Mine Closure 2022 - M Tibbett, AB Fourie & G Boggs (eds)
© 2022 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-4-1
doi:10.36487/ACG_repo/2215_90

Implementing phytostabilisation for tailings deposits remediation: project design and feedback from case studies in France

L de Lary de Latour *BRGM, France*

V Guérin *BRGM, France*

G Gatellier *BRGM, France*

C Piat *BRGM, France*

Abstract

Due to economic and environmental reasons, French mines closed down in the 19th and 20th centuries. In 2012, a legacy of more than 2000 metallic mine waste deposits was identified in the framework of an inventory resulting from the European Directive on the management of wastes from extractive industries. The dispersion of solid particles, especially tailings due to their fine grain size, can contribute risks to the environment and specifically to surface water through transport and leaching. Waste deposits with bare surfaces can result in significant transfers of sediments through hydraulic erosion. In this context, phytostabilisation strategies are valuable remediation options to mitigate the risk of transfer. However, only a few full-scale phytostabilisation implementations have yet been completed in France.

This paper deals with the deployment of phytostabilisation to remediate legacy tailings deposits in the French context, focusing on operational aspects and feedback from several case studies (former Ag-Pb mines from Massif Central and Sn and Au mines from the Pays-de-la-Loire region). Phytostabilisation relies on the use of plants and amendments to reduce mobility of pollutants in soil and transfers trough environment. In the French context, the aim is to reduce, to an acceptable level, transfers from waste deposits to the surrounding environment, particularly due to surface erosion and, to a lesser extent, leaching.

Conventional approaches to confining mining waste are mainly based on water management, landform design and covering the soil with subsequent revegetation. With this approach, plants are used to stabilise the soil layer that has been deposited above the tailings. Thus, plants do not directly stabilise mine tailings, as is the case with phytostabilisation strategies. From case studies, we show that evaluating the benefits of phytostabilisation requires using appropriate new criteria for the cost-benefits analysis in order to capture the ecosystem services that control the stabilisation process (ecosystem services such as soil creation, water regulation, erosion reduction). Costs are expected to be lower because it tends to minimise intervention. Furthermore, long-term perspectives, technology readiness, constraints due to access and site immobilisation, costs of remediation and maintenance and social perception are key criteria that also require appropriate evaluation.

As biological organisms, plants have inherently variable responses that must be considered in project management. Thus, based on case studies, strategies have been developed to tackle uncertainties by implementing laboratory and pilot tests. A phytostabilisation project needs a sound understanding of site functionality that can be synthetised on a conceptual site model. Based on a case study, we show that design at a detailed scale can optimise phytostabilisation solutions. Evaluation of pollutant fluxes enables prioritisation of actions on zones with critical transfers. Identification of stable (no transfers) zones due to spontaneous vegetation minimises intervention, costs and ecological impact. To complement phytostabilisation, other solutions are necessary to reduce erosion on critical zones or adapt the technology to site constraints (e.g. soil cover, fascines, areas for rainwater infiltration).

Perspectives for long-term site evolution are then discussed in terms of the solutions implemented (conventional or phytostabilisation). Return of experience still needs to be gathered in the years to come in order to improve management by phytostabilisation.

Keywords: *phytostabilisation, tailings, mine waste, erosion, ecosystem services.*

1 Introduction

After centuries of production, many French mines closed down in the 19th and 20th century, due to economic and environmental reasons. In 2012, a legacy of more than two thousand metallic mine waste deposits was identified as part of an inventory resulting from the European Directive on the management of waste from extractive industries (European Union 2006; GEODERIS 2012). Waste rock and tailings deposits often contain significant concentration of metals (Pb, Zn, Cd, Sn, W, etc.) or metalloids (As, Sb) mainly from natural mineral origin. Due to mining and ore processing, metal(loid)s have been brought into contact with climatic agents (rain and oxygen). Furthermore, the reduced grain size of tailings has increased the mobility of these metal(loid)s in the environment. The dispersion of solid particles induces risks for environment and specifically for surface water through transport and leaching.

A significant number of former mining sites were abandoned with no or only limited measures to contain wastes due to operator bankruptcy or lack of environmental standards at that time. As a result, some tailing deposits still have bare surfaces shaped by intense erosion (Figure 1). Additionally, numerous legacy mining sites are located in mountainous or semi-mountainous relief zones with steep slopes and abundant rainfall, which further increases erosion. Furthermore, the oldest deposits were often located close to streams in order to use hydraulic power. Given their locations, former mining deposits could still generate significant sediment and associated metal(loid)s transfers to the environment by hydraulic erosion.

