geotextile fabric was extended over a heavily contaminated section and covered with a soil layer, to encapsulate the wastes and reduce the impacts of weathering. However, a lack of maintenance of these rehabilitation solutions over the years led to their deterioration. The Contaminant Factor (CF) and Pollution Load Index (PLI) for PTEs (Pb, Cd, As, Zn and Cu) in the soil range from considerable to very high contamination, whereas surficial water samples collected from the wetland treatment system and mine ponds yield low pH values and high conductivity values (Ferreira da Silva et al. 2005, 2006, 2009).

### 3 The LIFE RIBERMINE Project

To try to understand how best to tackle the problems of AMD generation and erosion at the Lousal mine, the LIFE RIBERMINE rehabilitation project was implemented in the mining area in 2019. The project aimed to restore the aquatic habitats located downstream of the mining areas through a holistic approach that combines a) topographic regrading through geomorphological rehabilitation solutions; b) design and construction of a soil amendment to help neutralize lateral subsurface water flows and AMD; and c) revegetation of the reclaimed soils.



**Figure 2.** Aerial view of the intervention area of the LIFE RIBERMINE project before the rehabilitation actions.

A single drainage basin, approximately 1.7 hectares in size was set up as a pilot area to test the combination of a geomorphological remodelling intervention, with the treatment of acid water run-off by chemical neutralization, and edaphic cover using native species. The project area corresponds to a terrain heavily contaminated by fine grained pyrite downstream from the old railway station where crushed ore was shipped for many decades to a sulphur factory in Setúbal. The project aimed to neutralize the acidic run-off into the retention basin that precedes the previously installed phytoremediation treatment (Sánchez-Donoso et al. 2024).

A pioneering method - GeoFluv-Natural Regrade- was used to geomorphically design the new topography of the intervention area. GeoFluv is a fluvial-geomorphic method for land rehabilitation to help the user design landforms like those that would naturally form by fluvial and hillslope geomorphic processes under the climatic and physiographic conditions at the mine site. Suitable and stable reference areas were identified to provide design input values for the rehabilitation design. Natural Regrade software aids the user to make and evaluate GeoFluv designs in a Computer Aided Design (CAD) format. The GeoFluv-Natural Regrade method allows designing landforms that will function as mature and “natural” ones. The most suitable designs are those that meet the wastes material volume (zero-mass balance), operation conditions and specific characteristics and constraints of the rehabilitation project, while fulfilling the condition to stabilize erosion. Essentially, the method compresses time by creating steady-state landscapes with approximate balances among erosive forces and resistances. Mining areas reclaimed using a geomorphological rehabilitation approach not only provide long-term stability, but also maximize the recovery of local biodiversity, visually integrate into their surroundings, and achieve a high level of acceptance by the population and administrations (Martín-Duque et al. 2015, 2020).

Chemical remediation solutions were integrated and combined with the geomorphic-based rehabilitation activities, to reduce the impact of AMD generation and PTE mobilization (Sánchez-Donoso et al. 2021). LIFE RIBERMINE did not use structural layers (geotextiles) as a remediation solution. The solutions implemented in Lousal have been designed and implemented to show that there are more efficient alternatives to tackle the AMD than the geotextiles. Therefore, we used mineral and organic soil layers to address the AMD.



**Figure 3.** New geomorphic design of the intervention area, already with its two-layer soil cover, combined with three open limestone channels that direct flow through the area.

A soil cover was designed to be applied over the new topography. A first layer, 10 to 15 cm thick, consisted of a mixture of clay and lime gravel to neutralise water infiltration, facilitate groundwater circulation, and help retain water for plant growth. A top layer of around 10 cm of fertile soil mixed with animal manure was placed on top of this to favour plant growth. The construction of a soil cover helped to develop a suitable soil substrate for the revegetation of endemic plants and shrub species. This soil cover was combined with the construction of open limestone channels, which consist of three constructed channels that direct the flow through the area. Open limestone channels are economical ways of treating AMD by promoting the precipitation of dissolved metals, in this case mainly Fe and Al oxides and hydroxides. Open limestone channels were chosen over other alternative options for surface AMD neutralisation methodologies due to their adaptation to the geomorphic design approach.

