Engineering Geology 223 (2017) 59–70

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Assessment of tailings pond seals using geophysical and hydrochemical techniques

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ARTICLE INFO

Keywords:
Tailings pond
Restoration
Electrical resistivity imaging
Ground penetrating radar
Water quality

ABSTRACT

Tailings impoundments associated with former mining districts are currently sources of pollutants to soils and waters. Because of this issue, many of these tailings ponds have been treated by restoration and sealing processes in recent years.

In this work, the efficacy of geophysical techniques (electrical resistivity imaging and ground penetrating radar) as tools for assessing the effectiveness of the insulating process of these structures has been analysed. For this purpose, we selected the abandoned mining district of Linares-La Carolina (Southern Spain) where, during the mining activity, these materials were stockpiled without corrective measures. This study demonstrates the usefulness of electrical resistivity imaging (ERI) for characterising the inner structure of abandoned tailings ponds, determining the geometry of such deposits and evaluating the potential risks that they pose. Furthermore, ERI makes it possible to visualise higher moisture zones associated with the leaking of leachates that circulate through these residues. The presence of humid areas could denote defects at the sealing stage.

The ground penetrating radar (GPR) technique was very useful for an accurate analysis of the most superficial part, where the seal is constructed. In particular, the technique made it possible to differentiate between various encapsulation levels created during sealing, as well as detect imperfections in the insulation layers and zones with higher moisture at a low depth.

A chemical quality analysis of the surface waters surrounding the dumps studied indicates that, with the exception of As, the concentrations of most metal(loid)s analysed (Al, Ba, Co, Cr, Cu, Fe, Mn, Ni, Pb, Rb, Se, Sr and Zn) have significantly decreased after the restoration works. However, it appears that leaks continue to appear in some sludge pond sectors that favour the mobilisation and even incorporation of certain toxic elements from the mining waste into the riverbed. Therefore, Pb (20 μg/L) and Se (1.5 μg/L) dissolved in the surface waters continue to exceed the maximum concentrations allowed by the European Union environmental quality standards.

1. Introduction

Exploitation of mineral deposits involves a series of environmental changes that, in many cases, can be very negative (Thornton, 1996; Cooke and Johnson, 2002). Despite this, until a few decades ago, no pertinent regulations existed in most countries to protect the environment in this respect. While recent legislation regulates any new exploitation of natural resources, making it much more respectful of the environment, these modifications do not affect abandoned mining areas, which are currently one of the main sources of environmental pollution (Bundschuh et al., 2012; Ji et al., 2013). The old mining districts generated a huge volume of waste (sterile, flotation sludge, smelter slag, etc.) that were accumulated in the vicinity of the facilities without any corrective measures. For this reason, they have polluted the soil and water of the surrounding areas, in many cases for decades after the closure of the exploitation. There are many studies focusing on soils and waters affected by mining operations in different countries, which suggests that this is a worldwide problem (Herbet, 1997; Gratton et al., 2000; Martín-Crespo et al., 2010; Bundschuh et al., 2012; Gómez-Ros et al., 2013; Yun et al., 2016).

The sulphides present in gangues are unstable in the oxidising conditions to which they are exposed. This instability has negative consequences on the environment by generating leachates with high contents of sulphides and certain metallic elements, as has been

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http://dx.doi.org/10.1016/j.enggeo.2017.04.024
Received 24 October 2016; Received in revised form 11 April 2017; Accepted 30 April 2017
Available online 01 May 2017

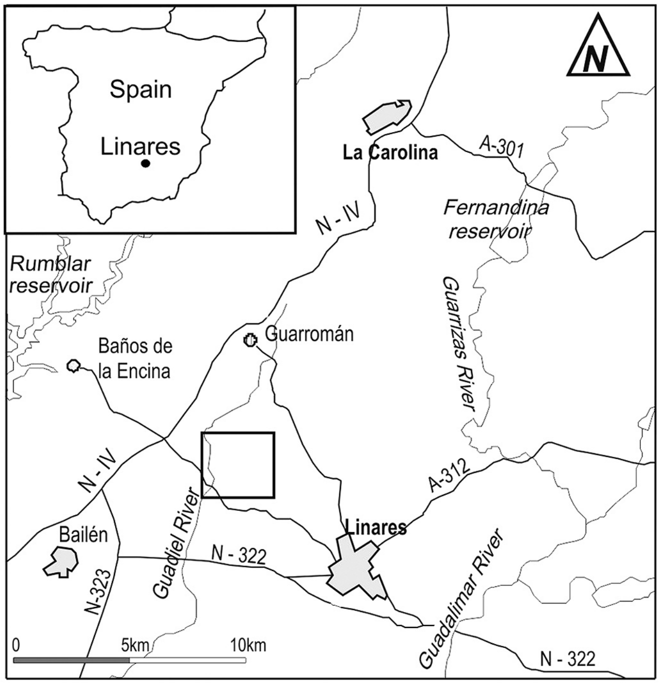

Fig. 1. Location of the study region.

described in different regions (Sobanska et al., 2000; Li and Thornton, 2001; Hidalgo et al., 2006, 2010; Chopin and Alloway, 2007). In addition to this environmental hazard, a serious safety issue exists due to the structural instability of the materials themselves when deposited on a topographic slope with a base that is generally saturated with water (Martínez et al., 2012; Martínez et al., 2014).