Figure 1 Example of highly eroded tailing deposit in a semi-mountainous region (case study 1, France)

After a prioritisation step based on risks to human health and environment, several legacy deposits are currently being rehabilitated by the French state. Conventional approaches used so far are based on mining waste confinement with water management, appropriate landform design and covering with soil with subsequent revegetation (Barthe et al. 2018). Observation of former deposits in France shows that vegetation can develop spontaneously on mining waste and gradually lead to the formation of a fertile soil providing ecosystem services (plant support, water regulation, biodiversity support, etc.) and limiting sediment transfer. However, this natural process can take decades or even centuries and is too slow to be used as a management option and solutions are required to accelerate this process. Thus, phytostabilisation appears as a valuable option to speed up post-mining rehabilitation. In addition, this solution could lead to significant savings in a project because it is designed to minimise intervention. Phytostabilisation relies on using plants and mineral or biological amendments to reduce the mobility and transfer of pollutants in the environment. However, only a few full-scale phytostabilisation implementations have yet been achieved in France (for example in the Salsigne district; Hasselt et al. (2006)) and several challenges associated with phytostabilisation need to be addressed. In this context, this paper deals with the deployment of phytostabilisation to remediate legacy tailings deposits in the French context, focusing on singularities of implementation of phytostabilisation and on operational aspects a project owner needs to manage. It is mainly based on two French case studies.

2 Approaches for phytostabilisation in mining context

2.1 Phytostabilisation as a tailings management solution

Several mechanisms enable phytostabilisation (Nandillon 2019; Mertz 2021). Depending on the objective of the project, one or several mechanisms could be used (ITRC 2009), as indicated in Figure 2:

- Mechanical stabilisation of substrate against transport by wind and/or water through roots, interception by canopy.
- Chemical and biological sequestration by amendments and/or by root zone.
- Reduction of water inflow in soil due to plant transpiration and subsequent reduction of leaching.