Endemic plants with a wide ecological range, capable of surviving in different environmental and substrate conditions, were chosen to ensure the establishment of a widespread vegetation cover in the intervention area. Several species of native leguminous, herbaceous and grass species were selected, and a 'freehand' sowing technique was used to spread the seeds.



**Figure 4.** Detail of the widespread vegetation cover in the intervention area (native leguminous, herbaceous and grass species).



**Figure 5.** Aerial view of the intervention area of the LIFE RIBERMINE project after geomorphic remodelling, edaphic cover, and endemic re-vegetation.

To assess the evolution of the water quality and riparian ecosystems near the reclaimed area, two piezometers were installed in the lower part of the intervention area. The depth of the permeable sections was selected based in the groundwater level determined on a preliminary geophysical study (Sánchez-Donoso et al. 2022; 2024)

#### 4 First results and discussion

The distribution of surface runoff in small sub-basins, and the scalloped landscape composed of ridges and swales, reduces the erosive potential of surface runoff, so the edaphic cover remains mostly unaffected by erosion processes. The effects of the integrated physical and chemical rehabilitation actions have already started to become visible. Within the intervention area, the water lines established as part of the geomorphological remodelling are functioning perfectly and there is no sign of erosion on the ground despite the heavy rainfall recorded last winters. The limestone neutralization effect of the acidic run-off water is a process that will take some time to be demonstrable by chemical monitoring. However, the signs of metal retention are already obvious in the reddish colour of the limestones that occupy the bed of the water lines.



**Figure 6.** Evidence of metal retention: the limestones that occupy the bed of the water lines already changed from their typical white colour (left) to reddish (right)

Additionally, just a few months after the intervention, the infamous 'red lagoon', located at the drainage point of the intervened area and which receives the corresponding contaminated water

from the acid mining drainage, has gone from a red colour to a turquoise blue comparable to nearby freshwater lagoons.



**Figure 7.** The 'red lagoon', located at the drainage point of the intervention area, which receives the water contaminated by AMD, has changed from its red colour (left) to a turquoise blue comparable to the fresh water nearby (right).

The intervened area has already had three complete flowering cycles, between 2022 and 2024. The exuberant increase in animal biodiversity is also a notable result of the project. Some monitoring studies have already begun in the post-LIFE period (5 years). Despite the very heavy rains of the last two winters, the area has not been eroded and the natural cycle of the primary-colonising plants has repeated, intensified and self-progressed.



**Figure 8.** Lush flowering season in the LIFE RIBERMINE mine reclamation area.

The LIFE RIBERMINE project is a pilot project and ongoing research. The project does not aim to provide closed, universal, and guaranteed answers. However, the results already obtained strongly indicate the sustainability of the ecosystem created, requiring very little maintenance. In fact, this is the key to the economic viability of this solution in future green mining or mine reclamation scenarios, showing that it is possible to reconcile mining activity with the return of land to nature with the least possible impact, making environmental sustainability an intrinsic value of mining activities. The operation also provides a showcase for society, mining companies and political decision-makers.

## Acknowledgements

Thanks are due to the LIFE RIBERMINE research team for fruitful discussions and inspiring ideas and contributions. We acknowledge the on-site team at *Centro Ciência Viva do Lousal* for unbeatable

support and hard work during the preparation and execution of the project.

The study was funded by the European Union's LIFE programme (LIFE18 EN/ES/000181), and the Portuguese *Fundação para a Ciência e Tecnologia* (FCT), *I.P./MCTES* through national funds (PIDDAC): UID/50019/2025 and LA/P/0068/2020 (<https://doi.org/10.54499/LA/P/0068/2020>). Ramón Sánchez Donoso was funded through a Postdoc grant by the Education and Research Department of Madrid Autonomous Region Government (REMEDINAL TE; S2018/EMT-4338).

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