These environmental and structural problems make it necessary to characterise both the geometry and the inner structure of this mining waste and to seal it. In this regard, many former mining districts have been conducting restoration works and sealing off waste dams (Bradshaw, 1997; Cooke and Johnson, 2002; Zornoza et al., 2012).

Our study is focused on the metallogenic district of Linares-La Carolina (Southern Spain, Province of Jaen, Fig. 1), characterised by the presence of a phyllonian network of metallic deposits, primarily composed of galena (PbS) (Azcárate, 1977; Lillo, 1992). These mineral deposits had historically been the object of intense exploitation and were then abandoned towards the end of the 1970s. Their vast expanse meant that they were subjected to underground mining for centuries. This activity produced large amounts of waste that was deposited in the vicinity of the mining sites (Contreras and Dueñas, 2010).

This mining activity led to the development of a mineralurgic industry with the creation of many gravimetric and flotation washeries. In the latter process, the mined material was finely ground for subsequent treatment in the flotation plant, where the sterile particles and non–recoverable minerals (e.g., pyrite and arsenopyrite) became part of the tail process. This refuse was transported as an aqueous sludge to the dump, where it was decanted without any prior conditioning because this was not required by law at the time. Thus, the current sludge deposits are composed of medium-fine granulometric materials containing, among other mineral species, sulphides of low economic interest that were rejected by the flotation plant, as well as a small fraction of metallic ore particles that were not used because of a defective extraction technology, poorly developed ore material, or their limited economic value (Martínez et al., 2016).

Starting in 2000, after the passing of regional laws, the various abandoned sludge deposits in Andalusia (Spain) have been inventoried for subsequent planning and execution of corrective measures.

In this context, during the past few years, the regional authorities have closed down and restored several abandoned mining waste deposits. The goal of the proposed actions was to stabilise the deposits both physically and chemically, thereby guaranteeing their structural safety and avoiding any further pollution processes. In general, all projects have been treated by encapsulating the mining sludge.

In this research, we analyse the effectiveness of the treatments of these tailings ponds to determine whether the proposed goal has been achieved. For this purpose, indirect geophysical prospecting techniques have been used; specifically, ground penetrating radar (GPR) and electrical resistivity imaging (ERI). The latter method has been used in the mining district of Linares-La Carolina (Martínez et al., 2012; Rey et al., 2013), as well as in other mining regions (Gómez-Ortiz et al., 2010a; Martín-Crespo et al., 2015; Zarroca et al., 2015), where its usefulness in reconstructing the morphology of tailings ponds, locating water recharge-discharge zones and identifying the contact between the residue and the substrate has been demonstrated. In addition, a hydrochemical study of the groundwater and surface water of the area has been performed to compare the degree of pollution before and after sealing the structures. This methodology for the structural analysis of the tailings ponds and the verification of the effectiveness of sealing them can be extrapolated to other mining regions with similar problems.

2. Description of the study area

In the mining district of Linares-La Carolina, hydrothermal vein deposits are hosted in a Palaeozoic basement and fossilised by a Triassic sedimentary cover. Bedrock is composed of metamorphic rocks (mainly phyllites with alternating quartzites), intensely deformed during the Hercynian orogeny and affected by a granitic intrusion. This Palaeozoic basement is severely fractured and characterised by the presence of a dense dyke network associated with the granitoid massif (Azcárate, 1977; Lillo, 1992). The exploited ore consists of Pb-Ag sulfantimonites and Cu-Fe sulphides. Dominant ore minerals are galena, sphalerite, iron sulphides (pyrrhotite, pyrite, marcasite) and chalcopyrite. Gangue minerals are ankerite, quartz, calcite, amorphous silica, barite, and minor amounts of kaolinite.

For this study, the waste deposits of an old flotation plant (Adaro washery, Fig. 2a), in the mining district of Linares-La Carolina, were chosen. Two tailings ponds currently exist in this sector, one located along the left bank of the Guadiel River (restored in 2011) and another (unrestored) on the right bank. The aim of this study is to assess the dams using geophysical and hydrochemical techniques to evaluate the effectiveness of the sealing techniques employed.

A sub-vertical vein deposit with a N90-100E strike was exploited in the study area (Fig. 2a). This ore vein is hosted in the granitic body, which outcrops around the tailings ponds and presents an intense surficial weathering. On the other hand, this granite becomes very competent with depth, except in fracture zones.

During the 20th century, the vein was exploited by means of the sublevel stoping technique, which was based on drifts separated by 35 m. The ore was extracted collapsing the lower drift, resulting in a mining void with an average width of 1.7 m. Exploitation depths were variable, reaching 400 m in this sector. The extracted material was treated in the mine vicinities (Fig. 2a) and the wastes were accumulated in two tailings impoundments.

The first tailings pond consists of a sizable hillside heightening of the dam. It has a length of 160 m, a width of 120 m and a depth of approximately 35 m, with an estimated volume of 300,000 m^3. Fig. 2 shows two photographs of the tailings pond. The first picture (Fig. 2b), taken before the restoration, shows enormous gullies associated with sludge flows towards the Guadiel River. This process even led to repeated obstructions of this section of the river damaging the fluvial ecosystem. The second picture (Fig. 2c) shows the current state after restoration.

Prior to the restoration, a characterisation of the dump was undertaken (García-Fernández and Gallego, 2009). Initially, 13 surface