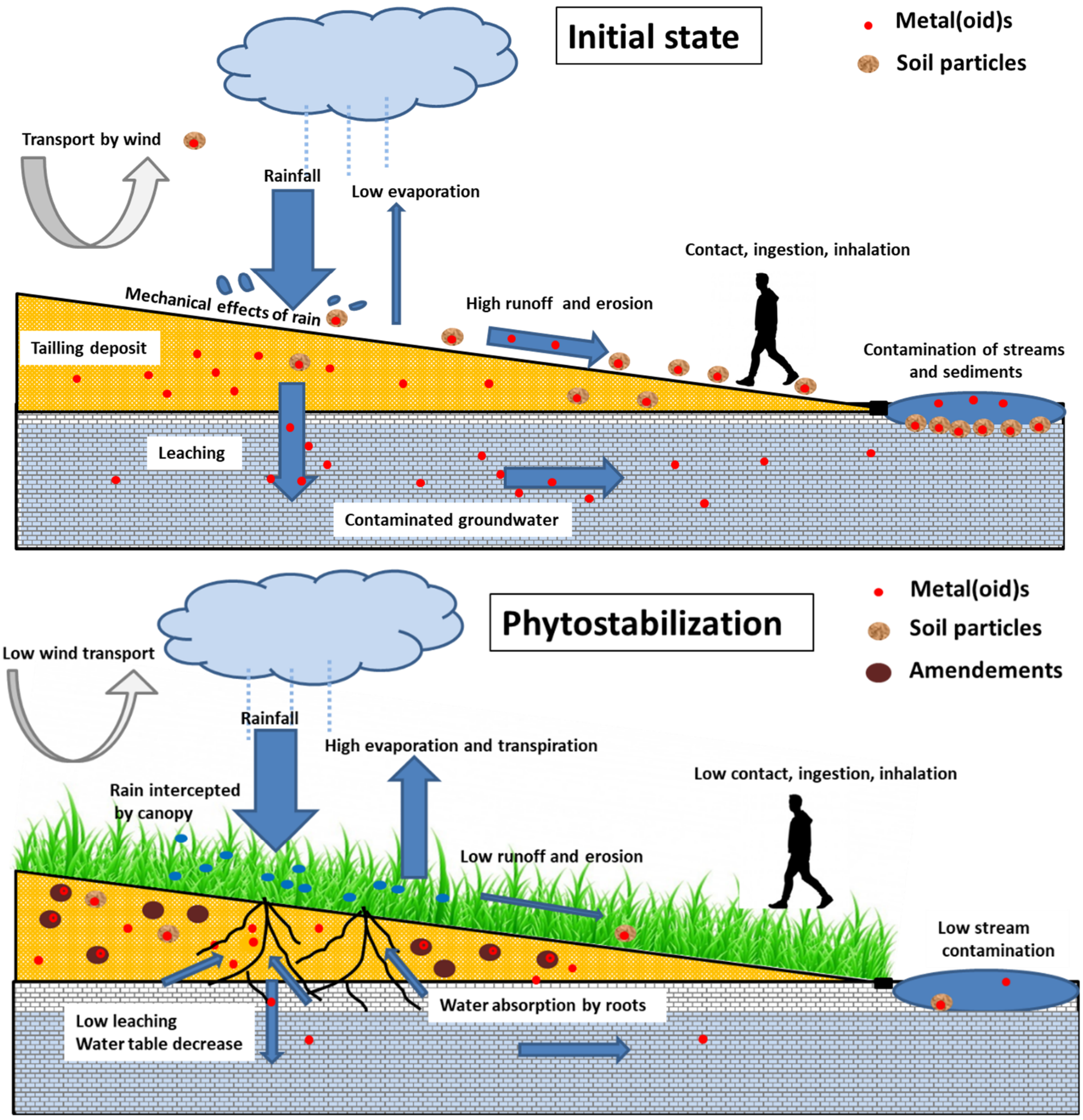

Figure 2 Conceptual models for tailings management by phytostabilisation

Phytostabilisation does not eliminate the pollution source but aims to decrease transfer of contaminants from the source to potential receptors (e.g. human health, streams, water table, biosphere). Residual transfers to humans and the environment, to biota by the food chain, to water by residual erosion or leaching must be evaluated and maintained at acceptable levels. Many criteria must be considered when choosing suitable plants (Larcheveque et al. 2014). These include development of the root system, transfer of metals to the aerial parts of plants, resistance to pollutants, adaptation to climate and soil, seed costs, etc. Finding a plant that meets all these criteria is sometimes a real challenge (Sheoran et al. 2013).

2.2 Conventional versus phytostabilisation approaches

Conventional approaches for rehabilitation used to date in France (example in the Pontgibaud District; Bellenfant et al. (2013)) are based on mining waste confinement. Typically, this relies on water management, landform design and covering with a minimum 30 cm thick soil with subsequent revegetation with local species (Barthe et al. 2018). Under this approach, 3D geosynthetics are set up in steeply sloping areas in order to ensure appropriate cohesion between tailings and topsoil. Impermeable cover (membrane) is not necessary when the objective is only to reduce erosion and human contact with tailings. On average, more than half of the total rehabilitation costs are dedicated to the earthwork (to obtain appropriate shape and creation of access) and set up the topsoil. Thus, it is on these budget lines that the potential for costs reduction is the most important.

With phytostabilisation solutions, the objective is to minimise interventions in order to reduce costs, ecosystem disturbance and footprint of project. Thus, earthwork is focused only on zones where the stability of the tailing deposit is too low, while taking into consideration the spontaneous vegetation onsite.

Amendments can be set up in two different ways (Figure 3):

- Creation of an amendment layer upon the tailings. This situation reproduces the first organic layer of a natural soil. It might be more appropriate in case of high phytotoxicity of tailings and/or to ensure a minimum coverage of tailings. In this case, the amendments can be set up in places that are difficult to access by simple projection or depositing. Nevertheless, roots often develop mainly in the first layer, which can lead to less cohesion with tailings and higher risks of hydric stress.
- Mixing amendments with tailings. In this situation, plants must be able to start growing directly in contact with tailings with a limited proportion of amendments (e.g. 5% compost by mass on the 20 upper cm of substrate). Appropriate agricultural tools are needed to mix soil and reduce heterogeneities. This can lead to risks of reducing the cohesion of the substrate surface and promoting erosion. The depths explored by the roots can be greater with this solution.

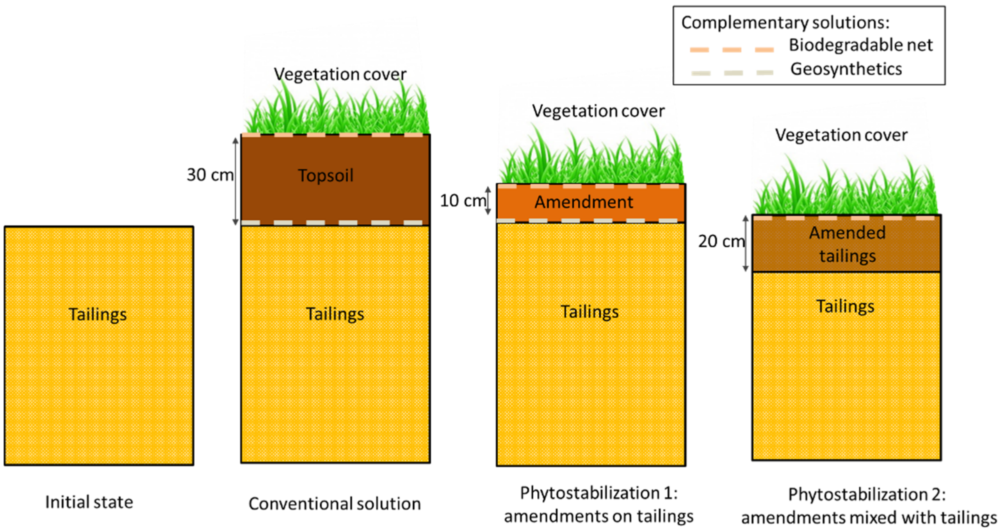

Figure 3 Conventional and phytostabilisation solutions used for tailing rehabilitation. Thickness of layers is indicative

Whatever the phytostabilisation solution, the amendment only partially corrects the soil properties and plants must be adapted to tailings. This is the main difference with confinement solution where the plants do not need to be adapted to the confined material. Thus, sound plant selection and soil engineering should be implemented.

2.3 Dealing with agronomical properties of tailings

Quality of soil is one of the most crucial parameters for successful plant development, especially in a long-term perspective (Sheoran et al. 2013). Consideration of the agronomic quality of mining tailings is an essential prerequisite for starting any reflection on phytostabilisation.

For French former mine tailings that need rehabilitation, the following main aspects are generally observed (based on a large number of soil analyses):

- Texture is mainly sandy or sandy/loamy and could be appropriate for the growth of some plants. Water retention is often low in sandy tailings because it is directly linked to loam and clay proportions. Texture cannot be changed easily because it is directly related to grain size.
- Structure of soil, defined as the way particles are assembled, do not evolve significantly against time in mining tailings leading to a decrease in porosity, permeability and aeration. This phenomenon could lead to water stagnation and anoxic conditions.
- pH influences the uptake of soil nutrients and mobility of phytotoxic elements. Many French ore deposits contain sulphide minerals and have the potential to generate acid. Thus, pH can be as low as 2 or 3 pH units which is far from optimum range for plant growth between 6 to 7 (Piramid 2003).
- Soil organic matter is at the origin of soil life and most soil functions; however, it is close to zero in non-vegetated tailings. Thus, soil organisms are nearly absent.
- Trace element (Fe, Cu, Zn, etc.) and mineral (N, P, K, Mg, Ca) concentrations are usually very variable depending on the mine and processing.
- The exchange capacity of nutrients is low due to high sand content and low organic matter.

Due to these characteristics, many French tailings are typically unsuitable for plant growth. Thus, it appears necessary to improve significantly the agronomic properties of tailings in order to support a dense and perennial vegetation cover. Although it may always seem possible to implement a phytostabilisation solution, in some cases the corrections required are too substantial to be economically viable. A simple agronomic analysis can give an order of magnitude indication of the difficulty of implementing a phytostabilisation solution and enable identification of organic and/or mineral amendments to correct soil properties in a specific setting.

3 Phytostabilisation project design

3.1 Introduction to case study 1

Case study 1 is a former Ag-Pb mine from the Massif Central in central France that closed down at the beginning of the 20th century (Courtin-Nomade et al. 2016). The associated legacy is a waste rock and tailing deposit of about 3 ha with several weight percent Pb and about 100 mg/kg As. High slopes (average ca. 40%) and abundant rainfall (more than 1000 mm/y) lead to intense erosion and sediment/tailings transport to a nearby stream. About half of the deposit is already partially or totally covered by spontaneous vegetation but the other part has remained bare since mine closure (Figure 1). Due to several protected species of bats and sensitive habitats, the site is part of the European Natura 2000 network which requires special environmental protection.

3.2 Fine scale site characterisation

A phytostabilisation project needs a sound understanding of site functioning. For case study 1, beyond characterisation of the source of pollution, stream (water and sediment), porewater, erosion and spontaneous vegetation were monitored for 18 months to build a conceptual site model and evaluate fluxes. The erosion rate was estimated using more than a hundred wooden pegs to measure variation of elevation interpreted as substrate loss or deposit. This rather imprecise method was considered appropriate due to the intensity of erosion rates. We measured non-significant substrate movements in vegetated areas, whereas in non-vegetated areas soil movements could reach several centimetres or even decimetres per year (Figure 4). Based on a global mass balance, transfers of Pb and As by erosion (sediment transfer) were several orders of magnitude greater than transfers to groundwater through tailings. Thus, remediation prioritisation among site areas were based on erosion flux. A totally bare tailings zone (Figure 1), representing less than 25% of the area of the site was responsible for about two thirds of the transfer of metal(oid)s away from the source area.

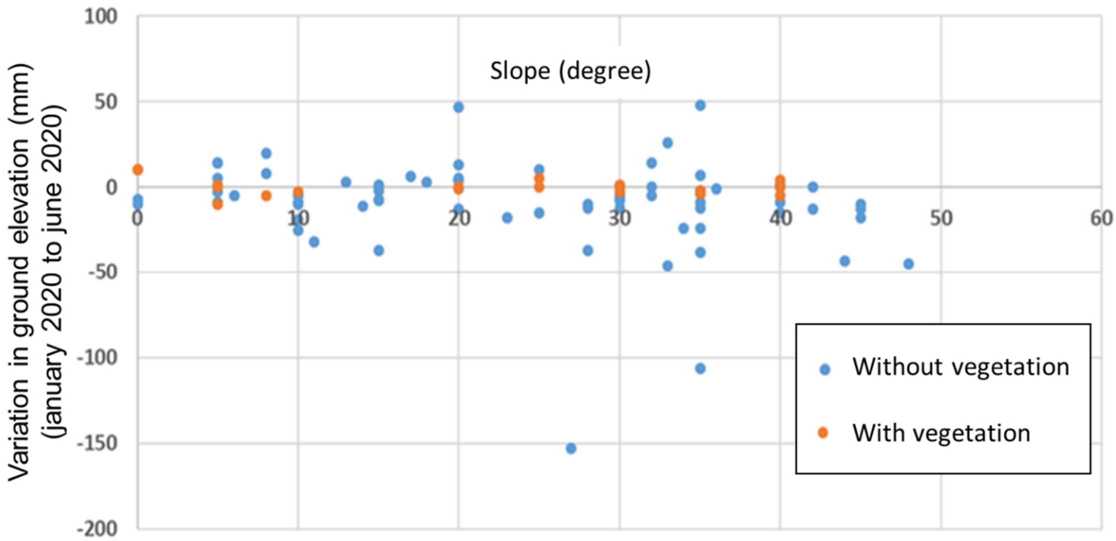

Figure 4 Variation in ground elevation on mine tailings deposits (case study 1 for a six months period). Influence of vegetation

3.3 Cost-benefit analysis of phytostabilisation

A cost-benefit analysis was performed on case study 1 to rank scenarios and enable decision-making. Following French methodology for managing contaminated lands (Ministry in Charge of Environment 2017), five categories of criteria were used (technical aspects, costs of rehabilitation and maintenance, environment and security, social and juridical aspects).

In terms of technical criteria, the technology readiness of phytostabilisation is lower than conventional solution (confinement) due to limited operational feedback (i.e. the small number of sites remediated with this technology in France as well as the limited time for feedback). Performance of pollutant immobilisation is also expected to be better for confinement, thus this solution could be more appropriate for zones with high risks transfers.

Costs of remediation using phytostabilisation are expected to be lower due to minimalistic intervention. Transports costs and environmental impacts could be considerably reduced with a phytostabilisation solution. As an example, a solution with 5% of compost-type amendments requires only about 15 kg of compost per square metre (solution with 5% of compost by mass mixed with the 20 first centimetres of tailings; bulk density of soil 1.3 tons/m^3) On the other hand, adding 30 cm of soil above the mine tailings (traditional solution) requires adding about 400 kg of soil per square metre. The mass factor between the two solutions is therefore greater than an order of magnitude. These figures are given for illustrative purposes only and correspond to a specific case study. The sizing of the phytostabilisation solution (type of amendment, content, method of incorporation, plant choice, etc.) must be carried out on a case-by-case basis and validated onsite (these aspects are more detailed for case study 2). Thus, phytostabilisation may be an appropriate solution for poorly accessible zones where amendments can only be placed by small machinery or by hand. However, the costs of maintenance may be higher because this technology is more sensitive to hazards (extreme climatic events, destruction by pests, etc.), and needs more follow-up monitoring.

Phytostabilisation could be considered as more sustainable as the site should evolve to a new natural equilibrium. Environmental impact of engineering work for phytostabilisation could be substantially lower than for conventional solutions mainly because it is possible to put in place most of the habitats and because transport and earthworks are reduced. This results in simpler administrative procedures. Environmental benefits expected from phytostabilisation rely on ecosystem services (especially water regulation, soil creation) that enable the stabilisation process. To include these benefits in cost-benefit analysis we used the following new criteria: soil creation and water regulation.

Social perception of phytostabilisation is often positive due to the eco-friendly dimension. Nevertheless, it could be perceived as not enough intensive or technologically based.

We used these criteria to compare conventional solutions and phytostabilisation on case study 1. We found that the conventional confinement scenario had a better cost-benefit ratio for the zone with the highest transfers (representing less than 25% of the surface of the site, see Section 3.2) because of better confinement performance and because significant earthworks were deemed necessary to stabilise this zone. Alternatively, others zones with patchy vegetation, rather low erosion rates, difficult access and sensitive habitats had a much better cost-benefit ratio with a phytostabilisation scenario. Conclusively, the fine scale identification of zones though sound characterisation and the mixing of conventional solution and phytostabilisation lead globally to a better project. In parallel, tests were performed to validate the solution (results not shown for case study 1, but the method was the same as for case study 2).

4 Implementing phytostabilisation

4.1 Managing variability of response

As biological organisms, plants have inherently variable responses that must be considered in project management. Thus, we used the following strategies to tackle variability:

- Laboratory tests were performed to compare a wide range of plants, amendments and microorganisms with limited costs as well as to evaluate pollutant mobility and bioavailability for plants. These tests are commonly implemented without limiting factors in order to minimise the number or variable elements and assess only the variability of response due to pollution and amendments.
- In situ pilot tests and their follow-up, based on optimised formulations identified though laboratory tests, were used for evaluation of onsite variability of response and key features for successful operations. Based on feedback from several sites (among them case study 1 and 2) it appeared that the availability of water is a crucial parameter to be managed. As water retention could be weak for sandy tailings, hydric stress could be highly prejudicial especially for young plants. Figure 5 (site close to case study 2) shows that for the same site and plants, the dry biomass is three times greater in a humid area than in a relatively dry area. At this site, the plants that develop preferentially are significantly different depending on the humidity of the soil.
- Appropriate contracting had been set up to minimise project risks. Indeed, acceptance of work should be delayed enough after seeding in order to be able to assess the durability of the vegetal cover (e.g. 6 to 12 months). A guarantee for an appropriate period (e.g. one to several years), during which maintenance of the vegetal cover is performed by the work company, can be contracted by the project owner to minimise risks. A plant cover is much more sensitive to hazards during the first few years.

(a)

(b)

Figure 5 Examples of pilot tests of phytostabilisation on tailings contaminated by arsenic (June 2021): (a) Near the top of the deposit on a zone with risks of hydric stress; (b) In a low-lying area near a wetland (right)

4.2 Operational aspect of rehabilitation

4.2.1 Presentation of case study 2

Case study 2 is a former Au mine situated in the Pays-de-Loire region in the west of France. A deposit of about 150,000 tons of sandy tailings contaminated by As (to several thousands of mg/kg) is situated near a small creek. Before rehabilitation, about 1 ha was almost completely devoid of vegetation. Intense erosion had caused the silting up of mine water treatment ponds and subsequent decrease of treatment performance as well as gradual erosion of embankments maintaining hydraulic structures.

4.2.2 Diagnosis of causes

The approach adopted by the BRGM was to target site phytostabilisation operations as much as possible. Thus, no total rehabilitation was planned for budgetary reasons and to preserve the areas already stabilised by vegetation. A detailed understanding of the site, based on a naturalist-type diagnosis (observation, measures and analysis), was therefore necessary (Figure 6). At this site, mine tailings were very sensitive to erosion, because:

1. They were mobilised during the creation of treatment ponds (they lost their compactness).
2. They have no structure and therefore cannot ensure the functions of water regulation.
3. The vegetation growth is too low to avoid erosion.
4. The slope of embankments is steep (to 1H/1V).
5. There is no management of rainfall runoff.

Figure 6 Intensive erosion of tailings in case study 2

4.2.3 Design of solutions

A botanical inventory was carried out to identify the plants adapted to the site. Laboratory tests on tailings amended with 5% compost and seeded with endemic species showed growth of the same order of magnitude as a control with non-polluted topsoil. Nevertheless, tests carried out onsite (not shown) concluded that it was highly sensitive to drought. To limit the risks, we decided to use an amendment a 10 cm layer of soil of good agronomic quality (with organic matter content of 3%). The footprint of the area to be treated was defined onsite at a fine scale: areas naturally stabilised by spontaneous vegetation were identified in order to be preserved (Figure 7). That design at detailed scale optimises phytostabilisation solutions. In the end, only a quarter of the bare area was treated, which minimised intervention, costs and ecological impact. For the remaining bare area, no significant erosion is noticed one year after rehabilitation.

(a)

(b)

Figure 7 Embankments near treatment ponds: (a) Before rehabilitation with high erosion; (b) After phytostabilisation

As vegetation cover strongly reduces runoff, rainwater management infrastructures were reduced to a single ditch upstream of the most eroded zone. To complement phytostabilisation, other solutions were necessary to reduce erosion on critical areas or to adapt the technology to site constraints:

1. Soil cover (coco geotextile) was used to stabilise topsoil and reduce water evaporation.
2. Brushwood fascines and silt fences were set up to reinforce erosion protections near ditches and ponds (Figure 8).
3. Infiltration ponds were created to reduce runoff. These additional measures have a limited lifespan.

They are designed to have mainly transient effects while waiting for the plant cover to stabilise the site in a sustainable way.

(a) (b)

Figure 8 Examples of anti-erosion solutions around upstream rainwater ditches in case study 2: (a) Just after seeding; (b) One year after seeding

4.2.4 Implementation and operational feedback

Works began in November 2020 for a period of four months. The treated areas were defined on the ground on a case-by-case basis for each linear metre in order to leave as much existing vegetation as possible while minimising the slopes. The company selected for work, had difficulty at first working on such a fine scale. During the works phase, it was repeatedly asked to modify the earthwork to optimise it. Overall, the slope has been reduced beyond plans near the treatment pond (maximum slope about 1V/3H), which is an additional guarantee of stability. Nevertheless, the amount of material to be moved was consequently higher than initially forecast.

The implementation of the various devices to tackle erosion (fascines, geonets, coconut tubes, anti-sediment nets) also required tailoring and adapting to the site configurations to maximise the efficiency. This approach requires a strong presence onsite to validate the layouts and verify the correct implementation during the course of the work. This also increased the duration of the work.

Although sowing in October was initially planned to promote vegetation during the wet season (October to May in this region), due to the late start date of the work, sowing was only carried out at the beginning of April. The development of the vegetation was nevertheless generally satisfactory (Figure 7) probably due to the rather favourable weather during the 2021 summer (quite rainy and without heat wave during the period from June to August). In the following autumn, the objective of 70% plant cover was globally reached. Some limited surface areas (one to a few square metres) were poorly vegetated, however on the whole the area showed good resistance to erosion.

5 Conclusion

After several years of trials and a first rehabilitation using phytostabilisation, we conclude that this technology seems promising for managing deposits of mining residues, in particular in the event of erosion concerns.

Compared to traditional solutions, phytostabilisation advantages lie in the fact that this is a nature-based solution and therefore it has a priori of a low environmental footprint and it may be sustainable. In the medium or long-term, the maintenance of the phytostabilised site should be minimalist: the interest of phytostabilisation is to benefit from natural regeneration capacities so as to limit the need for intervention. However, interventions may be necessary to enable a good growth of vegetation over the long-term and in the event of excessive deterioration.

This solution, although simple in appearance, requires in-depth studies to be adapted to the site and to verify the extent to which it allows the rehabilitation objectives to be achieved with minimal work. Nevertheless, a number of difficulties must be managed, among them: sensitivity to drought, lack of operational feedback, need to carry out tests that can increase rehabilitation times, potential residual transfers to water or living beings through vegetal consumption. Thus this solution was found complementary to traditional confinement.

Even if phytostabilisation is based on natural solutions, it is advisable to set up site monitoring after the works, in particular to monitor the evolution of the plant cover, check the absence of degradation and verify that the residual impacts remain acceptable and improve the solution feedback.

References

Barthe, P, Eder, P, Saveyn, HGM, Orveillon, G & Garbarino E 2018, *European Commission, Joint Research Centre, 2018, Best available techniques (BAT) reference document for the management of waste from extractive industries: in accordance with Directive 2006/21/EC*, European Union, Luxembourg, https://data.europa.eu/doi/10.2760/35297

Bellenfant, G, Guezennec, AG, Bodenan, F, D'Hugues, P & Cassard, D 2013, 'Reprocessing of mining waste: combining environmental management and metal recovery?', in M Tibbett, AB Fourie & C Digby (eds), Mine Closure 2013: Proceedings of the Eighth International Seminar on Mine Closure, Australian Centre for Geomechanics, Cornwall, pp. 571-582, https://doi.org/10.36487/ACG_rep/1352_48_Bellenfant

Courtin-Nomade, A, Waltzing, T & Evrard, C 2016, 'Arsenic and lead mobility: from tailing materials to the aqueous compartment', *Applied Geochemistry,* no. 64, pp. 10–21.

European Union 2006, *Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC*, *Statement by the European Parliament, the Council and the Commission*, Luxembourg, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32006L0021

GEODERIS 2012, *Inventaire des dépôts issus des exploitations minières selon l'article 20 de la directive 2006/21/CE*. Synthèse des résultats (Inventory of deposits from extractive industries, article 20 of 2006/21/CE Directive), RAPPORT N2012/009DE-12NAT2120

Hasselt, IRH 2006, 'Phytostabilisation Difpolmine, Diffuse pollution from mine activity', Final Report, Budapest University, European program LIFE 02 ENV/F/000291, https://www.difpolmine.org/

ITRC 2009, 'Phytotechnology Technical and Regulatory Guidance and Decision Trees', revised, PHYTO-3, Washington, D.C.: Interstate Technology & Regulatory Council, Phytotechnologies Team, Tech Reg Update.

Larcheveque, M, Derochers, A, Bussiere, B & Cimon, D 2014, 'Planting trees in soils above non-acid-generating wastes of a boreal gold mine', *Ecoscience,* vol. 21, no. 3–4, pp. 217–231.

Ministry in Charge of Environment 2017, *Méthodologie nationale de gestion des sites et sols pollués* (French methodology for polluted soils management), DGPR http://ssp-infoterre.brgm.fr/sites/default/files/upload/documents/methodo_ssp_2017.pdf

Mertz, S 2021, *Devenir de contaminants métalliques (Pb, Zn) depuis un dépôt minier ancien: développement d'un modèle de transport réactif* (Fate of metal contaminants (Pb, Zn) from an old mine deposit: development of a reactive transport model), PhD thesis, University of Orléans, Orléans.

Nandillon, R 2019, *Phytostabilisation des éléments métalliques d'un technosol minier végétalisé par le genre Salix assisté par du biochar (*Phytostabilization of the metallic elements of a mining technosol vegetated by Salix assisted by biochar)*,* PhD thesis, University of Orléans, Orléans.

Piramid 2003, *The Passive Remediation of Acidic and/or Metaliferous Mine Drainage and Similar Wastewater,* University of Newcastle Upon Tyne, Newcastle Upon Tyne.

Sheoran, V, Sheoran, A & Poonia, P 2013, 'Phytostabilisation of metalliferous mine waste', *Journal of Industrial Pollution Control,* vol. 29, no. 2, pp. 183–192.